ABSTRACT

Title of Document: SIMULATION AND ANALYSIS OF ENERGY CONSUMPTION FOR TWO COMPLEX AND ENERGY-INTENSIVE BUILDINGS ON UMD CAMPUS

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The Microbiology Building and Hornbake Library are two multi-purpose and complex buildings, and are among the highest energy-intensive buildings on the University of Maryland College Park Campus. This thesis details the energy analysis and energy consumption models developed to identify energy savings opportunities for these two buildings. Three reports are given per building: one – a comprehensive summarization of relevant building information; two – a utility analysis, including an energy benchmarking study, evaluating the relative performance of each facility; three – a detailed energy model to replicate current operation and simulate potential energy savings resulting from no-and-low cost energy conservation measures. In total, 11 of the 12 measures simulated are strongly recommended for implementation. The predicted combined energy and utility savings are respectively 18,648.4 MMBtu and $436,128 annually. These actionable proposals to substantially reduce the buildings' energy consumption contribute to the University's commitment to achieve greater energy efficiency throughout campus.

SIMULATION AND ANALYSIS OF ENERGY CONSUMPTION FOR TWO COMPLEX AND ENERGY-INTENSIVE BUILDINGS ON UMD CAMPUS

by

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Professor Michael Ohadi, Chair
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Dedication

This paper is dedicated to my loving, patient, and devoted mother and father, Janis C. Long and Harry A. Savage.

Acknowledgements

I owe my time and success at the University of Maryland to my advisor, Dr. Michael Ohadi, for whose trust and support I offer my sincerest gratitude. Many thanks are also due to the UMD Facilities Management Department’s Chauncey Jenkins, whose instrumental role as an insightful and charming emcee cannot be understated. I also would like to give thanks to office-mates Stefan Bangerth, Fabio Bataglia, and Nail Rachidi for their welcome assistance and comforting presence in the lab. Dr. Farah Singer provided meaningful support in editing and finalizing this report. Finally, I am glad to acknowledge UMD faculty and staff members Kevin Fahey, Dorothea O’toole, Anne Turkos, Dr. Amir Shooshtari, and the late Dr. Serguei Dessiatoun, for their assistance.

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Nomenclature

ACH – Air Changes per Hour
AHU – Air Handling Unit
ASHRAE – American Society of Heating, Refrigerating, and Air Conditioning Engineers
BAS – Building Automation System
BMS – Building Management System
CAV – Constant Air Volume
CBECS – Commercial Building Energy Consumption Survey
CDD – Cooling Degree Day
CFM – Cubic Feet per Minute
CHW – Chilled Water
DHW – Domestic Hot Water
DDW – Desiccant Dehumidification Wheel
DDS – Desiccant Dehumidification System
ECM – Energy Conservation Measure
EEM – Energy Efficiency Measure
EF – Exhaust Fan
EIA – Energy Information Administration
EPA – Environmental Protection Agency
ERS – Energy Recovery System
EUI – Energy Use Index
E+ – EnergyPlus (an open domain building energy simulation environment)
FCU – Fan Coil Unit
FM – Facilities Management
HBL – Hornbake Library
HDD – Heating Degree Day
HHW – Heating Hot Water
HVAC – Heating, Ventilation, and Air Conditioning
KBTU – One Thousand British Thermal Units
KEB – Kim Engineering Building
LEED –Leadership in Energy and Environmental Design
MAH – Makeup Air Handler
MB – Microbiology Building
MBH – One Thousand British Thermal Units per Hour
MMBTU – One Million British Thermal Units
OA – Outside Air
PSI – Pounds per Square Inch
PSIG – Pounds per Square Inch (Gauge Pressure)
RAF – Return Air Fan
SAF – Supply Air Fan
SAT – Supply Air Temperature
SCUB – Satellite Central Utilities Building
UMD – University of Maryland
VAV – Variable Air Volume
VCB – Variable Control Box
VFD – Variable Frequency Drive
VRF – Variable Refrigerant Flow

Chapter 1: Introduction

1.1 Project Background and Goals

1.1.1 Project Background

This project is a continuation of the ambitious efforts enacted by the University of Maryland's (UMD's) Energy Sustainability Office and Facilities Management to reduce the campus' building energy consumption and carbon footprint. By the year 2020, UMD aims to reduce its electric consumption and purchased potable water, as well as its greenhouse gas emissions by 50% (Sustainability at UMD, 2014). Two top strategies and priorities in achieving these goals are "conducting existing building retrofit and making research-related resources that relate to energy efficiency and economic and environmental sustainability available to the campus" (UMD Climate Action Plan, 2009). In keeping with these two goals, the University has supported student-led research into energy auditing and modeling techniques as a prudent way of identifying and assessing potential retrofit feasibility, as well as making promised research-related resources available to the campus. This project was supported by some of these resources through UMD's Center for Environmental Energy Engineering (CEEE), co-founded by this project's director Professor Michael Ohadi.

1.1.2 Project Goals

The primary goal for this project was to produce energy models of two complex, multi-purpose, with energy consumption intensities that are among the highest of the buildings on UMD campus. These are the Microbiology Building (MB) and Hornbake Library Building (HBL).

Comprehensive energy models for these buildings can be used in energy projects to provide actionable suggestions for energy conservation measures (ECM's), simulate the impacts on thermal conditions due to operational changes, assess the economic feasibility of major retrofits, as well as directly predict future utility bills as a function of expected changes to the region's climate.

A second aim of this thesis is to propose a series of no or low-cost ECM's that will reduce annual utility consumption substantially. Achieving these goals will result in two major consequences: reduced utility costs and lowered annual energy consumption per square foot of floor space, measured as energy use index (EUI).

The project follows the works of two other CEEE members, Levy (2013) and Bangerth (2014), in which two independent energy audits and models were conducted on the Kim Engineering Building and Denton Dining Hall. Their efforts identified combined energy savings opportunities totaling 25,860 MMBtu and accompanying annual cost savings of $573,132 per year (Bangerth, Ohadi, & Jenkins, 2017).

Following the successful completion of these two highly-technical and challenging projects, the Microbiology Building and Hornbake Library were identified by UMD Facilities Management (FM) as two of the most energy intensive buildings on campus and thus ideal candidates for continued research in energy auditing and modeling practices.

A final aim of this project is to strengthen the relationships established by Levy, and Bangerth as well as foster communication between students, faculty, and FM staff in order to encourage sustainable education and provide guidance on similar projects in the future.

1.2 Energy Modeling

1.2.1 Energy Modeling Overview

According to the 2013 U.S. Energy Information Administration (EIA), global energy use was 524 quadrillion BTUs in 2010 and is predicted to grow by 56% from 2010 to 2040. The U.S. consumes the second largest amount of energy annually, behind only China, accounting for 19% of global energy consumption in 2010 (U.S. EIA, 2013). In the United States, the buildings sector is responsible for approximately 41% of primary energy consumption in 2010, 22% from residential buildings and 19% from commercial buildings (U.S. DOE, 2012).

However, the potential for energy savings in buildings is widely acknowledged. A 2009 review conducted by the Pacific Northwest National Laboratory indicated that a reasonable range of energy savings in existing commercial buildings falls between 10-20% (Belzer, 2009). The American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 90.1 – 2011: *Energy Standard for Buildings Except Low-Rise Residential Buildings* provides full-scope strategies and technical guidance to achieve at least 30% energy savings using multiple targets (ASHRAE, 2011). ASHRAE also provides function-specific Advanced Energy Design Guides for achieving additional energy savings up to 50% to registrants (ASHRAE, 2017).

Building Energy Modeling is defined as physics-based software simulation of building energy use. Two key applications for this technology are in retrofit design, and analysis of energy consumption. Accurate models of energy consumption projections work in support of minimizing energy use without compromise on comfort and indoor air quality in the buildings.

A building energy model takes a description of a building that includes geometry, construction materials, lighting, HVAC, refrigeration, water heating, and control strategies, as well as descriptions of the buildings use and occupancy as inputs. Combined with inputs on local weather conditions, a simulation engine consisting of physics equations, specifically those relating to thermodynamic and heat transfer processes, is used to calculate thermal loads and the subsequent energy consumed to manage these loads. Figure 1 illustrates this general dataflow of a building energy model simulation instance (Maile, Fischer, & Bazajanac, 2007).

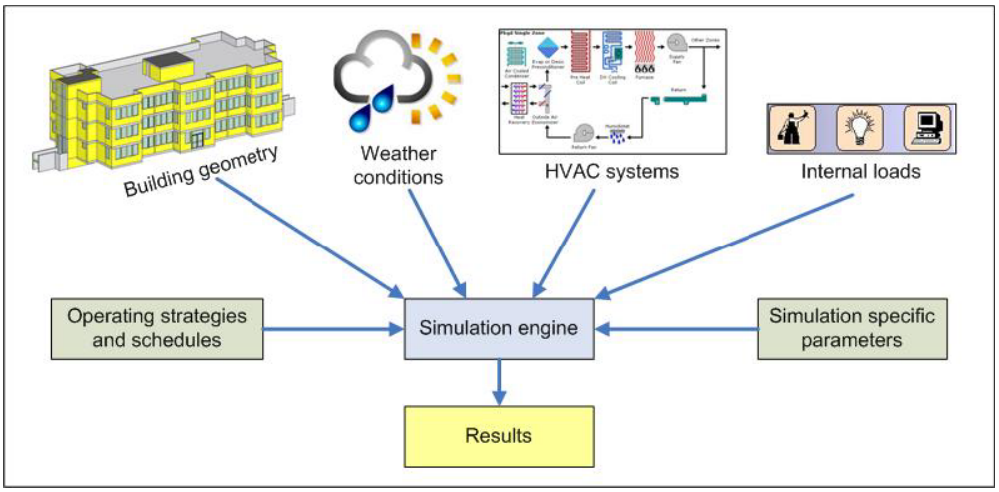

Figure 1: General data flow of building energy models

Building energy models excel in their ability to simulate a multitude of complex systems and interactions with relative ease and efficiency. Their results are useful for a broad range of applications including architectural design, HVAC design and operation, building performance ratings, and building stock analysis. (U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy., n.d) Furthermore, in the context of university campuses, engineers, facility managers, faculty and staff, as well as students must all be engaged in the development of a successful building energy model, and the resulting work can determine or advise collaborative strategies to lower campus energy consumption in a cost-effective manner.

The United States Department of Energy (DOE) has been actively supporting research, development, and deployment of building energy modeling since the 1960's. All three of their major building energy modeling software packages: eQUEST, EnergyPlus, and OpenStudio were utilized throughout the course of this project. A brief discussion of these simulation environments are discussed next.

1.2.3 Energy Modeling in eQUEST

The eQUEST simulation environment is underpinned by the DOE-2.2 engine. Originally designed to study whole-building energy performance during the design, DOE-2 was sponsored by the DOE, though its source code predates the department and originates back to the 1960's. Steady development continued under the Lawrence Berkeley National Laboratory until its last official release in 1994. DOE-2.2 remains one of the most widely used thermal simulation engines for its ease of use, fast simulation times, and the vast library of knowledge and expertise accumulated from its long-standing presence in the marketplace (Crawley, et al., 2001).

The DOE-2 engine simulates the thermal behavior of spaces in without data feed-back. As illustrated in Figure 2, user inputs are combined with the materials, and construction library into the Building Description Language (BDL) input processor which transforms the inputs into an appropriate data format that is used by the four subprograms. User input data specifying building geometries need to be simplified from real geometries.

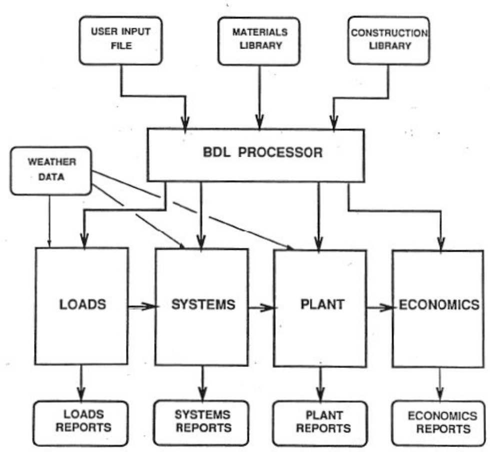

Figure 2: Dataflow of the DOE-2 thermal simulation engine

The four subprograms: LOADS, SYSTEMS, PLANT, ECONOMICS, are executed sequentially. The LOADS subprogram uses the BDL descriptions and weather data to calculate heat losses and gains. Assumed heating and cooling loads of related systems at fixed space temperatures govern these calculations. The second subprogram, SYSTEMS, uses the calculated gains and losses to determine additional heating or cooling needs for each space according to user-defined temperature set points. The PLANT subprogram then calculates the fuel requirements of HVAC components to meet the calculated loads found in the SYSTEMS subprogram. Lastly, the ECONOMICS subprogram calculates the cost based on these fuel requirements and utility pricing structures (Birdsall, et al., 1990) however, this subprogram was not utilized during this project.

DOE-2 has several limitations, many of which are explicitly stated official user manuals. As mentioned previously, lack of data-feedback can cause thermal comfort simulation results to be inaccurate. DOE-2 assumes well-mixed space temperatures and is therefore not useful for simulating spaces containing defined hot-spots as may occur in data centers. Some notable DOE-2 HVAC omissions include solar thermal, radiant cooling or heating systems, and the ability to directly model steam loops (Hirsch, J. H. & Associates, 2010).

1.2.4 Energy Modeling in EnergyPlus and OpenStudio

EnergyPlus is an open-source (public domain) program built from two existing programs: DOE-2 and BLAST. Originally sponsored by the Department of Defense (DOD) in the early 1970's, development of both of these programs continued to be supported by the federal government for several decades.

Development of EnergyPlus began in 1996 and was a project meant to merge the best capabilities and features from both of its parent programs. Although EnergyPlus was based on DOE-2 and BLAST, its code was written from scratch in a joint effort from U.S. Army Construction Engineering Research Laboratories (CERL), University of Illinois, Lawrence Berkeley National Lab (LBNL), Oklahoma State University, and DOE (Crawley, 2001).

Figure 3 shows the program structure of EnergyPlus (Illinois). EnergyPlus was developed with the expectation that third-party user interfaces would be developed. In this way, third-party software can be used to create a text file that describes the building of interest, pass the file to EnergyPlus for the annual energy simulation, and view results in graphics or spreadsheets. Two open-source third-party software packages were utilized in this project for a more user-friendly interface. The first is Trimble SketchUp Make, an architectural tool that was used to define the location of all surfaces and nodes in three-dimensional space. The second is OpenStudio, a "cross-platform collection of software tools to support whole building energy modeling using EnergyPlus" (National Renewable Energy Laboratory). OpenStudio can be used to develop a complete energy model for simple buildings or can be used to lay the foundation of an energy model for complex projects. The OpenStudio software package contains a plug-in for SketchUp which allows both programs to be used simultaneously.

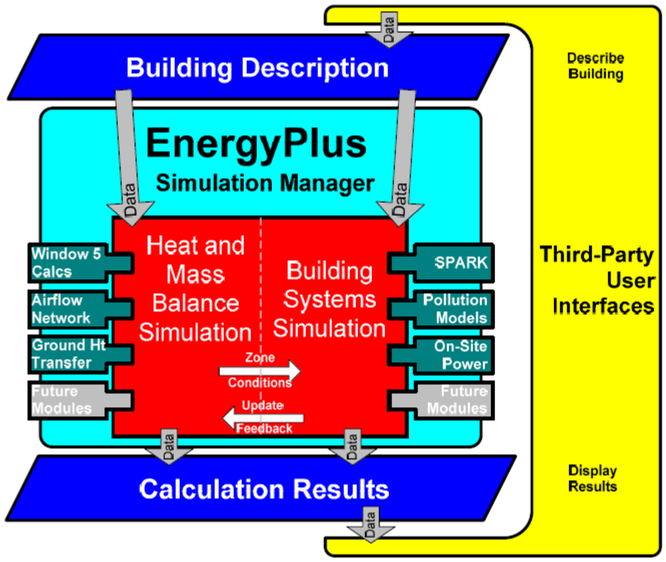

Figure 3: EnergyPlus program structure

Chapter 2: Literature Review

2.1 Energy Savings and Sustainability on U.S. Academic Campuses

An increasing focus on energy efficiency and sustainability is taking place nationwide. State and local governments are investing more resources to actively monitor, analyze, and reduce municipal energy consumption. States like California and Washington, as well as cities such as Philadelphia, New York City, Chicago, and Washington DC have enacted energy benchmarking laws that require building owners to report their annual energy consumption (Coven, 2017). Furthermore, the large size, population and complexity of many university campuses cause many to regard such campuses as 'small cities'. As such, the University of Maryland (UMD) is one of over 650 colleges and universities that have signed the American College and University Presidents' Climate Commitment (ACUPCC) which is described as "a high-visibility effort to address global climate disruption undertaken by a network of colleges and universities that have made institutional commitments to eliminate net greenhouse gas emissions... and to promote the research and education efforts of higher education to equip society to re-stabilize the earth's climate (The Presidents' Climate Leadership Commitments, 2015). Since first signing in 2007, UMD has put forth a Strategic Plan in 2008, a Climate Action Plan in 2009, a Facilities Master Plan in 2011, a Sustainable Water Use and Watershed Report in 2014, and several other guiding documents relating its actions in achieving sustainability. UMD's 2016 Progress Report states among other things that "UMD has achieved a 22% reduction in greenhouse gas emissions compared to 2005… expanded and restructured its internal energy management program by creating a department of Energy and

Engineering within Facilities Management… and purchased 65,081,000 kWh of renewable energy."

The goal of sustainability can be met with economic resistance as building retrofits and renewable energy projects are capital intensive. As stated in the UMD 2015 Climate Action Plan Progress Report, "Some aspects of the Climate Action Plan have saved our institution money (such as energy conservation measures and power purchase agreements) while other aspects are costly and do not save the institution money (such as adding public transit routes, installing bicycle infrastructure, adding positions to support climate action plan implementation, compostable bags for food waste collection and others). Since our institution is so decentralized, we have not done a comprehensive analysis of costs and savings across all departments. We believe that the energy savings will eventually outweigh most of the costs, but the upfront investments have not yet been paid back from the savings achieved to date" (University of Maryland, 2015). Energy conservation measures such as those presented in this thesis, can offer low- or no-cost ways to reduce energy consumption, greenhouse gasses, and utility bills and are a foundational component to any campus sustainability effort (Alshuwaikhat & Abubakr, 2008).

Many of these energy conservation measures have been recognized for decades. In a 2003 pamphlet distributed to customers of the energy company National Grid entitled "Managing Energy Costs in Colleges and Universities," some of the "quick fixes" include turning off lights, computers, office equipment, and chilled-water drinking fountains, as well as closing laboratory vent hoods, and implementing building management systems" (E Source Companies LLC, 2003). As we will see, there is still room for improvement in implementing many of these simple but recognized energy conservation measures in buildings on campus.

2.2 Laboratory Energy Strategies

Research laboratories face unique and significant challenges when developing sustainability plans and energy management strategies. Labs are typically 3-to-4 times more energy intensive than an average commercial building and can account for 40-70% of a given campus' energy consumption. Furthermore, efforts to reduce energy consumption in labs often conflict with standards and guidelines to ensure safe air quality, relatively high lighting densities, and operation of energy intensive equipment in the presence of hazardous materials.

Working to reconcile these conflicts, The Lawrence Berkley National Laboratory (LBNL), funded by the U.S. Department of Energy (DOE) and Environmental Protection Agency (EPA), is a leader in energy efficient design and operation of buildings in numerous sectors. Their Laboratories for the 21st Century (Labs21) program "provides facility designers, engineers, owners, and facility managers with tools, resources, and innovative solutions for designing, constructing, and maintain sustainable laboratory facilities (Laboratories for the 21st Century, 2003)." Their program aims to exceed many of the minimum requirements for energy-efficient building design given by ASHRAE Std. 90.1: *Energy Standards for Buildings* (ASHRAE, 2011). Such an additional effort is necessary due to the broad scope of Std. 90.1 which omits energy requirements targeted to laboratories as a trade-off for offering a broader scope of requirements applicable across multiple sub-categories of commercial buildings. Table 1 lists each of the Labs21 tools along with their general purpose (Wirdzek, Lintner, Mathew, & Carlisle, 2004).

Table 1: The Labs21 toolkit

Tool	Purpose
Design process tools:	
Labs21 Process Manual	Guidance for sustainable design process.
Design Intent Tool	Documentation of design intent – objectives, strategies, metrics.
Environmental Performance Criteria	Point-based rating system for sustainability, based on LEED™.
Core information resources:	
Design Guide	Reference manual on energy efficiency features in laboratories.
Best Practice Guides	Information on design, construction and operation of specific technologies and strategies.
Case Studies	Whole building case studies of high-performance laboratories.
Energy Benchmarking	Energy use data for laboratory systems and buildings.
Overview resources:	
Intro to Low-Energy Design	Overview of key strategies for high performance labs.
Labs21 Video	Examples of high performance labs.

A number of these tools proved invaluable throughout the course of the research. Documented Case Studies conducted between 1999 and 2010 were to gain insight to common practices in designing and retrofitting laboratories for sustainability (I2SL, 2010). A total of 13 case studies were reviewed for featured technologies incorporated in their design. The frequency of the featured technologies is displayed in Figure 4.

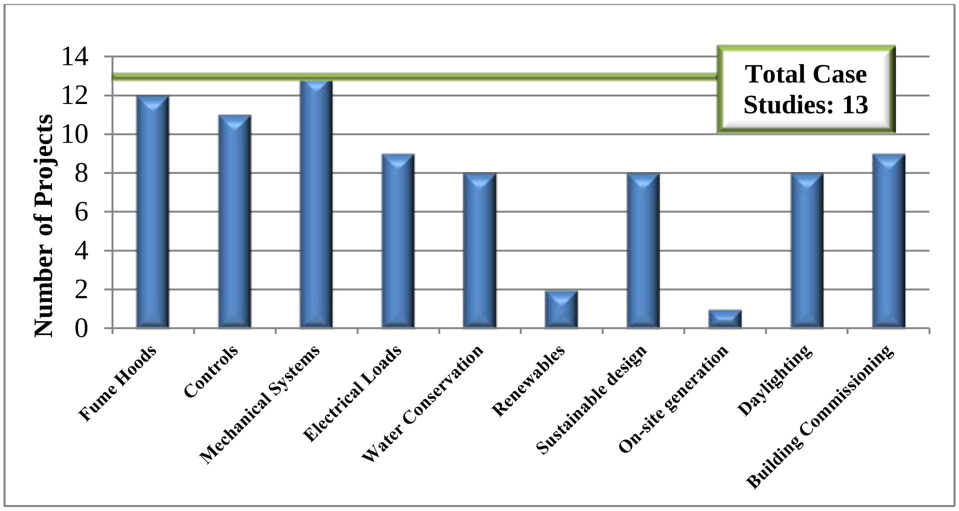

Figure 4: Frequency of technologies featured in Labs21 case studies

From this figure, we see fume hoods (use of reduced velocity fume hoods), controls, and mechanical systems are virtually ubiquitous featured technologies in the case studies reviewed. This is relatively unsurprising as fume exhaust, ventilation methods, mechanical systems, and the controls governing these technologies are all directly related and make up a majority of labs' energy consumption in almost every case. Details and lessons learned from these case studies will be referenced throughout this report.

The latest effort by the DOE to encourage sustainability in laboratory buildings is the Smart Labs Accelerator program as set forth by The Better Buildings Initiative in 2016. The program is one of a set of "Better Building Accelerators designed to demonstrate specific innovative approaches which… will accelerate investment in energy efficiency." Partners of the Smart Labs Accelerator program agree to establish energy efficiency targets, develop and share their plans with the DOE, as well as collaborate and share with other partners in their efforts in achieving the energy efficiency targets.

2.3 Library Energy Strategies

Unlike laboratories, libraries are not generally known for high energy consumption patterns. As will be discussed in Section 5.2.2, the average nationwide library energy use intensity (EUI) is around 3 times less than that of labs. As such, there is no government-sponsored Labs21 equivalent program dedicated to sustainable design of libraries. Nonetheless, libraries can be incredibly large facilities requiring specific strategies to reduce and mitigate energy consumption. The Library of Congress Office of the Inspector General conducted a survey of the library's energy conservation efforts in July, 2009 (Schornagel, 2009). The report stated that "[The Library of Congress] has adopted the spirit of the Energy Policy Act of 2005 (EPACT, 2005) and the Energy Independence and Security Act of 2007 (EISA). Among other things, these require: Reductions in annual energy use (up to 30 percent by fiscal year 2015 as compared to fiscal year 2003); An energy audit of all congressional facilities every four years; Developing and implementing a cost-effective energy and water conservation plan for all congressional facilities; and Annual reports to Congress which document actual past performance and specify plans and expectations." Since 2005 the Capitol Complex has met or exceeded their energy reduction goals. They have done this by, among other things, "replacing existing chilled water pump motors with premium efficiency motors,… installing variable frequency drives on pump motors, replacing air handler fan motors with premium efficiency motors,… replacing magnetic ballasts,… [and] installing occupancy sensors in designated areas."

ASHRAE requires fewer air changes per hour (ACH) for libraries than for laboratories. This generally results in lower relative energy expenditures for heating and cooling. In addition, ASHRAE 90.1 requires a lighting power density of 1.7 W/ft2 in stacks; this among the highest of any lighting power density in any building sector. For these reasons, University Library energy audit case studies and retro-fit projects tend to focus on reducing electricity consumption specifically on the end use of lighting.

San Jose State University (SJSU) implemented spectrally enhanced lighting at their flagship building, the Dr. Martin Luther King, Jr. Library (King Library). Spectrally enhanced lighting is the practice of changing the color of light to be closer to daylight, causing spaces to appear brighter. By retrofitting the existing fixtures and ballasts with SEL ballasts and installing motion sensors to the stack areas, SJSU was able to reduce lighting energy consumption by 72%, reduce maintenance costs, and recoup the $1.3 million investment within 2.28 years (Center, 2010). A 2012 lighting retrofit conducted at California State University Chico's Meriam Library consisted of the replacement of 5,300 lighting fixtures as well as the installation of 60 occupancy sensors. Existing T12 fluorescent lamps with standard ballasts were replaced with more efficient 28-watt T8 lamps and low power ballasts. After a photometric study was conducted, the team concluded that the retrofit could also remove 940 fixtures entirely without compromising the appropriate lighting levels. In total, the project invested $637,000 and accomplished annual energy and cost savings of 889,600 kWh and $110,300, respectively.

While these projects highlight successful retrofit projects, they don't include a full building energy analysis or simulation. A 2015 study conducted in Tianjin Polytechnic University, China performed a full simulation and analysis of a university library energy consumption based on the DOE building simulation software eQUEST. In this study, researchers used the control variables method to examine the effects that adjusting lighting power density, occupant density, summer indoor design temperature, and summer supply air temperature had on annual energy consumption. Similar to the conclusions stated above they found that lighting power density had the greatest impact on annual energy consumption (Song, Zhang, & Meng, 2015).

2.3.1 Special Collections/Sensitive Materials

Large institutional libraries often house a significant population of special collection and sensitive materials. As will be discussed in the next chapter, these materials require careful temperature and relative humidity control to preserve their condition. In these cases, strategies to reduce energy consumption and improve sustainability are more complex. The National Archives and Records Administration (NARA) has one of its largest storage facilities located only minutes from the UMD College Park campus, and is a prime example of a facility that requires such environmental conditions. The NARA releases annual Strategic Sustainability Performance Plans which detail their strategies to "reduce energy intensity 30% by FY 2015 as compared to FY 2003 baseline." The NARA exceeded their goal, reducing their EUI 37% to 114 $kBtu/ft^2$ (Sprouse, Pham, & Anderson, 2016). To accomplish this, the NARA implemented the following energy conservation measures at each facility:

- "Upgrade and optimize energy management control systems;
- Improve heating plants;
- Reduce steam distribution losses;
- Rebalance HVAC systems;
- Re-set condenser water temperature;

- Reduce water usage;
- Reduce bathroom exhaust fans run times;
- Retrofit lighting and controls;
- Upgrade building envelopes."

The funding for these measures came through two Energy Savings Performance Contracts, one of $5.8M the other of $5.7M, with 7 and 8-year respective return on investments.

Chapter 3: Building Descriptions

3.1 Microbiology (MB) Building Overview

The Microbiology Building (MB), Bldg. 231 at UMD, is a mixed-use research, teaching, and administrative facility. Originally constructed in 1932 as the United States Bureau of Mines Building, the University of Maryland received ownership in 1968 and is presently supported by the UMD Department of Cell Biology and Molecular Genetics. Figure 5 shows the main entrance (facing east) of MB.

Figure 5: The University of Maryland Microbiology Building (Bldg. 231)

MB has undergone numerous renovations the approximate cost of which totals $25,506,861, and the building was renamed the Microbiology building after one such renovation in 1980. The building houses multiple chemical and biological research laboratories including an Animal Care Unit and a Biosafety Level 3 (BSL3) laboratory "appropriate for work involving microbes which can cause serious and potentially lethal disease via the inhalation route" (Wilson & Chosewood, 2009). MB has a replacement value, defined as the total design and construction cost to replace the building to modern codes/standards, of $51,013,722 and is designated a Facility Quality Index Code 4: "Comprehensive modernization" by UMD Facilities Management (FM). Including the ground floor, it is a five-story building with a gross floor area of 88,285 ft^2 and a net assignable floor area of approximately 50,000 ft^2.

The facility exemplifies a "mixed-use laboratory" in function and floor plan lay-out. Apart from teaching spaces, all of which are located on the first floor, an example of each of the building's main functions can be found on every floor. Lab, office, and storage spaces are found on each floor, both in the core and perimeter of the building. Figure 6 shows a floor plan of MB's first floor obtained from FM archives, and Table 2 details the floor space designated to each of the buildings principle activities.

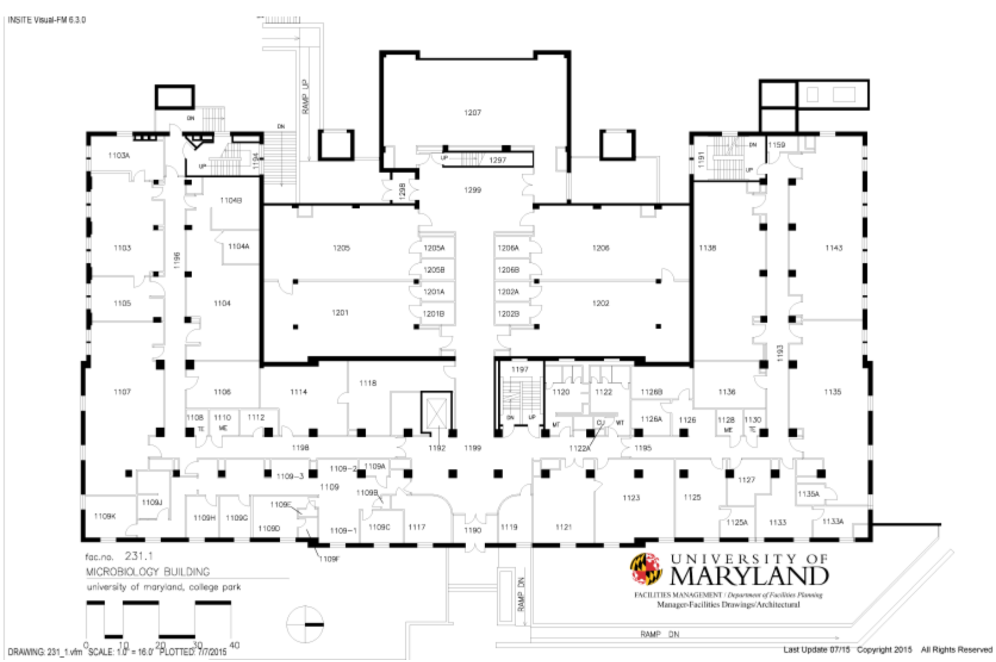

Figure 6: First Floor Plan of MB

Table 2: Floor space allocation in MB by principle space activity

Principle Space Activity	**Floor Area [ft^2]**	**Percentage of Net Assignable Floor Area**
Laboratory	16670	30%
Mech. Engineering	12340	22%
Corridor	8929	16%
Office	8010	15%
Other	5847	11%
Classroom	3111	6%
Total	**54907**	**100%**

MB's doors are open from 7:30 a.m. to 5 p.m. Sunday through Saturday; though the building can be entered by approved student, staff, and faculty 24 hours through swipe card access. While occupant density typically mirrors normal business hours, researchers occasionally occupy office and lab space late into the night. For this reason, the building holds constant operating conditions at all times.

3.2 Microbiology Building Details

3.2.1 Architecture and Lighting

Architectural drawings were unavailable during the course of this audit. Thus, all data presented in this section was collected via inspection through building walk-throughs conducted with the guidance of Facility Management personnel.

The category of envelope construction of MB is almost certainly that of a brick veneer/reinforced concrete block cavity-wall. The brick veneer and concrete blocks are clearly visible from the exterior and interior of the building, respectively. Furthermore, sources indicate that this method of construction gained widespread use in the 1920's immediately prior to the building's original construction (AWT, 2015).

Figure 7 shows a schematic of the construction of this type of wall (Masonry Systems).

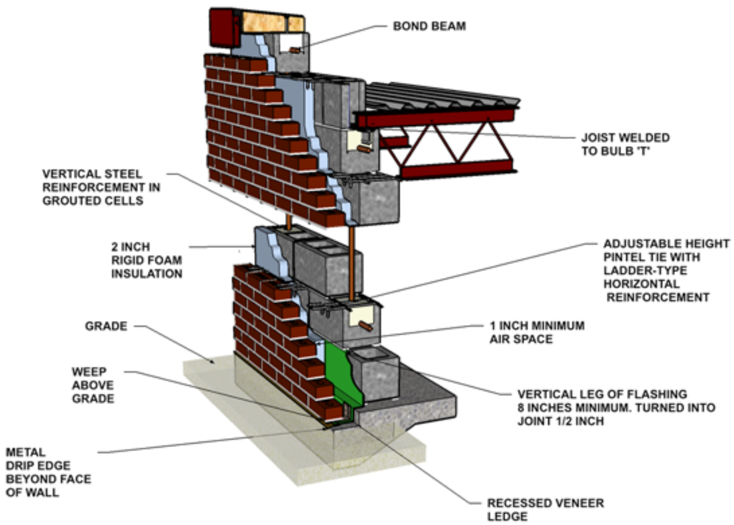

Figure 7: Schematic of brick veneer/reinforced concrete block cavity-wall

R-values of these types of walls can vary substantially between 3.0 hr-°F-ft^2/BTU having only an air-gap as insulation to as much as 20.6 hr-°F-ft^2/BTU with 1" of polyisocyanurate rigid foam board insulation (The Brick Industry Association, 1998). Due to the age of the building it is reasonably assumed that the actual R-value falls on the low end of this range of values.

Ceiling heights throughout the building were relatively uniform apart from the small atrium space on the first floor, the unconditioned penthouse, and the large basement mechanical room. Corridors were measured to be 10ft and all other working spaces were approximately 12ft.

Fenestration details were collected by measuring the dimensions of easily accessible windows and doors with measuring tape and applying these measurements as appropriate throughout the building.

A building-wide lighting retrofit, in which existing T12 fluorescent bulbs were replaced with more efficient T8 fluorescent bulbs, was conducted in 2013. Furthermore, during a building walk-through, no substantial task lighting was observed.

3.2.2 Laboratory Equipment and Environmental Chambers

MB houses a number of specialized laboratory equipment. Most notably, there are 2 steam autoclaves, 11 ultra-low-temperature freezers, 8 environmental chambers, and no less than 20 constant volume fume hoods, through which the vast majority of exhaust air exits the building. Other equipment identified included centrifuges, refrigerators, computers, and microscopes.

3.2.3 Heating, Ventilation, and Air Conditioning (HVAC)

MB consumes energy from three energy commodities: electricity, district steam, and district chilled water. Electricity is purchased from the grid and has a multitude of end uses. These include lighting, motors powering fans pumps and compressors, computers, laboratory equipment, ultra-low-temperature freezers, environmental chambers, and other various plug loads. Steam is received from the University of Maryland Combined Heat and Power Plant (CHP) at saturated conditions under a pressure of 115 psi before being reduced to medium and low pressure steam. Steam is used to heat water for domestic and heating end uses, as well as consumed in the building’s autoclaves to sterilize laboratory equipment.

Chilled water (CHW) is a closed loop system that is cooled in heat exchangers within a Satellite Central Utilities Building (SCUB) located approximately .5 miles from MB. Chilled water enters MB at a design temperature of 42°F and is used solely in cooling coils within the facility's air handlers. The chilled water is subsequently returned to the SCUB plant.

MB employs a dedicated outdoor air HVAC system (DOAS) with control air volume (CAV) and variable air volume (VAV) reheat. Six Air Handler Units (AHU) preheat and/or precool 100% outdoor air for the entire facility. This set-up is common practice due to the presence of volatile chemicals and other biohazards. In other words, there are no return air paths and all supply air is directly exhausted from the building.

The building's AHU layout is done primarily with respect to building wings. AHU-1 serves the north wing with the exception of the basement Animal Care unit, which is served by AHU-4a/b. AHU-2 serves the entire East wing of the building as well as the corridors of the core of the first floor. AHU-3 serves the south wing, AHU-5 serves the north wing, and AHU-6a/b is dedicated to BSL-3 laboratory on the fourth floor. Figure 8 shows the layout of AHU supply air on MB's first floor. After examining this AHU layout and similar layouts of the other floors, it was concluded that due to the mixed-use allocation of floor space, each and every AHU serves both laboratory and office space.

Figure 8: MB First Floor Supply Air Layout

AHU's 1,2,3,5 are all schematically similar. They each contain (in sequential order of air processing) an outdoor air damper, a pre-filter, a glycol energy recovery coil, a hot water heating coil, a chilled water cooling coil, and a draw-through supply fan. These AHU's differ in their coils' respective heating capacity and fan power, as well as their supply air temperature setpoint. After air is discharged from an AHU, it travels through a ducted path to a hot water reheat terminal unit, either VAV or CAV, and is discharged at the temperature set by a thermostat located within the space.

AHU-4a/b provides the basement Animal Care unit with 100% outside air. The system consists of two air handlers (AHU-4a and AHU-4b) that are identically configured and operate on a 30 day rotation. Each has an outdoor air damper, pre-filter, chilled water (CHW) cooling coil, hot water heating coil and a draw though supply fan. Supply air is delivered from AHU-4a/b at a constant 60°F and reheated via hot water coils in VAV terminal units and is discharged at 72°F. AHU-4a/b also has humidifier integration in between supply air from the air handler and the VAV terminal units to maintain a relative humidity setpoint of 50%. A summary of MB's HVAC specifications are shown in Table 3.

Table 3: MB AHU Design Specification Summary

	AHU-1	AHU-2	AHU-3	AHU-4a/b	AHU-5	AHU-6a/b
Location	Main Mechanical Room					4th Floor Mech.
Service Area	North Wing	East Wing	South Wing	Animal Care Unit	West Wing	4th Floor BSL3 Lab
System Type	DOAS w/ CAV and VAV Reheat					
VFDs	No	No	No	No	No	No
Energy Recovery Coil	Yes	Yes	Yes	No	Yes	No
Design CFM	17,000	32,000	17,000	4,200	21,500	3,000
Total Static Pressure (in H_2O)	3.5	3.2	3.2	4	3.5	3
Supply Fan HP	30	50	30	10	40	10
Return Fan HP	-	-	-	-	-	-
CHW Cooling GPM	200	370	200	60	240	40
HW Pre-heating GPM	55	105	55	15	70	10

3.2.4 Building Automation System (BAS)

Two different and independently operating BAS' were present in MB. A Talon/AX system monitors and controlled the operation of the exhaust and energy recovery ventilation system as well as AHU 6a/b, while a separate "main" system, designed and installed by Automated Logic Corporation (ALC), monitored or controlled the remaining AHU's, environmental chambers, steam loop, CHW loop, and select office VAV terminal reheat units. No evidence was found to suggest that these systems communicated in any way. The ALC server's "Logic" tab was used to determine AHU control schemes and sequences and historical "trend" data was crucial in identifying operational issues. Figure 9 shows an example AHU graphically represented in the ALC server. As we can see, multiple temperature stats, coil valve operation, and pre-filter status are all points for gathering historical data useful in evaluating AHU performance.

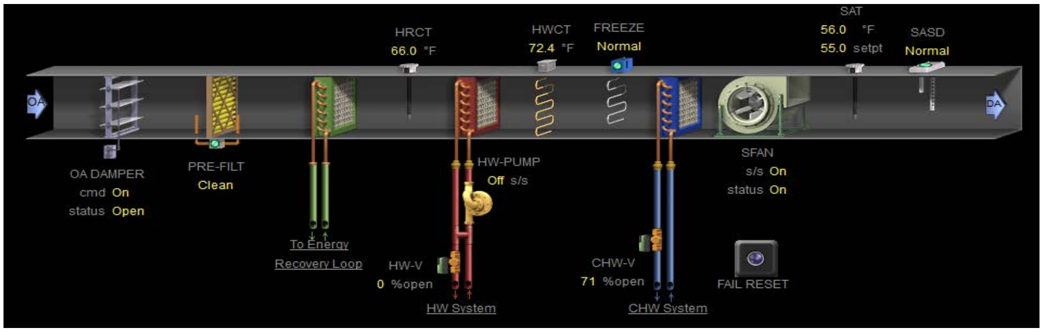

Figure 9: Graphical representation of AHU-2 as shown in ALC BAS

Both BAS' provide opportunities to implement detailed scheduling and optimize control sequences efficiently.

3.2.5 Energy Recovery Ventilation System

A Packaged Exhaust Fan and Energy Recovery Unit (ERU) Glycol system was installed and began operation in summer 2014. The packaged exhaust fan system consists of four exhaust fans connected to a common manifold plenum. The ERU Glycol system consists of two 200 GPM pumps, energy recovery coils located in the packaged exhaust fan system, two coil control valves for ERU coil isolation, and a glycol system BTU meter. A system flow diagram of the 4 ERUs is displayed below in Figure 10. At least 3 of the 4 exhaust fans operate continuously and the ERU glycol system is enabled when outside air temperature is below 40°F for heating energy recovery, or above 80°F for cooling energy recovery. The project is a retrofit, as glycol piping, storage containers, and energy recovery coils in the effected air handlers were pre-existent.

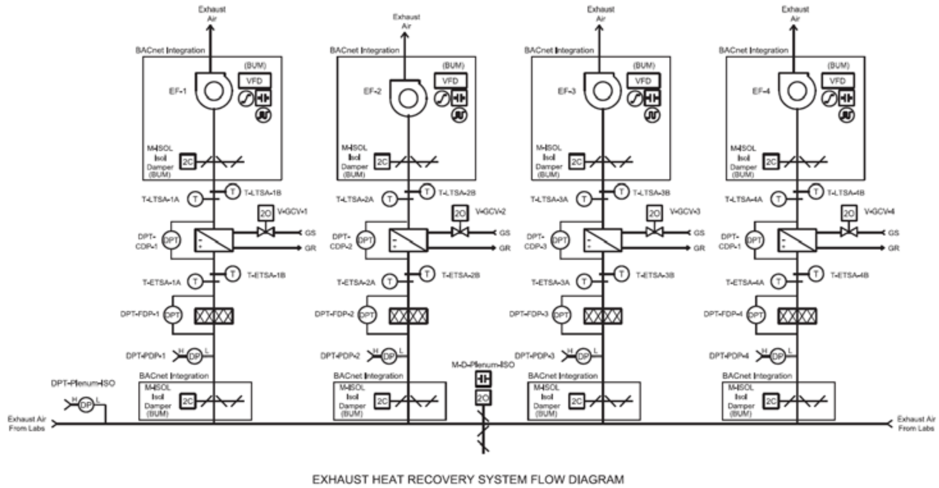

Figure 10: FM Documentation of System Flow Diagram of Exhaust ERUs

<u>*3.3 Hornbake Library (HBL) Overview*</u>

Hornbake Library (HBL) at UMD is a multi-purpose library whose current primary functions are the archival storage of various forms of sensitive media, and the housing of administrative offices and classrooms. HBL is located on the east side of Hornbake Plaza and coincidentally faces the Microbiology Building. A picture of HBL's main entrance (facing west) is shown in Figure 11.

Figure 11: The University of Maryland's Hornbake Library (Bldg. 147)

Since its construction in 1972, HBL has undergone at least one change to its primary function, and several renovations to its envelope, fire protection controls, and HVAC systems. As with MB, the library is designated Facility Quality Index 4:

“Comprehensive Modernization” and has estimated replacement values and total renovation costs of $116,190,550 and $84,819,102 respectively. Including the basement and ground floor, it is a 7 story facility with a gross floor area of 279,986 ft^2, and a net assignable floor area of 196,836 ft^2.

Excluding floor space used for mechanical equipment, corridors, and restrooms, 6 area use categories are identified in the building. Their contributions to floor space use are shown in Table 4.

Table 4: Floor Space Allocation in HBL by Principle Space Activity

Space Use	Floor Area (ft^2)	% of Floor Space
Stacks	84,550	42%
Office	52,700	26%
Mixed Stacks	28,930	14%
Media Lab	23,222	12%
Classroom	8,057	4%
Lobby	3,128	2%

The space use categories “stacks” and “mixed stacks” are respectively those whose primary function is the storage of archival media and office space- i.e. relatively isolated book stacks and book stacks in the immediate vicinity of human work spaces. As seen in Figure 12, the building is generally divided into two sections. The north side of the building is referred to as the “library side” and the south wing of the building is referred to as the “school side.” The library side of the building contains the library’s stacks and mixed stacks and the school side of the building contains the large majority of the offices as well as the entirety of the classrooms.

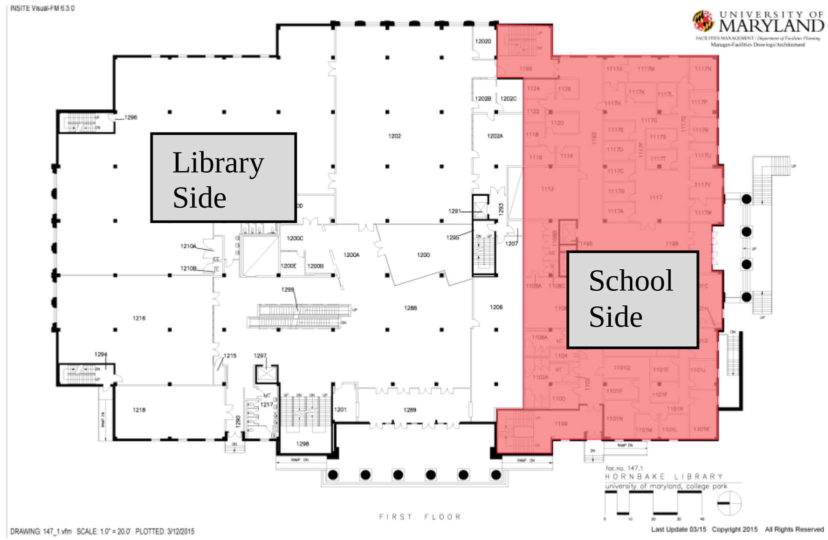

Figure 12: First Floor of Hornbake Library-"school side" shaded in red

The building's typical operating hours are divided into the "Special Collections" hours and the "Media Services" hours. Generally speaking, spaces accessible to students fall under the category of Media Services, while staff and faculty occupy the "Special Collections" hours. These operating hours roughly translate to "occupancy patterns" which are detailed in energy models section and appendices. Mixed-stack and office spaces are used year-round on a typical business week pattern. Classroom spaces are occupied only when school is in session and stack spaces are occupied more frequently when school is in session, though are generally unoccupied.

When construction was completed in 1972, the building served a more regular purpose as the UMD Graduate School library. Through the renovations listed in Table 5 the building was repurposed to serve as a primary special collections and sensitive materials archival storage facility for UMD.

Table 5: Summary of major renovations to HBL

Year of Completion	Renovation Description	Area(s) Affected
1998	• Replacement of existing fan coils, terminal reheat units and ductwork • Installation of new Air Handler (AHU-8)	Third Floor – School Side
1999	• Fire protection, electrical measures renovated	First, Second Floors
2001	• Installation of advanced Air Handlers with desiccant dehumidification wheels (AHUs-9 and 10) • Archival Materials and Special Collections Introduced	Whole Building
2004	• Replacement of control air volume terminal units	Ground Floor-Library Side
2006	• Designation of "Wasserman Library" • Replacement of ductwork, select lighting • CAV terminals units replaced with VAV	Second Floor-Library Side
2007	• Designation of "Prange Collection" • Fire protection, electrical measures renovated • Select ductwork rerouted	Fourth Floor-Library Side

The 2001 renovation was the most extensive and costly, as its design was to retrofit the building with the equipment and controls to maintain strict temperature and humidity bands essential in the archival storage of sensitive materials. The renovation included the addition of two custom AHU's (AHU #'s 9 and 10) each of which contain a desiccant dehumidification wheel and reverse osmosis humidification unit. These air handlers provide make-up air to the entire library side of the building via additional air handlers, as will be discussed in detail later in the chapter.

3.4 Hornbake Library Details

3.4.1 Architecture and Lighting

Architectural drawings became available late in the modeling process of Hornbake Library. In spite of this fact, they still proved very useful in determining important characteristics of the building: most notably, R-values for exterior and interior walls, as well as fenestration details. Figure 13 is a cross-section of a typical exterior wall taken from an original architectural drawing. Note the presence of the 2” rigid polystyrene insulation board. Interestingly, a 2001 report by The Building and Safety Division of the Municipality of Anchorage confirmed that criteria to measure and compare R-value performance developed in the early 1970's did not provide accurate rates. Considering HBL’s construction occurred during this period, it’s not unreasonable to assume that insulation performance may be less than quoted at the time of construction.

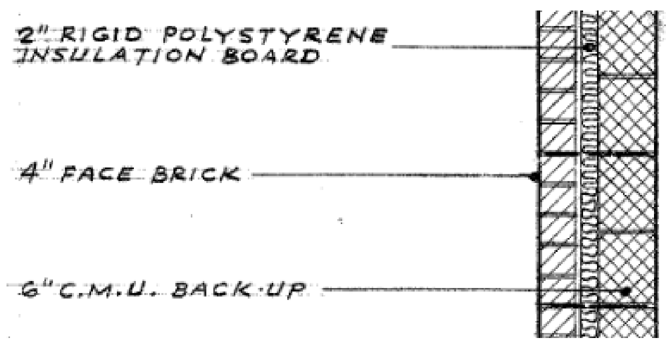

Figure 13: Architectural detail of typical HBL exterior wall

Interior wall constructions and finishes vary throughout the building but generally differed by space function. Architectural finish schedules indicated that the construction of office walls were most often painted dry-wall, the construction of classroom and stack space walls were most often painted concrete, both either having no finish or being finished by some vinyl fabric. However, due to the numerous renovations and low impact on modeling performance, all interior walls were assumed to be painted drywall. Floors were constructed of either concrete, stone, or wood, and were finished with either ceramic tile, rubber tile, or most often vinyl asbestos tile with carpeting.

Ceiling heights reliably differed by space function. Corridors, offices, and classroom had ceiling heights of approximately 10ft, while stack spaces had substantially higher ceilings of approximately 17ft. Prior to receiving architectural drawings, the distance between floors and various ceiling heights were measured with measuring tape. Examination of architectural drawings confirmed these approximate measurements, as actual floor-to-floor heights ranged between 14 and 18 ft., but also provided more details than were necessary for the purposes of modeling Therefore a weighted approximate height of 15ft was assumed to be uniform throughout the building.

As mentioned in the literature review chapter, libraries are prone to over-lighting- especially in stack areas. Electrical drawings indicated that the building was originally affixed almost exclusively with T8 or T12 fluorescent bulbs, however during a building walk-through with FM personnel, it was mentioned that some of the buildings lights and fixtures had recently been replaced with T5 fluorescent bulbs.

According to building staff, lights in stack and office spaces ("Special Collections") were scheduled to turn on 1 hour prior to opening at 7 a.m. and turn off 1 hour after closing at 6 p.m. Upon visiting the building, these schedules were found to be relatively accurate; however some building residents expressed skepticism as to the schedules consistency.

3.4.2 Heating, Ventilation, and Air Conditioning (HVAC)

Identical to the Microbiology Building, Hornbake Library consumes three energy commodities: grid-purchased electricity, campus-produced district steam from the UMD Combined Heat and Power Plant, and campus produced chilled water from a University SCUB. Electricity's primary end uses are lighting, office equipment, and the powering fans and pumps. Chilled water is consumed in air handler cooling coils as well as in fan coils located in perimeter spaces on the school side (south wing) of the building. High pressure steam entering the building is either condensed and consumed as hot water, or it's reduced in pressure and consumed as medium pressure steam. Hot water is used solely for heating in four capacities: AHU hot water heating coils, reheat terminal unit hot water heating coils, baseboard radiators located in perimeter spaces on the building's library side, and the previously mentioned fan coils located in perimeter spaces on the building's school side. Medium pressure steam is consumed in three ways: in heating domestic hot water, in heating water produced by reverse osmosis for humidification, and in heating reactivation air via steam coils for dehumidification.

Figure 14 shows the required psychrometric conditions in HBL's library side. On the chart three areas have been highlighted. Outlined in green are the environmental conditions outside of which will trip building alarms. In blue are the thermal comfort standards given by ASHRAE Std. 55-2004 (ASHRAE, 2004). The intersection of these two areas are striped blue-green and outlined in red.

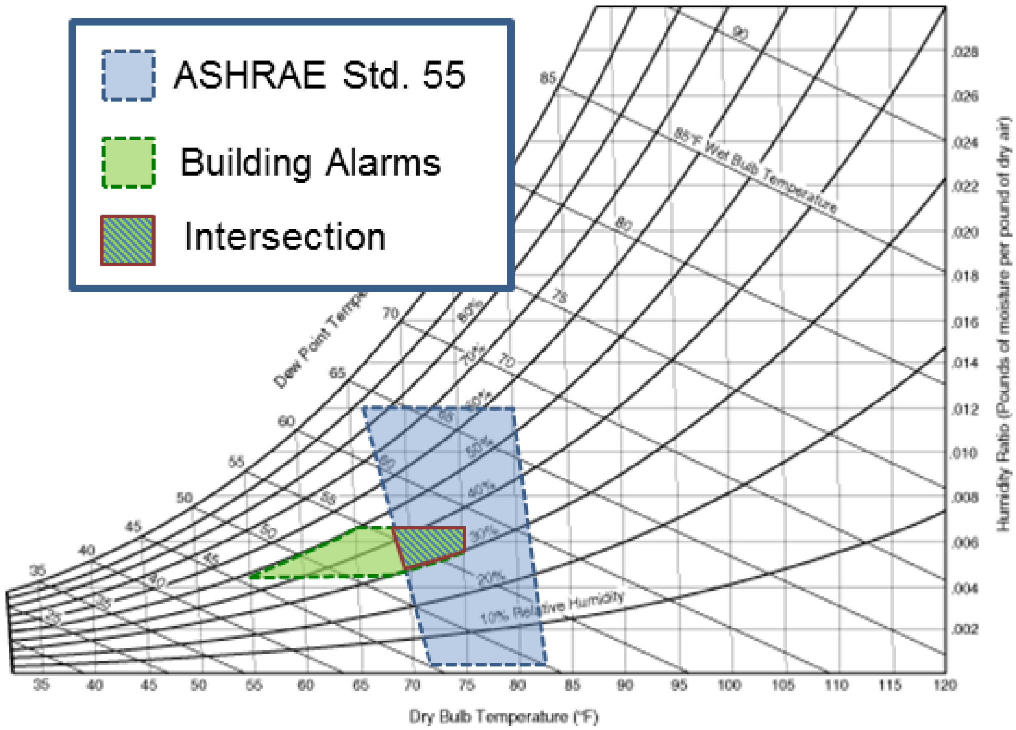

Figure 14: Required Psychrometric Conditions of HBL's Library Side

Hornbake Library's HVAC system is a patchwork of original and retrofit components whose layout generally mirrors the building's school-side/library-side division discussed previously. There are 11 AHU's, 10 of which were in operation at the time of this report. Of these 11 AHU's, numbers 9 and 10 were the newest and most advanced- being custom designed and installed by the Munters Corporation in 2001. Figure 15 shows the system flow diagram of AHU-9 as presented in documentation provided by FM. In the supply air stream we see a glycol preheat coil, a pre-cooling coil, a desiccant dehumidification wheel, steam humidifier, post-cooling coil and, in the return air stream we see reactivation pre-heat steam coil.

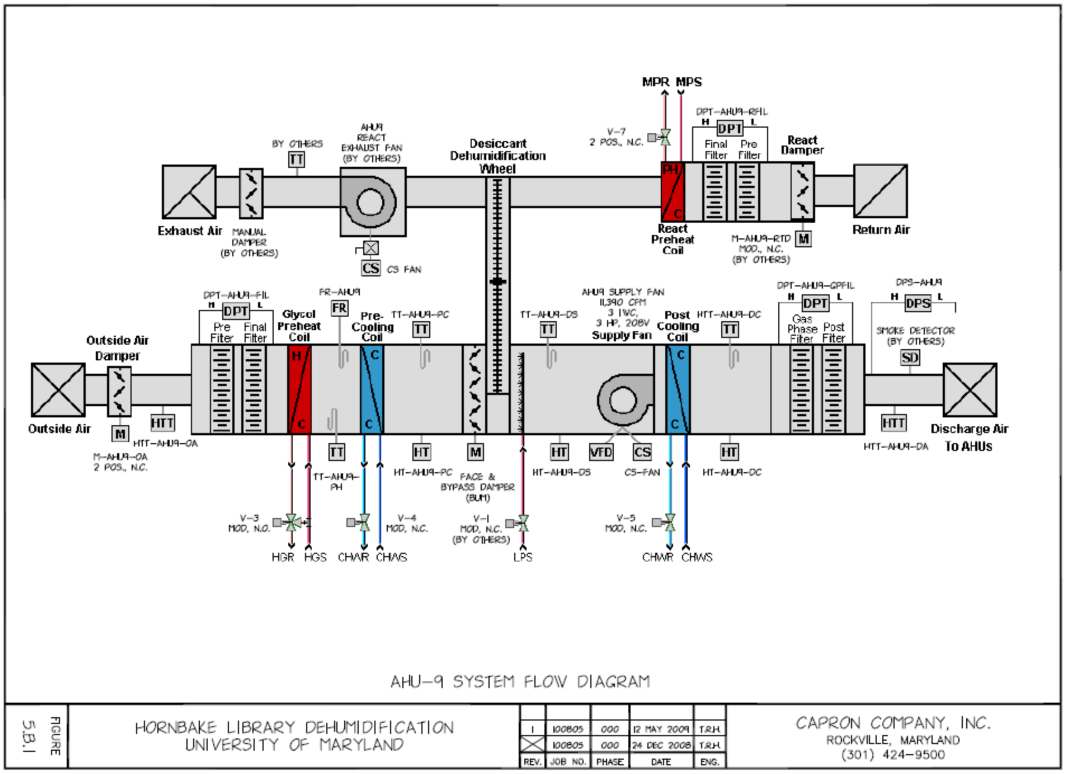

Figure 15: FM documentation of AHU-9 system flow diagram

AHU-10 is nearly identical apart from the placement of the humidifier, which is down-stream of the post-cooling coil.

The remaining AHU's were installed at the time of construction and were, for the most part, in poor condition. Aside from AHU's-5 and 11, the remaining AHU's receive a portion of their make-up air from AHU's 9 and10 and the remaining portion as return air. These two air streams are mixed and forced through a CHW cooling coil via a constant volume supply fan to CAV terminal reheat units. Playfully described by FM personnel as "held together by duct-tape and bubble gum," many if not all of these AHU's were under consideration for replacement at the time of writing. Table 6 presents more detailed specifications for these "old" AHU's in HBL.

Table 6: HBL AHU Design Specification Summary (excl. 7, 9 and 10)

	AHU-1	AHU-2	AHU-3	AHU-4	AHU-5	AHU-6	AHU-8	AHU-11
Location	Basement Mechanical Room					Penthouse Mech. Room		
Service Floor(s)	Ground	1st	Ground, 1st	Ground	Ground	2nd, 4th	2nd, 3rd, 4th	3rd
Service Area	Library	Library	School	Media Services	Lecture Hall	School	Library	School
Make-up AHU	AHU-9	AHU-9	-	AHU-9	-	-	AHU-10	-
VFDs	No	No	No	No	No	Yes	No	Yes
Maximum CFM	25,310	25,310	13,185	46,840	3,600	32,475	45,860	14,780
Minimum Make-Up (OA) CFM	6,328	6,328	3,296	11,710	(900)	8,119	11,465	(2,770)
TSP [inH_2O]	3	3	2.75	3		3	3.5	4.5
Total Supply Fan HP	20	20	10	40	2	25	40	20
Return Fan HP	20		5	20	0.5	5	20	10
CHW Cooling GPM	217.5	217.5	124	243.2	28.9	225.4	335.5	120
Heating Coil Capacity MBH	Removed/ Does Not Exist							307.2

3.4.4 Humidification and Desiccant Dehumidification

AHU's 9 and 10 and all equipment and systems therein are controlled by the Munters' packaged controls. These air handlers have two operational states: humidification mode and desiccant dehumidification mode. Equipment associated with these operational states is: the react air damper, react air exhaust fan, the desiccant dehumidification wheel the humidification control valve, and the face and bypass damper. The package controls govern the aforementioned equipment to provide a calculated space dewpoint temperature of 41°F by with a "selected average" space dewpoint.

An air handler enters the dehumidification mode when the face and bypass damper opens more than 10%. Conversely, an air handler enters the humidification mode when the humidification valve opens more than 3%. Because the operation of these two pieces of equipment, (the face and bypass damper, and the humidification valve), are not necessarily mutually exclusive, environmental conditions in which neither humidification nor dehumidification are required may cause the system to rapidly alter between the humidification and dehumidification operational states.

3.4.5 Building Automation System (BAS)

As with the Microbiology Building, Hornbake Library has two Building Automation Systems (BAS) monitoring spaces' environmental conditions, and controlling HVAC equipment to meet demand loads. The "legacy" *MS-1800* system monitors and controls AHU's 1-8 and 11 (serving the school side), while a "new" *Talon Tridium Niagra* system monitors and controls AHU's 9 and 10 (serving the library side).

Live viewing of the MS-1800 system was unavailable and so three years' worth of historical AHU temperature data from this system was provided by FM. This data provided knowledge about discharge temperatures, and AHU-scheduling.

The Talon Tridium Niagra system was accessible through a Java web-client for live viewing equipment operation, thermal conditions in building spaces, as well as alarm statuses. Furthermore, limited historical data was available through the web client. Figure 16 is a screen-grab of AHU-10 as shown in the Tridium Niagra BAS.

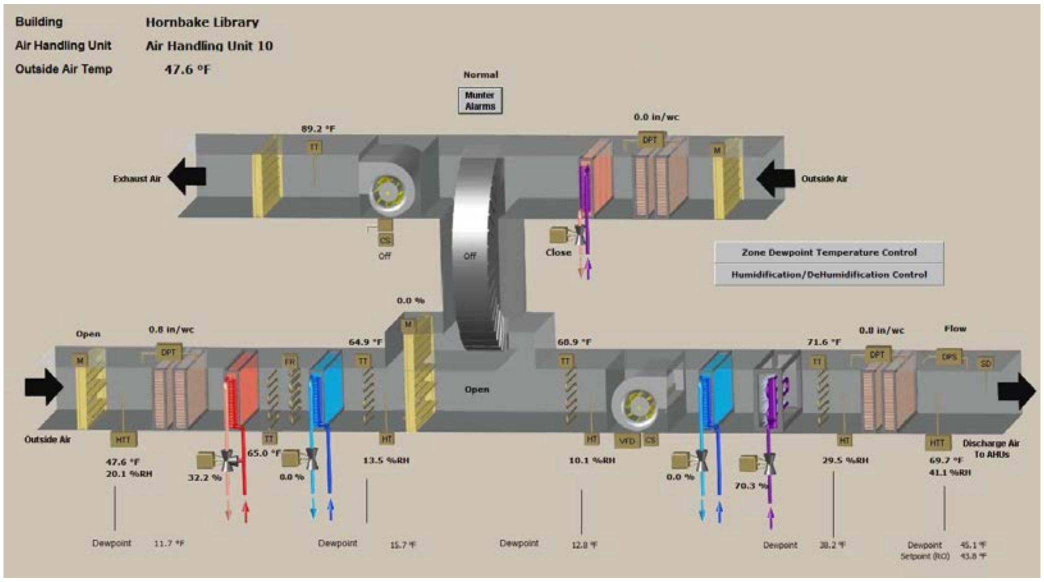

Figure 16: AHU-10 in Talon Tridium Niagra BAS

This BAS was viewed regularly throughout the audit and was crucial in detecting a number of operational issues that are discussed in detail in Chapter 6: Energy Models.

Chapter 4: Audit and Energy Modeling Methodology

A detailed approach to building energy analysis necessitates careful organization. The project can be generally divided into three phases: Building Comprehension, Energy Model Development, and Energy Conservation Measures Analysis. Figure 17 illustrates an outline of an organized flow chart the adherence to which can greatly assist in an efficient completion of a detailed energy audit project. The flow chart shown in Figure 17 was followed when completing the energy audits of both HBL and MB, and was developed from Levy (2014).

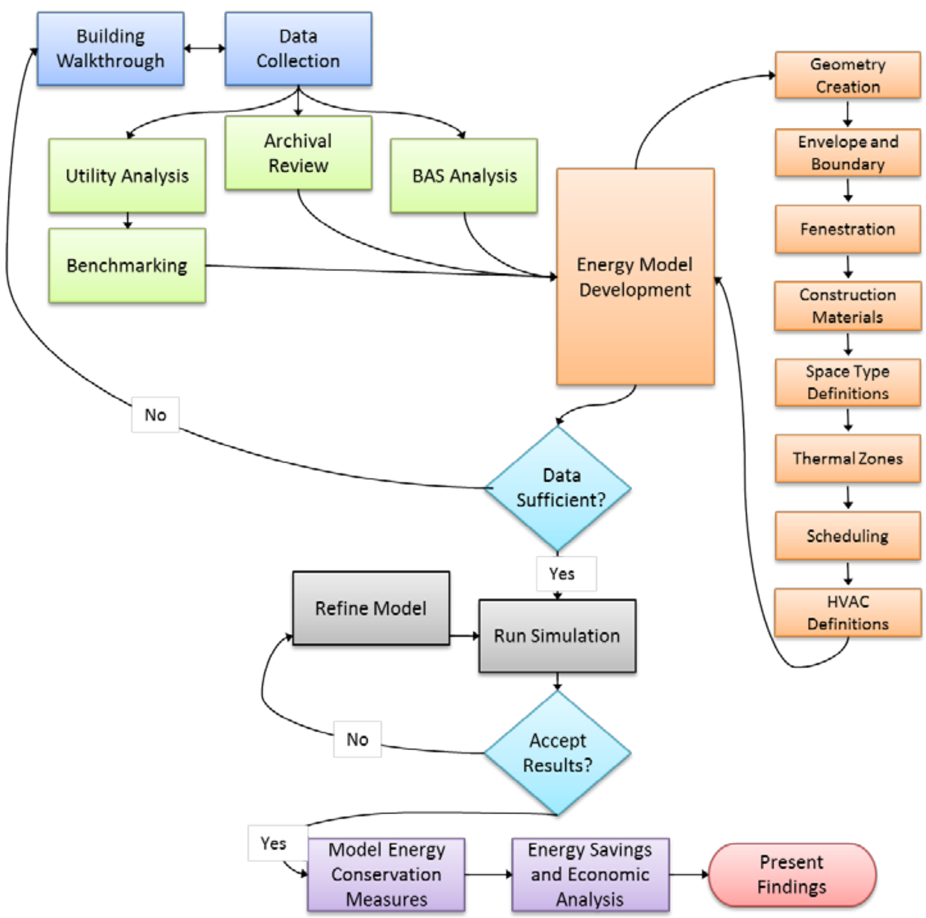

Figure 17: Building Energy Modeling Project Flow Chart

4.1 Building Comprehension

Building comprehension is the continuous process of data collection and analysis and is divided roughly into four categories: utility analysis, building walkthrough(s), archival review, and building automation system monitoring. As Chapter 5 details the procedure and findings of the utility analyses, a brief discussion of the other 3 methods of obtaining building comprehension are discussed below. Figure 18 illustrates these categories, the general order in which they were performed, as well as their central tasks.

Figure 18: Recommended Building Comprehension Order

4.1.1 Building Walkthroughs

A building walkthrough is performed in the very early stages of the project and may be repeated multiple times as necessary. The initial walkthrough is ideally conducted alongside a building supervisor, facilities management personnel, as well as building designers. Its aim is to provide an intimate first-hand examination of all building spaces and equipment, especially those not available to the public, as well as establish relationships with people involved in the building's operation and administration. The walkthrough will often reveal operational issues, and help elucidate use patterns that cannot be found anywhere else. Multiple visits to the building were necessary to gain a fuller understanding of the buildings' operations. Recommended tools to carry during a building walkthrough include a set of floor plans, notepad, camera, measuring tape, temperature and humidity sensors, luminance meter, and a flashlight. Building walkthroughs revealed data including the integrity of building envelope and mechanical systems, thermal zone temperature controls and setpoints, office and laboratory equipment, construction materials, and occupant behavior. No fewer than three walkthroughs were conducted for each building.

4.1.2 Archival Review

An archival review of each building's documentation was conducted after the building walkthrough and utility analysis, and before development of the buildings' energy models. For both facilities, facilities management provided documentation of floor plans, architectural, mechanical, electrical, and plumbing (MEP) in PDF format. Due to the numerous renovations that took place in both buildings, many years' worth of renovations needed to be examined and organized in order to gain a complete understand of the buildings in their present state.

Facilities management personnel were also able to provide additional documentation that aided in the construction of the energy models. Refer back to Figure 8: MB First Floor Supply Air Layout for a sample page from a set of color-coded floor plans illustrating the AHU air supply layout of MB's first floor. Similar drawings were created by the author for HBL and submitted to facilities management for record keeping, one of which is displayed in Figure 19. Very many people were involved in the collection of archival material, without whom a comprehensive understanding of these buildings would not have been possible.

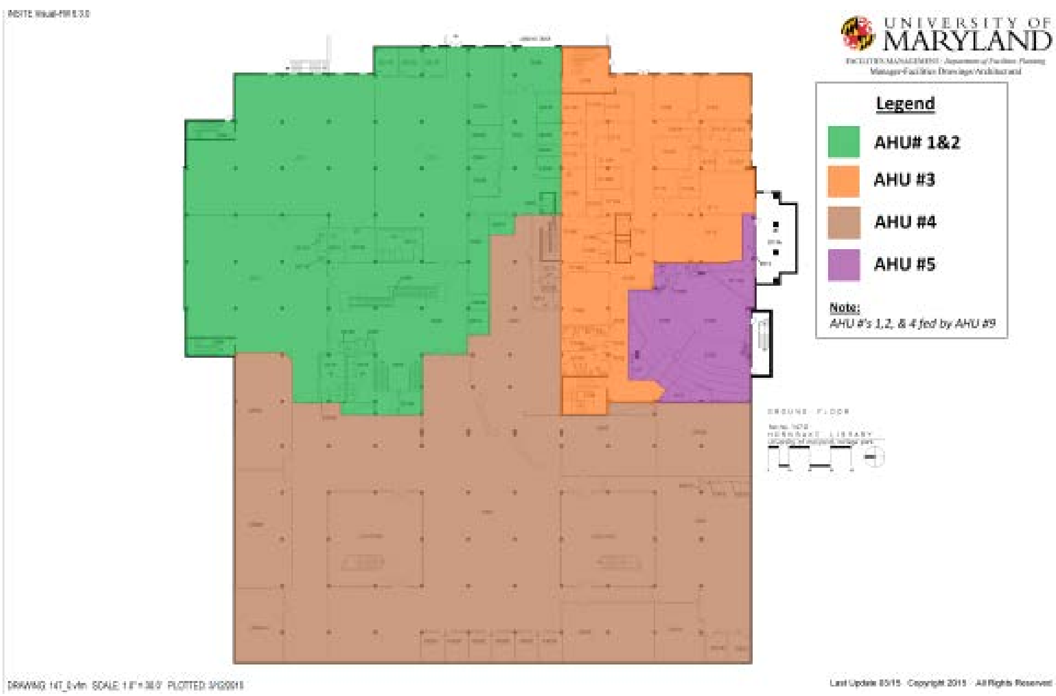

Figure 19: HBL Ground Floor Supply Air Layout

4.1.3 Building Automation System Data

According to Facilities Management, nearly all UMD campus buildings have at least limited implementation of a Building Automation System (BAS). As detailed in Chapter 3: Facility Descriptions, MB and HBL had a relatively high degree of BAS implementation. Read-only access was granted to most components of a building's BAS by Facilities Management after the initial building walkthrough was completed. Data provided by the BAS provided crucial insights to numerous aspects of the buildings' function most notably in the operation of mechanical systems. Other important data obtained through the BAS included historical trend data of air temperatures within AHU's and building spaces, operational scheduling and logic, instances of equipment failure, and more. Live access to BAS data, especially the older MS-1800 system, was at times difficult to obtain. However, requests to FM for historical data were met promptly and proved as instrumental in detecting trends and anomalies as live data viewing. One thing to note is that the volume of data can be so large as to be a distraction. As an example please refer back to Figure 16: AHU-10 in Talon Tridium Niagra BAS, and note that this snap shot contains no less than 19 data points, each of which has years of historical data that may or may not be useful during the audit.

4.2 Building Energy Model Development

The early stages of energy model development began after completing the utility analysis, initial building walkthrough, and once the archival review had begun. Figure 20 illustrates a preferential order of operations in energy model development and the associated archival review documentation associated with each step in the model development process. Two separate energy modeling software were used for these projects. The freeware eQUEST was used for MB, and EnergyPlus primarily via the OpenStudio interface was used for HBL.

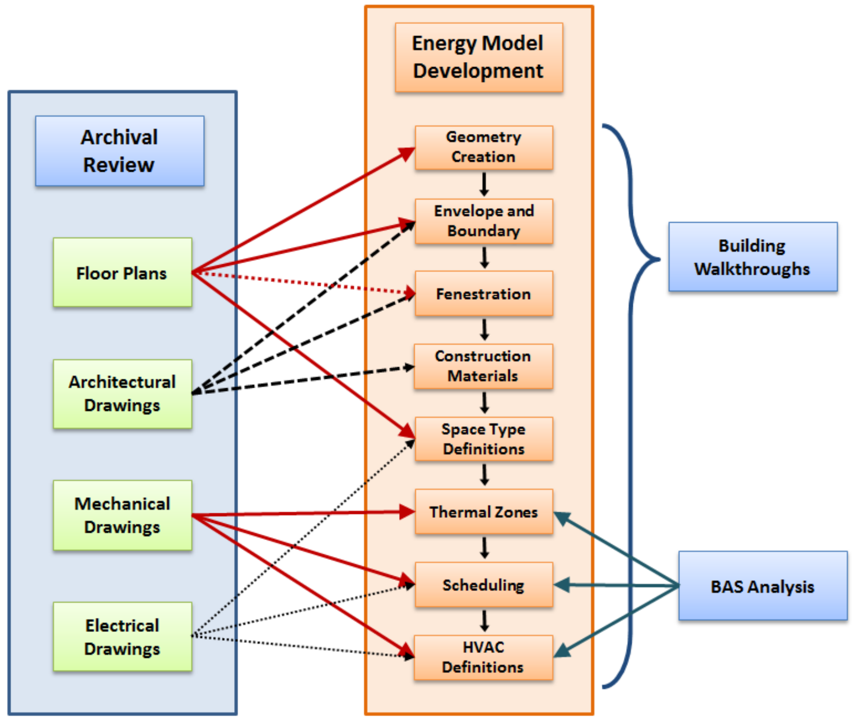

Figure 20: Energy model development flow and associated archival documentation

In general eQUEST was a simpler and more user-friendly simulation environment, and the baseline eQUEST model for MB was completed in approximately half the time as the baseline EnergyPlus model for HBL. However, the reason for the differing selection of simulation environments specifically the reason for selecting EnergyPlus to simulating HBL can be summarized in the following way: EnergyPlus offers greater customization of individual mechanical systems and provided a platform for modeling the desiccant dehumidification system, whereas eQUEST did not. Furthermore, EnergyPlus custom reporting measures were able to provide the monthly energy consumption of individual heating and cooling coils, individual pumps and fans, as well as entire air handling systems. Such measures made the energy and cost savings of certain HBL ECM's much easier to evaluate.

4.2.1 Microbiology Building Model Development: eQUEST

eQUEST is a freeware utilizing the DOE-2.2 simulation environment developed and provided by the Department of Energy and the Lawrence Berkley National Laboratory[1]. The software is qualified for commercial building tax deductions and has been widely used in comprehensive building energy analysis for over 20 years. eQUEST has two modes of data entry: "Wizard Data Edit," and "Detailed Data Edit." While the majority of building data can and should be entered using the more user-friendly Wizard Data Edit mode, advanced building schedules and mechanical systems can only be implemented using the Detailed Data Edit mode. Importantly, changes made in Detailed Data Edit mode will not be saved if the user switches back to the Wizard Data Edit mode.

Building geometry creation was performed directly in the eQUEST platform, by measuring pdf floor plan dimensions with another freeware ImageJ[2], and then inputting geometry rounded to the nearest foot via the eQUEST drawing tablet. The program is also able to import and trace DWG files when available. Building envelope and boundary conditions, fenestration, and construction materials, as well as simplified space type definitions, thermal zones, schedules, plant loops, and basic HVAC definitions were all entered using the "Schematic Wizard" and "Design Development Wizard." Similar to the caution offered with reference to switching between data entry modes, its crucial to note that once the switch has been made to the Design Development Wizard, all subsequent model alterations will be lost if the user switches back into the Schematic Design Wizard mode.

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[1] Available at http://www.doe2.com/equest/
[2] Available at https://imagej.nih.gov/ij/

Model refinement and final development of the model were completed by switching into “Detailed Data Edit” mode after all possible data entry into the “Wizard Data Edit” mode were exhausted. Advanced occupancy, equipment, lighting, and temperature set-point schedules, as well as the implementation of the building’s glycol energy recovery system were completed using the Detailed Data Edit mode. Figure 21 shows a screen capture illustrating numerous components of eQUEST’s Detailed Data edit mode. The left most list is the building’s “Component Tree” which contains all schedules and components relating to the selected “Navigation Bar” tab (Air-Side HVAC is selected here and highlighted in orange at the top). The additional window on top provides input fields for the Air-Side HVAC system currently active. Tabs below the navigation bar allow for different views of the selected component: “Air-Side HVAC System” is the graphical view displayed in the figure, “Spreadsheet” provides a tabular view and is useful for editing multiple components at once, while “Summary” is an un-editable table of related component specifications.

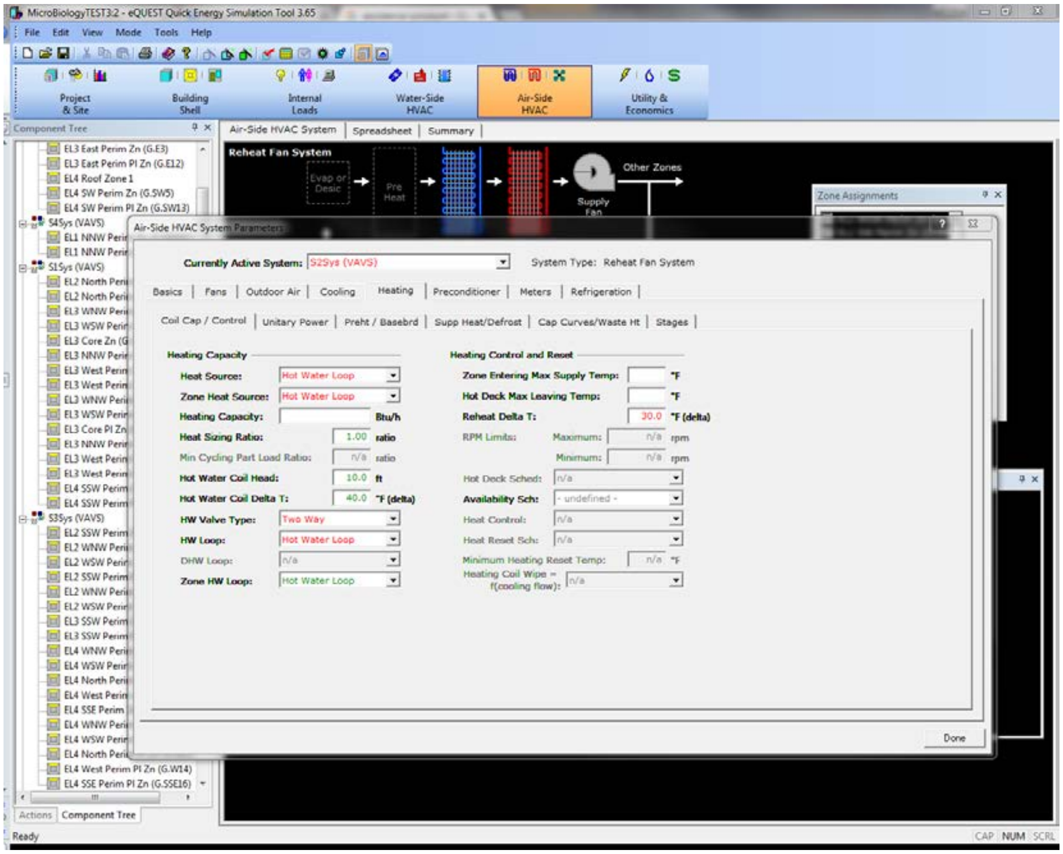

Figure 21: Example display of eQUEST "Detailed Data Edit Mode"

Simulation results were copy-pasted into preformatted Microsoft Excel workbooks for a streamlined comparative meter consumption analysis.

4.2.2 Hornbake Library Model Development: EnergyPlus and OpenStudio

EnergyPlus is another whole-building energy simulation program originating in the DOE that is widely used to model energy and water consumption for energy audits, design certifications, and retrofit analysis[3]. Its funding is provided by the DOE's Building Technologies Office and is managed by the National Renewable Energy Laboratory (NREL). EnergyPlus lacks the user-friendly graphical user

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[3] Available at http://apps1.eere.energy.gov/buildings/energyplus/

interface (GUI) that accompanies eQUEST, though there are numerous commercially available GUI's including NREL's free OpenStudio[4] software development kit.

Preliminary energy model development for Hornbake Library began in eQUEST, until it was discovered that comprehensive simulation necessitated the inclusion of model desiccant wheels. Since eQUEST has no native means of simulating desiccants and EnergyPlus does, the final model was completed using EnergyPlus.

Building geometries and fenestration, as well as space type and thermal zone assignments, were completed using the free 3D modeling software, SketchUp[5] with the associated OpenStudio Plug-in. Simplification of certain aspects of the building's geometry such as uniform ceiling heights and plenum spaces were made to reduce simulation time. The OpenStudio user interface provided a reasonably straightforward means of defining space type loads, construction materials, schedules, thermostats, and basic plant and HVAC loops.

Final model development was performed using the native EnergyPlus IDF editor shown in Figure 22, as well as through textual edits to the input data file (.idf) using a text-editor. This built-in spreadsheet based tool was used to model the two mechanically advanced AHU's featuring dehumidifying desiccant wheels and reverse osmosis humidifiers and incorporate them into the appropriate secondary air loops. Desiccant wheel control schemes were also refined in the IDF editor to match building operation.

[4] Available at https://www.openstudio.net/
[5] Available at https://www.sketchup.com/

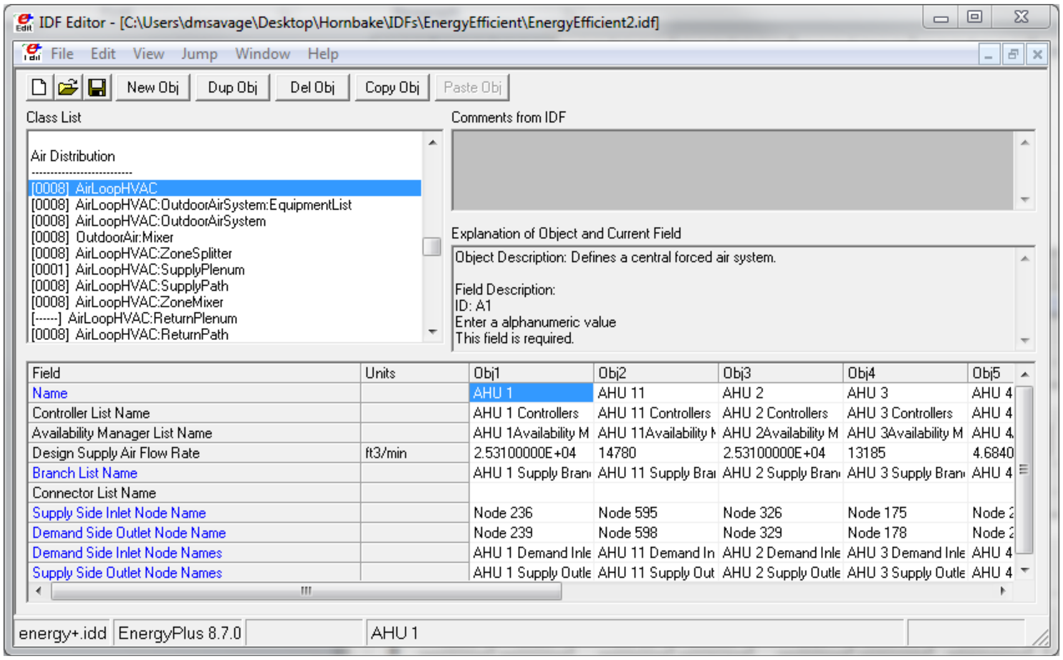

Figure 22: Screen grab of EnergyPlus IDF-editor

Of crucial importance was the use of "Parametrics": an EnergyPlus class that allows multiple simulation instances with predefined value or parameter changes to be run simultaneously. For example, a parameter would be created that sets multiple values for the thermal resistance of each exterior wall. Then up to four simulations (one per available CPU on the computer performing the simulation), each having a unique value for exterior wall thermal resistance would run simultaneously. The results of these simulations could then be easily processed and compared for sensitivity/uncertainty analysis or to evaluate the energy savings resulting from the installation of exterior wall insulation etc.

4.4 Energy Conservation Measure Analysis

To present the actions aimed at reducing building energy consumption and improving energy efficiency for each building, we categorize the suggestions into one of two sections. First, energy conservation measures (ECM's) are discussed individually and summarized in the "As-designed" Model. These measures address operational issues observed during the building comprehension phase of the audit. They are generally considered “low hanging fruit,” requiring little or no cost and can likely be easily implemented by qualified Facilities Management personnel.

The second set of measures are categorized as “energy efficiency measures” (EEM’s) to distinguish them from the first set of energy conservation measures. These measures typically have greater potential for energy consumption reduction, but may also require additional labor or capital investment. Each set of EEMs was chosen based on literature reviews of energy efficient design, operation, and retrofits of the two respective building types: laboratories for MB and libraries for HBL.

A variety of software tools were used to perform energy savings calculations including eQUEST parametric runs function, EnergyPlus *Parametrics* classes, Microsoft Excel, and MATLAB. Lastly, cost savings are estimated using approximate, static prices for energy commodities.

Chapter 5: Utility Analyses

Prior to development of a building energy model, a comprehensive understanding of a building's energy consumption patterns is acquired. Once notable patterns and characteristics of a building's energy consumption are known, they can be compared to available "benchmark" data to assess a building's relative performance. In the first section of this chapter we present the annual energy consumption patterns on a monthly basis for the Microbiology Building (MB) and discuss its relative performance through a benchmark comparison of similar mixed-use laboratory buildings. We then do a similar utility analysis and benchmark comparison for Hornbake Library (HBL) in the second section.

5.1 Microbiology Building Utility Analysis

5.1.1 Microbiology Building Historical Energy Consumption

Utility data from 2012-2015 was retrieved through UMD's Enterprise Energy Management (EEM) Suite and parsed to remove erroneous values attributable to the EEM Suite collection method as indicated by FM. Monthly energy consumption data for electricity, steam, and chilled water were collected in units of kWh, lbs., and ton-hr, respectively. This data was then averaged over the four years, converted to units of kBtu using conversion factors provided by the Environmental Protection Agency's ENERGY STAR Portfolio Manager[6]. These values are included in Table 7: Utility Rates and Conversion Factors. Figure 23 shows the average monthly

[6] Available at https://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager

consumption of each energy commodity: electricity, chilled water, and steam for the years 2012-2015 in aggregation in units MMBtu.

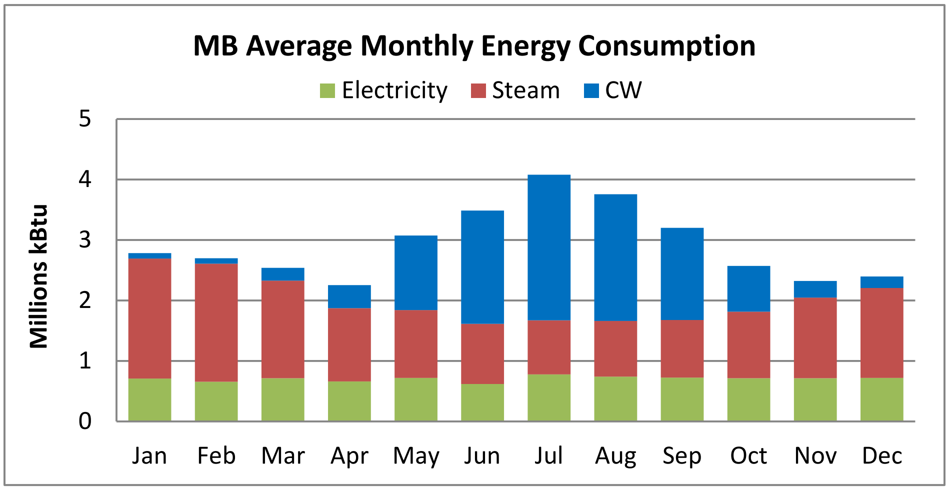

Figure 23: Average Monthly Energy Consumption by Commodity for MB (2012-2015)

Figure 23 provides a number of interesting insights. Electricity consumption remains very consistent throughout the year, with consumption values hovering very close to 200,000 kWh per month. This indicates that electricity does not play a significant role in heating and cooling. Furthermore, steam consumption is greatest in cold months and decreases during warm months. However, steam consumption is still very significant during summer months, contributing more to energy consumption than electricity. Three major factors help explain this trend. First, dehumidification requirements necessitate that air be cooled below the room setpoint temperature. Reheating end units consume steam to raise the cool air back to room's set point temperature. Second, a leaky hot water valve in AHU-2, the largest air handler in the building, allowed hot water to flow through heating coils even as control systems registered the valves "closed" resulting in unintended consumption of steam. Third, control systems for AHU cooling and heating coils are based on an improperly installed outdoor air thermostat. This would allow for simultaneous heating and cooling within a single AHU when actual outdoor air temperatures differed from those read by the faulty thermostat (as discussed in Chapter 3). These factors are discussed further in Chapter 6. Lastly, Figure 23 illustrates a pattern of peak chilled water energy consumption in the hot summer months (200,525 ton-hr in July), and very low base cooling load in the cold winter months (7,000 ton-hr in February). This corresponds directly to the magnitude of monthly cooling loads and is typical for buildings located in our climate.

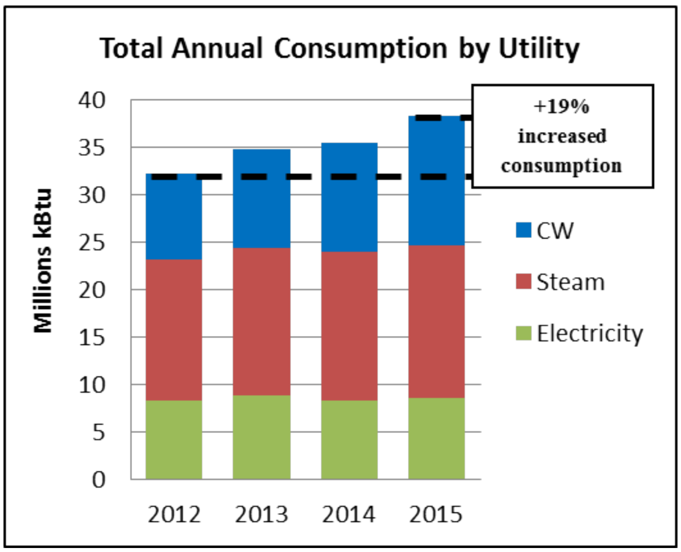

Figure 24: MB Annual Consumption by Utility 2012-2015

The trend of increasing total yearly energy consumption illustrated in Figure 24 was puzzling to all parties involved in this project. From 2012 to 2015 there was a 52% increase in chilled water consumption, a 7% increase in steam consumption and a 4% increase in electricity consumption for a total energy consumption increase of 19%. Furthermore, the dramatic increase in chilled water consumption cannot be attributed to warmer climatic conditions as there were actually 4% fewer cooling degree days (CDD55) in 2012 as there were in 2015. One possible explanation for the increase is the control systems governing operation of the energy recovery ventilation system

(ERS). While ventilation rates increased with the installation of the new centralized ventilation system in 2014 (as already discussed in Chapter 3), control of the (ERS) is managed by a software platform separate from the software platform governing AHU operations. An examination of the effect of these discrepancies had on building energy consumption is discussed later, in Chapter 6.

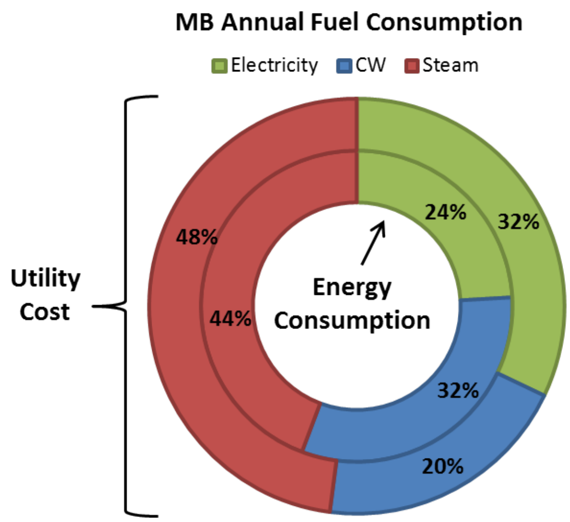

Figure 25: MB Utility Cost vs Energy Consumption by Energy Commodity

Auxiliary utility rates collected from the UMD Sustainability Office are used to perform a brief economic analysis of the buildings. Throughout the university, buildings are almost never billed directly for utility consumption since energy commodities are received from a variety of sources. MB receives steam from the University of Maryland combined heat and power plant (CHP) and chilled water from one of the five Satellite Central Utilities Buildings (SCUB). The price per unit of each utility is included in Table 7. Figure 25 shows the averaged relative contributions of utilities' to total energy consumption and utility bill. The average total energy bill for MB is $810,933.

Table 7: Utility Rates and Conversion Factors

Utility	Unit	Price per Unit	Conversion Factor to kBtu
Electricity	kWh	$0.1025	3.412
Steam	lb.	$0.0298	1.194
Chilled Water	ton-hr	$0.1700	12

5.1.2 Microbiology Benchmark Comparison

The benchmark comparison for MB is done to compare the building's energy consumption performance to similar laboratories around the nation and is a vital aspect of any energy analysis project. The standard metric used to compare buildings' energy consumption is the Energy Use Intensity (EUI) and is calculated as the total annual energy consumption divided by the gross square footage and takes units [kBtu/ft^2]. In calculating the operational EUI of MB, the author chose to omit 2012 energy consumption to reflect the trend of increasing energy consumption. Table 8 shows a summary of this calculation.

Table 8: Summary of MB EUI Calculations

Electric Consumption [kBtu]	8,549,879
Chilled Water Consumption [kBtu]	11,835,600
Steam Consumption [kBtu]	15,775,725
Building Gross Square Footage [ft^2]	88,285
Building EUI [kBtu/ ft^2/yr]	**410**

There are numerous benchmarking tools available for use by the public; the most widely used is the Environmental Protection Agency's (EPA) ENERGY STAR Portfolio Manager. The ENERGY STAR Portfolio Manager assigns buildings a score of 1-100 based on nationwide building energy consumption surveys conducted by the Energy Information Agency called the Commercial Building Energy Consumption Survey (CBECS) (CBECS, 2012). Due to the unique nature of MB's function as a mixed-use research laboratory, as well as the limited size of the CBECS dataset on laboratories (43 buildings) the ENERGY STAR Portfolio Manager was deemed insufficient as a benchmarking tool. The Labs21 Benchmarking Tool was developed by Lawrence Berkeley National Laboratory and maintains a dataset of 639 laboratory buildings throughout the United States (I2SL, 2010). The sources for their dataset are described as follows:

"The data in the Labs21 tool was provided by a wide range of laboratory owners and operators in the United States, including federal government agencies, universities, pharmaceutical companies, and other organizations. Identities of the buildings and organizations in the database are masked for confidentiality. The Labs21 database also includes 14 buildings from the U.S. Department of Energy's CBECS dataset."

From the full Labs21 dataset, only buildings having occupancy hours of 80 or less, in ASHRAE climate zone 4A, with a lab type of chemical, biological, or chemical/biological were considered. Next, following the Labs21 technical guidance bulletin, different lab area ratios and lab uses were examined. Table 9 shows the count of benchmarked buildings in the specified lab use category as well as each associated mean EUI.

Table 9: Labs21 Benchmarking Results

Lab Use	Lab Area/ Gross Area	Count	Mean EUI
All Uses	0.0-1.0	79	367
	0.3-0.6	44	368
	0.6-1.0	16	363
Research/ Development	0.0-1.0	56	368
	0.3-0.6	32	372
	0.6-1.0	14	366
Teaching/ Combination/ Others	0.0-1.0	21	331
	0.3-0.6	12	**357**
	0.6-1.0	2	340
Manufacturing	0.0-1.0	2	729
	0.3-0.6	0	0
	0.6-1.0	0	0

The Labs21 definition of "Lab Area" is:

> *"...the area requiring 100% outside air. It typically includes lab spaces and lab support spaces. It does not include office spaces, conference rooms, lobbies, breakout spaces, mechanical rooms, restrooms, corridors, stairways, etc."* (Laboratories for the 21st Century, 2003)

Because the lab area ratio of MB is squarely within the middle range, and a reasonable description of MB's "Lab Use" is "Teaching/Combination/Others," the expected weather-normalized EUI of MB is 357 kBtu/ft^2-yr as seen in Table 9.

Two additional considerations concerning the applicability of this benchmark should be mentioned. First, MB's use of an energy recovery ventilation system is not considered in the expected EUI since comparative data lacked any indication as to whether benchmarked facilities employed such systems. However, the presence of the energy recovery system on MB would be expected to have a substantial reductive effect on said number. Second, greater than 50% of MB's floor space does not fit the definition of "Lab Area" in so far as office space, corridors and lecture halls do not require 100% outside air. However, the entire building is in fact using 100% outside air. Both of these considerations direct the conclusion that the highest expected EUI of MB is 12.9% lower than its present EUI.

5.2 Hornbake Library Utility Analysis

5.2.1 Hornbake Library Historical Energy Consumption

Methods for data collection and processing for Hornbake Library (HBL) were similar to those used in the utility analysis of Microbiology (MB). Like MB, Hornbake Library's energy commodities consisted of electricity, district steam, and district chilled water. Monthly consumption data was again retrieved from University of Maryland's EEM suite for the years 2012-2015. The data was parsed to remove erroneous values, averaged over the 4 years, and converted to units of kBtu using the conversion factors in Table 7. Results of this data processing are displayed in Figure 26.

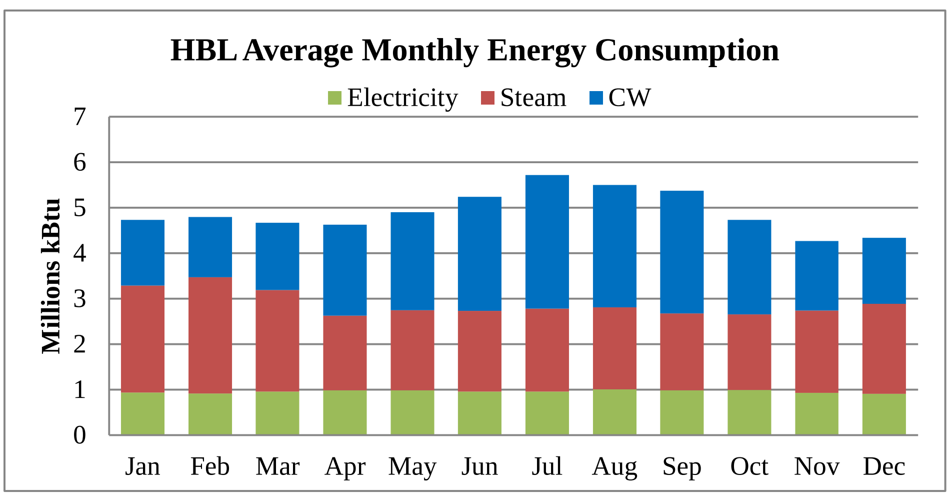

Figure 26: Average Monthly Energy Consumption by Commodity for HBL (2012-2015)

Monthly electricity consumption for HBL remains relatively constant throughout the year; monthly consumption does not vary more than 5% from the average monthly value of 281,464 kWh. Similar to MB, this allows us to conclude that electricity does not play a significant role in heating and cooling. HBL's monthly chilled water consumption trend is also similar to that of MB. Peak consumption occurs in July (244,680 ton-hr), and declines as cooling demands lower during the winter months. However unlike MB, there remains a large base load of chilled water consumption even as cooling demands drop.

HBL's minimum average monthly chilled water energy consumption of 110,000 ton-hr in February can be attributed to three primary causes. As explained in Chapter 3, the building employs two desiccant wheels in AHU's 9 and 10 to maintain strict the dehumidification requirements of sensitive materials year-round. This process causes air to be heated above space temperature set points and so needed cooling prior to being discharged from these AHUs. Second, the AHU's processing dehumidified air from AHU's 9 and 10 were continually operating at full capacity in an attempt to meet an artificially low discharge setpoint of 50°F in order to meet strict temperature requirements in thermally unstable zones. These two reasons, coupled with aging equipment and ductwork of questionable integrity (see Chapter 3) necessitated consumption of chilled water energy exceeding the energy requirement to simply meet cooling demands.

HBL's steam consumption also deviates from what one might expect. While peak consumption does occur when heating loads are highest (2,142,250 lbs. in February), minimum consumption does not occur when heating loads are lowest. Instead we see a trough occur in March (1,379,075 lbs.), followed by a relative peak in July (1,529,150 lbs.) and then another trough in October (1,395,500 lbs.). This is due to two major end uses. First is the consumption of steam in reactivation coils during the desiccant dehumidification process. The second is in the consumption of hot water in terminal reheat units that raises over-cooled air back to room setpoints to meet the thermal comfort standards of occupants.

The irregular trends of both the steam and the chilled water should be understood as occurring in the context of a mixed-use building. Because the vast majority of floor space must be treated as containing both occupants *and* sensitive materials, both in a building with equipment of sub-par integrity, additional energy is required to meet these strict and irregular thermal standards.

A brief economic analysis was conducted in a similar manner to that done for MB. The same utility cost rates displayed in Table 9 were used in the analysis, and the results are displayed in Figure 21. From 2012-2015 HBL had an average annual utility bill of $1,266,514 accounting for approximately 3% of the University of Maryland's total annual utility bill (Corry, 2016). The economic snapshot allows us to better target our priorities when searching for savings. It is interesting to note that even though HBL's energy consumption of steam and chilled water are comparable, Figure 27 illustrates that steam comprises a far greater share of the HBL's utility bill.

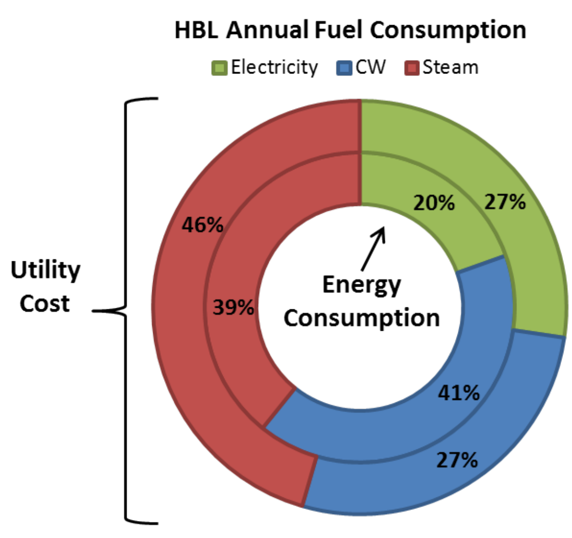

Figure 27: HBL Utility Cost vs Energy Consumption by Energy Commodity

5.2.2 Hornbake Library Benchmark Comparison

The approach to energy benchmarking of HBL differed significantly from that of MB. In addition to calculating HBL's building, or *site* EUI, its *source* EUI was considered. A building's source EUI "represents the total amount of raw fuel that is required to operate the building… It incorporates all transmission, delivery, and production losses," and is considered to be, "the most equitable unit of evaluation" by the EPA. Using HBL's utility data from 2013-2014 (the only years in which monthly energy consumption data was wholly complete) as well as ENERGY STAR source-to-site conversion factors, a total source EUI was obtained (EPA, DOE, 2015). Site EUI contributions were calculated similarly to MB. Additionally, the ENERGY STAR Portfolio Manager tool was used to find a weather normalized source EUI. These calculations are summarized in Table 10.

Table 10: HBL Site and Source EUI Summary

Energy Commodity	**2013-2014 Average Annual Consumption (kBtu)**	**Site EUI Contribution**	**Source-Site conversion factor**	**Source EUI Contribution**
Electricity (Grid Purchase)	11,782,565	42.08	3.14	132.1
Steam Produced by CHP	23,091,011	101.92	1.01	102.9
Chilled Water	28,536,182	104.56	1	104.6
Total Site EUI		**248.6**		
Total Source EUI				339.6
ENERGY STAR: Weather Normalized Source EUI				**359.3**

Source EUI was considered for HBL due to the additional benchmarking resources made available in doing so. For example, there is no independent databank of library energy consumption as there was in the Labs21 benchmarking tool. Furthermore, while there are enough library data points in the 2012 CBECS database (37 points), there were not statistically sufficient data points to apply additional filters for weather normalization, total square footage, etc. Finally, a 2009 benchmarking study by the District of Columbia Department of Energy and Environment as well as a 2011 Energy Benchmarking Report for New York City Municipal Buildings consider only source EUI. Table 11 summarizes the benchmark site and source EUI calculations performed using ENERGY STAR national averages.

Table 11: HBL Benchmark Site and Source EUI Summary

Area Usage	Square Footage	% HBL Floor Space	Benchmark Site EUI	Benchmark Source EUI	Benchmark Site Energy Consumption	Benchmark Source Energy Consumption
Stacks	113,480	41%	91.6	235.6	10,394,768	26,735,888
Office	52,700	19%	67.3	148.1	3,546,710	7,804,870
University Building	108,210	39%	130.7	262.6	14,143,047	28,415,946
Total	274,390	100%	**102.35**	**229.44**	28,084,525	62,956,704

These calculations indicate that HBL's site EUI is 143% greater than expected while its source EUI is only 57% greater than expected. The smaller deviation from benchmarked source EUI to HBL's source EUI can be attributed to its use of district chilled water for cooling. However as discussed in previous chapters, HBL's function as special collections facility would increase our expected energy consumption by a substantial margin. While estimating that margin is difficult due to the lack of available data, the case studies of energy consumption in similar special collection holding facilities (Chapter 2) gives a better understanding of what that estimation would be.

5.3 Comparative PRISM Analysis

Inverse modeling methods can be valuable tools in evaluating and improving building energy efficiency (Moncef, 2011). They can be used to identify time periods with abnormally high energy consumption, provide estimates of expected savings from a set of ECMs, and verify savings achieved through retrofit implementation. To further illustrate HBL's abnormally high base heating and cooling loads, a simple inverse modeling method called PRISM analysis was performed for MB and HBL. In this analysis the energy consumption of a billing period can be estimated using the following expression:

$$E_{H/C} = 24 \times \frac{BLC}{\eta_{H/C}} \times DD_{H/C}(T_{b,H/C}) + E_{base,H/C}$$

Where H/C is "heating" or "cooling" and,

$E_{H/C}$ is the energy consumption during the heating or cooling season

BLC is the building loss coefficient

$\eta_{H/C}$ is the average seasonal energy efficiency of the heating or cooling season

$DD_{H/C}(T_{b,H/C})$ is the heating or cooling degree days as a function of the balance temperature, $T_{b,H/C}$

$E_{base,H/C}$ is the base-load for building energy use.

For our analysis, data for energy consumption and net degree days were available on a monthly basis. Thus, by dividing the energy consumption and net degree days by the number of days in the month, we can find the correlation between a degree day and the expected heating/cooling energy consumption from a linear regression analysis. Figure 28 displays both building's average daily heating energy (steam consumption) as a function of heating degree day with base temperature of 55°F (HDD_{55F}) and Figure 29 displays both building's average daily cooling energy (CHW consumption) as a function of cooling degree days with base temperature of 57°F (HDD_{57F}).

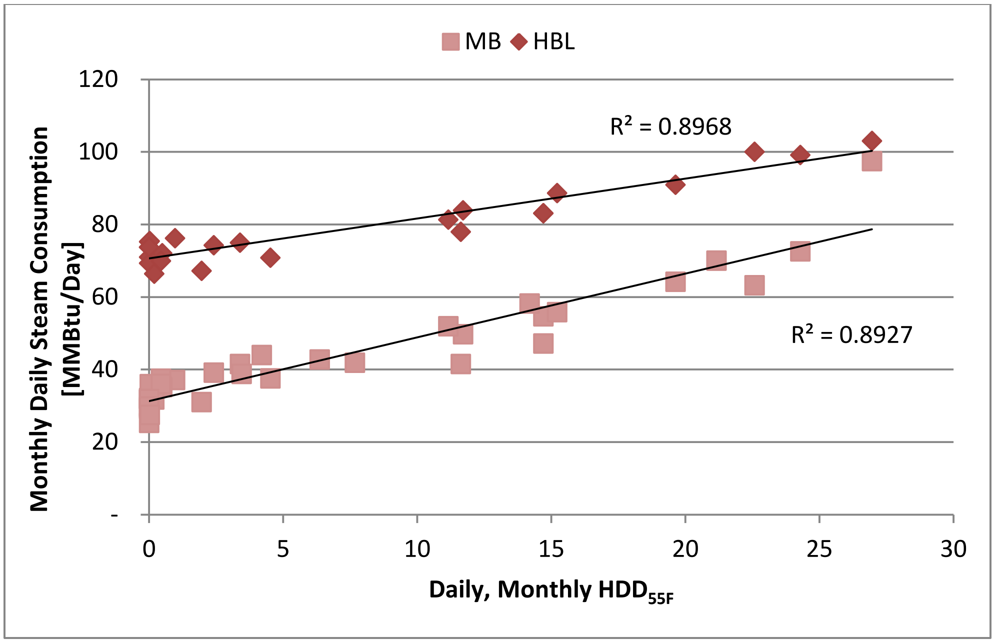

Figure 28: Analysis of steam consumption as a function of monthly heating degree days

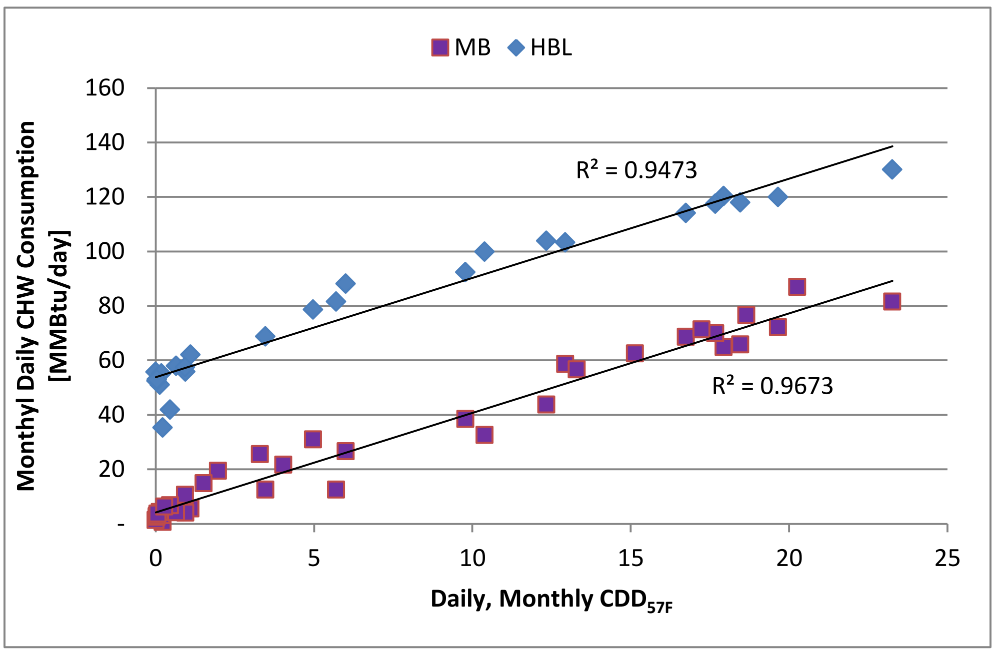

Figure 29: Analysis of CHW consumption as a function of monthly cooling degree days

The numbers from Table 12, relate directly to the regression analysis shown in Figures 21 and 22. Simply put, each y-intercept is E_{base}, and the each slope is $24 \times BLC_H/\eta$. Note that the heating and cooling base consumption of HBL is respectively 2.25, and 12.87 times those of MB. These numbers can be used to estimate energy savings from ECM's that clearly reduce a building's base heating or cooling energy consumption.

Table 12: PRISM Analysis Summary

	MB	**HBL**
$E_{base/H}$ [MMBtu]	31.27	70.615
$24 \times BLC_H/\eta$ [MMBtu/°F-days]	1.757	1.100
$E_{base/C}$ [MMBtu]	4.181	53.802
$24 \times BLC_C/\eta$ [MMBtu/°F-days]	3.654	3.644

Chapter 6: Energy Models

6.1 The Microbiology Building Baseline Energy Model

6.1.1 Energy Model Overview

The physical structure of MB was drawn using the eQUEST native geometry creation tool using simple floor plans for reference. Floor dimensions were calculated using the documented reference scale and the freeware, ImageJ. Ceiling heights were measured on site and assumed to be equal for each floor. All dimensions were rounded to the nearest foot. Only the internal walls separating thermal zones as determined by examining the mechanical drawings and AHU assignment area documentation were drawn into the model. Internal doors and aesthetic architectural features such as towers were also neglected. Figure 30 shows the 3-D representation of the building model as rendered in eQUEST.

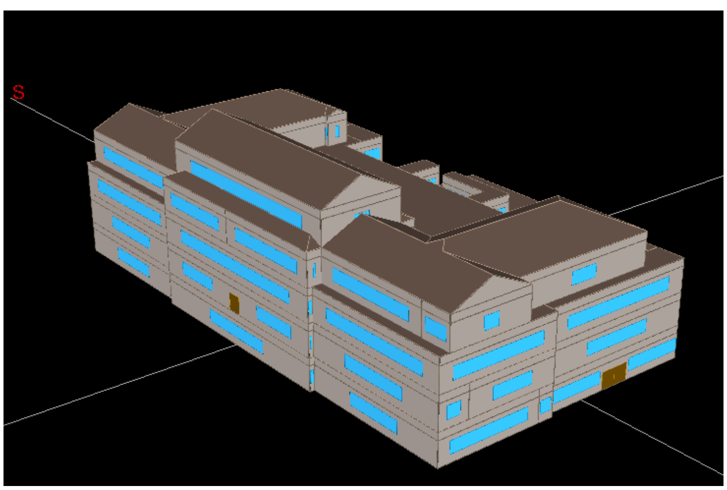

Figure 30: MB energy model as rendered in eQUEST Building Shell 3-D Geometry Tab

Each of the 5 floors was drawn separately and adjusted to match adjacent floors appropriately. Fenestration details were modeled using the window-to-wall ratio method, a standard simplification method whereby the total area of windows is divided by the total exterior surface area of exterior walls per floor, to reduce simulation time. Roof incline angles were also estimated due to lack of architectural documentation.

The energy model had a total of 30 thermal zones. Each thermal zone represented the space served, or not served, by an AHU on a given floor. A single floor had at most 8 thermal zones. Each zone was provided with unique VAV terminal unit specifications, exhaust capacities, and thermostats.

Six space types were defined to specify lighting, plug loads, occupancy, and their associated schedules: Office (Executive/Private), Mechanical/Electrical Room, Corridor, Conference Room, Comm/Ind Work (Hi/Bio/Lab), and Classroom/Lecture. These definitions were developed through the process of building comprehension as discussed in Chapter 4. Building walk-throughs, mechanical documentation, occupant interviews, ASHRAE standards, and data collected through instrumentation such as light meters, power meters, and infrared thermometers were of crucial significance in this process. Finally, physical observations and interviews with knowledgeable FM staff allowed for informed assumptions determining the building's construction materials. Architectural documentation would have provided more concrete justification for some of these assumptions but was unfortunately unavailable during the course of the audit.

6.1.2 Energy Model Results

Calibrating the baseline energy model to closely match actual building energy consumption data is crucial. As discussed in Chapter 3: Utility analysis, three energy commodities served MB: electricity, district steam, and district chilled water. Interquartile monthly utility consumption data was averaged and compared to eQUEST simulation results using a formatted Microsoft Excel sheet. Figure 31 shows the results of the energy model's baseline monthly electricity consumption as compared to the actual building consumption data. Baseline simulation very closely aligns with temporal utility patterns, and the predicted total annual energy consumption deviates -2.4% from actual annual consumption. Slight adjustments to electric equipment space load scheduling were made to mimic the irregular summer increase in electricity consumption.

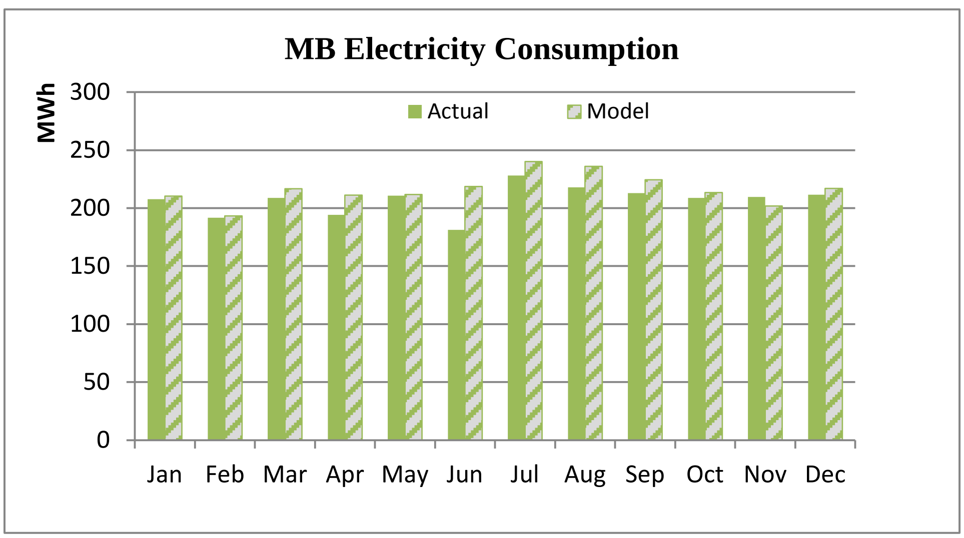

Figure 31: Electricity consumption - utility bills vs. baseline simulation

It is important to note a few pitfalls of the eQUEST simulation environment here. As applies to this section, the two most relevant pitfalls are eQUEST's inability to directly model steam loops and the inability to directly model district chilled water loops. An on-site boiler and hot water distribution system was used to approximate the consumption of district steam, and an on-site electric chiller system was used to approximate the consumption of district chilled water. Figure 32 shows a schematic of the model hot water loop. In the simulation, a boiler consumes natural gas to create hot water that is used throughout the building's heating coils with a default heat input ratio of 1.253. It is therefore assumed that simulation gas consumption be adjusted by this factor to simulate the total amount of steam consumed.

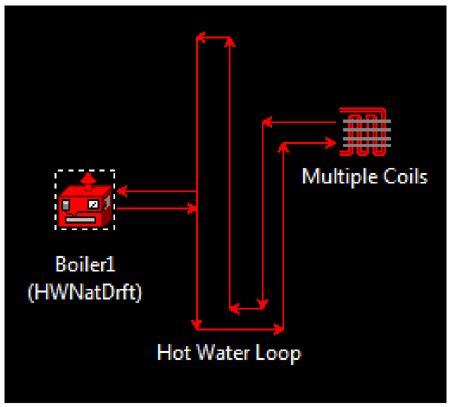

Figure 32: MB Energy model HW loop schematic

Figure 33 plots monthly utility steam consumption and baseline simulation results using the model hot water distribution system after processing raw output as described above. Aggregate baseline steam simulation consumption had an annual deviation of -2.7% from actual utility consumption. On a monthly basis, the simulation's maximum total deviation is -8%, and occurs during the month with the lowest utility consumption: July. Reasons explaining the general trend of higher-than-expected actual building steam consumption during summer months is discussed later in this chapter.

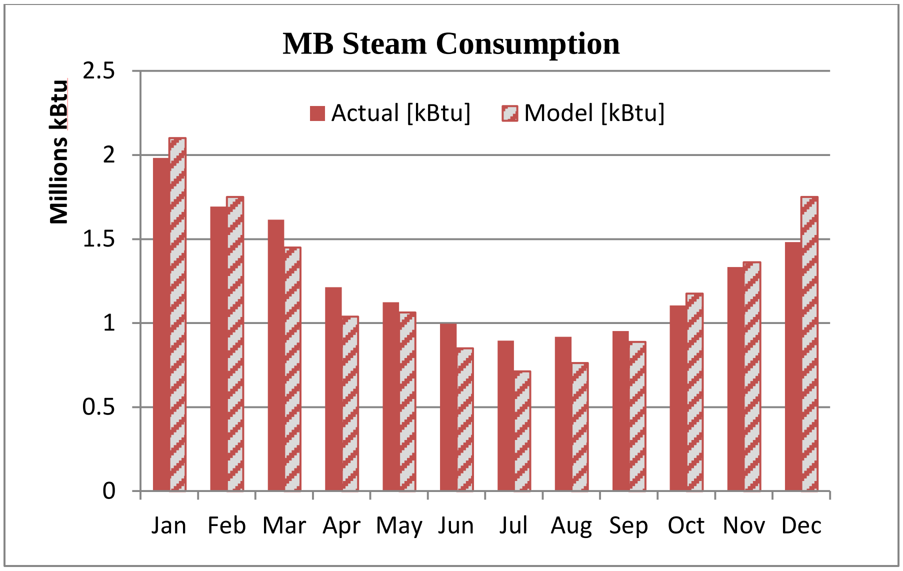

Figure 33: MB Steam consumption - utility bills vs. energy model

Raw simulation data for CHW needed to be processed in a similar manner to steam. The simulation provides the electrical load in kWh from a simulated chiller and condenser. The default efficiency value is then used as a conversion factor to calculate the appropriate total simulation cooling load in TonHr.

Simulation results for the final energy consumption commodity, CHW, are shown in Figure 34. The model's predicted CHW consumption tended to be too low year round. Reasons for these deviations are discussed in the next section. The CHW consumption simulation results deviated from utility data by -7.7% annually.

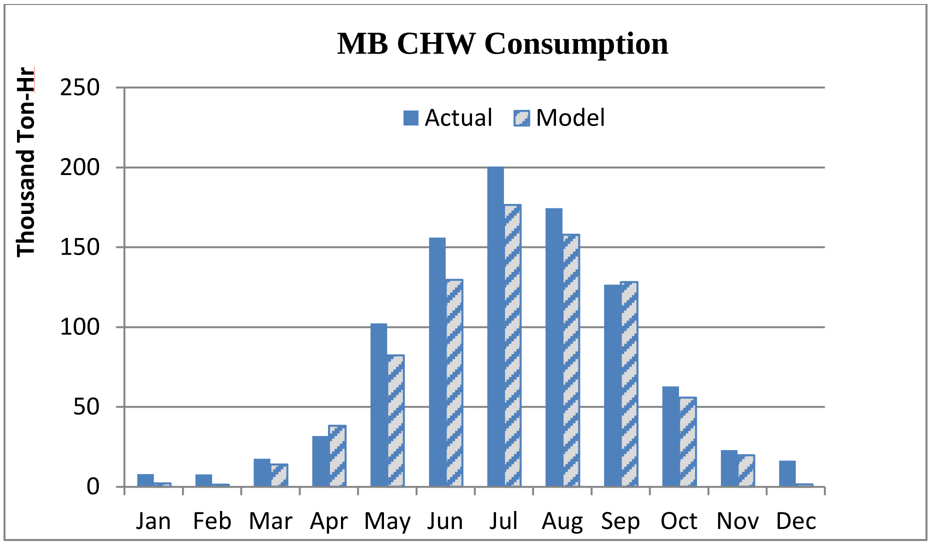

Figure 34: MB CW consumption - utility bills vs. baseline simulation

Overall, the baseline energy model deviates from total actual building energy consumption by -3%. This close alignment is also reflected in the simulated proportion of total energy consumption by end use, as seen in Figure 35. Recall from the utility analysis that the actual percent of total energy consumed by MB as reported in the utility analysis steam, CHW, and electricity respectively amount to 44%, 30%, and 26%. Those values deviate from the predicted proportions by at most -2%.

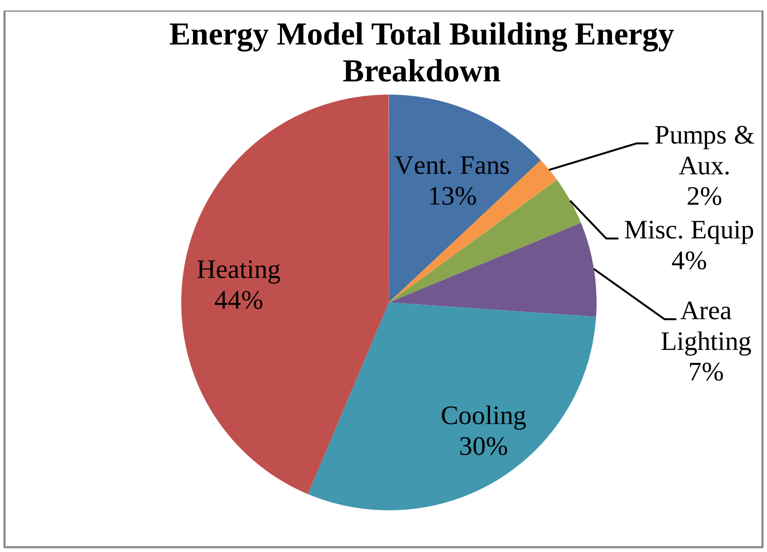

Figure 35: Annual MB energy consumption by end use

6.1.3 Uncertainty Analysis

As an important step in model calibration, an uncertainty analysis was conducted to determine the effect that varying model inputs have on simulation results. Eight parameters were selected for examination. These parameters were selected due to their accepted significance in affecting either actual building energy consumption, energy simulation results, or both. Table 13 details these parameters, and Figure 36 shows the resulting effects as percentage deviations from total baseline simulation energy consumption. Numerous sources were consulted in determining an appropriate minimum and maximum parameter values; however, due to the lack of architectural drawings, age of the building and the numerous renovations therein, typically a wider-than-normal range was considered.

Table 13: MB uncertainty analysis parameters

Parameter	**Unit**	**Baseline Value**	**Low Value**	**High Value**
Roof Thermal Resistance	ft^2-hr-F/Btu	17.9	6.9	24.9
Infiltration	cfm/ft^2	N/A	0.001	0.1
Plug Load Density	W/ft^2	N/A	-50%	+50%
Energy Recovery Coil Sensible Effectiveness	Ratio	0.52	-50%	50%
Zone Thermostat Set Point	°F	70	67	73
Exhaust Fan Pressure Rise	inH2O	0.75	0.45	2.5
Fan Efficiencies	Ratio	0.41	0.21	0.61

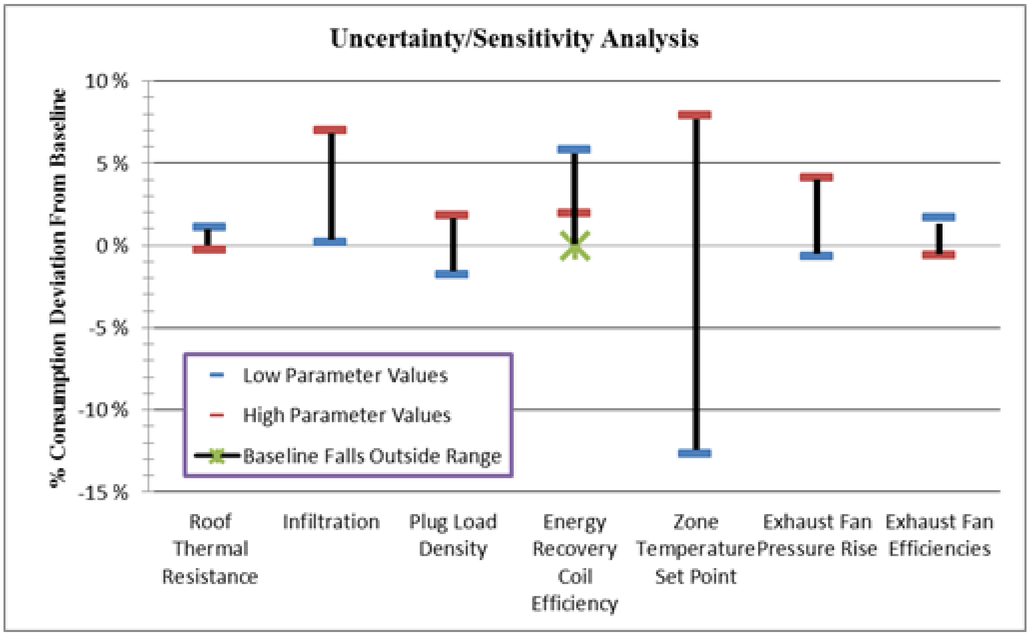

Figure 36: MB Uncertainty/sensitivity analysis results

From the results of the uncertainty analysis we see that the zone thermostat set point and infiltration rate hve the highest effect on total energy consumption. Perhaps surprisingly, reduced thermostats set points have an overall net reduction in energy consumption of up to 12%. Also surpsingly, both reducing and increasing the sensible effectiveness of the heat recovery coils has the effect of *increasing* the total energy consumption as compared to the base line.

6.2 As-designed Microbiology Building Energy Model

The MB "As-Designed" energy model was designed to simulate what energy consumption would be, if it was functioning as it should. In other words, it simulates what energy consumption would be if all of the known operational issues were resolved. Most of these operational issues relate to basic BAS controls. Unfortunately, resolution of these problems likely requires a substantial audit of multiple temperature stats, valve positioning sensors and controls, as well as logic schemes governing equipment operation. Therefore, individual savings estimates are not presented for ECM's #1.1 and 1.2. Instead, the energy consumption due to heating and cooling predicted by the baseline simulation are assumed to result from a "Sensors and Controls Audit."

6.2.1 MB ECM #1.1 – Proper Installation of Outside Air Temp Stat

Through examination of historical trends via the building automation system (BAS), it was determined that the outside air temperature (OAT) stat was giving faulty readings in the late afternoon. Comparing hourly temperature data at Baltimore-Washington International Airport to the MB OAT stat revealed that the building's reading was high by as much as 21°F due in the afternoon (Weather Underground, 2017). After consulting with knowledgeable FM personnel, the stat was found to be improperly installed as it was exposed to direct sunlight without a radiation shield as is pictured in Figure 37.

Figure 37: Improperly Installed OAT Stat

The faulty readings had the effect of confusing automated controls and logic schemes. Table 14 summarizes the logic conditions governing availability of heating and cooling in MB, and the resulting supply air setpoint.

Table 14: OAT Conditions for Heating/Cooling in MB

AHU	Heat/Cool	Rule	OA Temp Control	Resulting Supply Air Set Point											
				Sep	Oct	Nov	Dec	Jan.	Feb	Mar	Apr	May	Jun	Jul	Aug
1	H	Allow Heating if OAT <	55	57	57	57	57	57	57	58	58	58	58	58	58
	C	Allow Cooling if OAT >	60	61	61	61	61	61	61	60	60	60	60	60	60
2	H	Allow Heating if OAT <	55	58	58	58	57	57	59	63	57	57	57	57	57
	C	Allow Cooling if OAT >	55	61	61	61	62	63	64	68	62	62	62	62	62
3	H	Allow Heating if OAT <	55	59	59	59	59	59	59	59	59	59	59	59	59
	C	Allow Cooling if OAT >	55	61	61	61	61	61	61	61	61	61	61	61	61
4	H	Allow Heating if OAT <	55	54	54	54	54	54	54	54	54	54	54	54	54
	C	Allow Cooling if OAT >	60	56	56	56	56	56	56	56	56	56	56	56	56
5	H	Allow Heating if OAT <	55	56	56	56	56	56	56	56	56	56	56	56	56
	C	Allow Cooling if OAT >	55	61	61	61	61	61	61	61	61	61	61	61	61

Thus, at any time when the actual air temperature was below 55°F but the building OAT stat falsely read above 55°F, all AHU's would function improperly. In a case such as this, every AHU would enter the "allow cooling" mode. Thus, heating is disallowed, CHW is unnecessarily consumed and the less efficient CAV and VAV terminal heating coils must make up the additional heating requirement. This problem could be solved either by reinstalling the thermostat, or by adjusting logic controls to read from a different, existing thermostat connected to the glycol energy recovery system.

6.2.2 MB ECM #1.2 – Energy Recovery System Logic Fix

As discussed in Chapter 3, MB's glycol energy recovery system (ERS) is controlled by a BAS separate from that which monitors and controls all AHU's except AHU-6. After observing the ERS' operation periodically over the course of a few months, instances of questionable operation appeared. Pictured in Figure 38, is an example of the ERS behaving improperly. To the left, the ERS is appropriately enabled and in the "heat" mode, since the OAT is less than 50°F and glycol pump -1 is "On." However, assuming all other labels including arrows indicating glycol flow direction are correct, the temperature drop across the energy recovery coils suggests that heat is actually being *removed* from AHU's as opposed to being added as should be occurring.

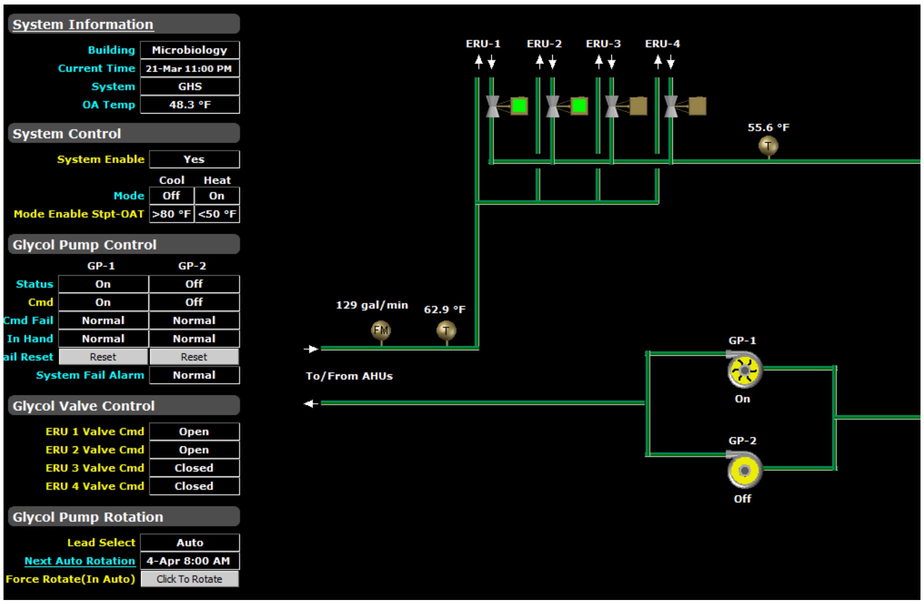

Figure 38: BAS View of Faulty Glycol ERS Operation

A possible reason for this is a controls logic switch, since the system only needs to reverse the flow direction to switch from heating to cooling. However, if the problem is only with the direction of the arrow labels, there is no fail safe, since as mentioned in the previous section air temperature stats are unreliable and the two BAS' do not communicate.

As stated in the introduction to this section, energy savings resulting from ECM's 1.1 and 1.2 are taken to be the predicted heating and cooling energy consumption of the baseline model. This is a reasonable assumption because as stated in the eQUEST Training Workbook, "DOE-2 has always assumed 'perfect' control where capacity and operations permit" (James J. Hirsch & Associates, 2004). A summary of the energy savings resulting from ECM #1: "Sensor and Controls Audit" are shown in Table 15.

Table 15: MB ECM #1: Sensors and Controls Audit energy savings

	CHW [ton-hr]	Steam [lbs]	Total Energy Saved [kBtu]
Annual Energy Saved	67,078	344,213	1,215,926
% Reduction	7.2%	2.7%	3.6%

6.2.2 MB ECM #2 – AHU-2 HW Coil Temperature Stat and Valve Fix

Another problem discovered through observation of the BAS, was the presence of a leaking hot water (HW) heating coil control valve. AHU-2 showed consistent air temperature increases of between 5°F and 10°F, across their respective hot water heating coils during times when the valves read 0% open. Upon further inspection, it became relatively clear that the HW valve was rarely read by the BAS as being open by any percent at all. Furthermore, the temperature stat reading air temperature after passing through the heating coil exhibited very strange behavior. Figure 39 displays temperature and CHW valve position for the week of March 17th, 2016. Before discussing this figure further, it should be noted that similar issues exist in every other AHU, though not to the degree seen in AHU-2.

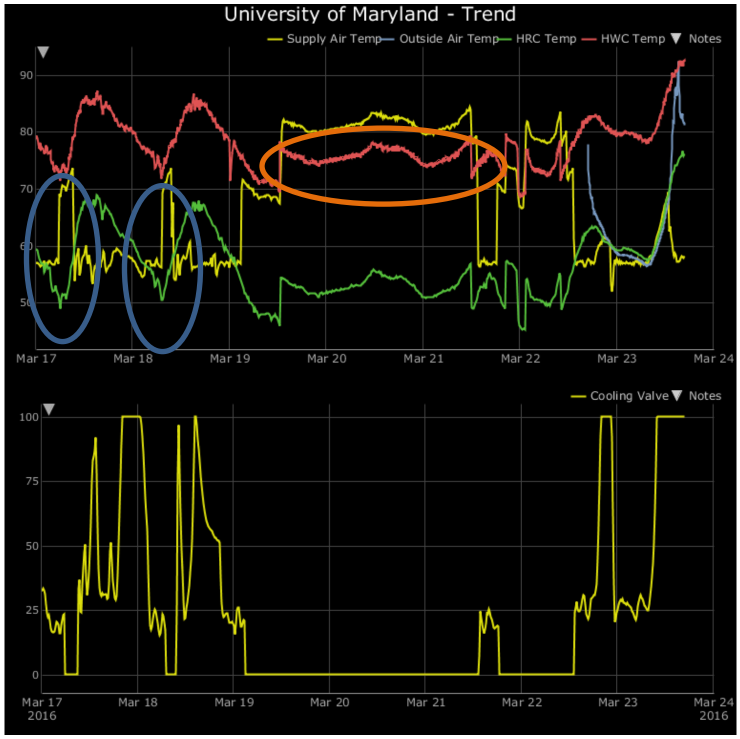

Figure 39: Time Plot of AHU-2 Temperatures Week of March 17th, 2016

In the top chart is pictured, listed in sequential order of air processing, the outside air temperature (blue), the air temperature after passing through the heat recovery coil (green), the air temperature after passing through the hot water coil (red), and finally the supply air temperature (yellow). Refer back to Figure 9: *Graphical representation of AHU-2 as shown in ALC BAS* for a graphical representation of this order of air processing. The bottom chart (yellow) shows the cooling valve status, ranging from 0% open at the bottom and 100% open at the top. *Not* pictured is a similar chart showing the heating coil reading 0% open throughout the entire period. One final note is that we should take the green line as OAT, since as mentioned in the above section; the actual OAT sensor does not provide correct readings.

Three problems are apparent in this figure. First, is that air temperatures after passing through the hot water coil (red) are at minimum 10°F higher than the assumed OAT (green). This may be evidence of a leaking valve or a faulty thermostat. Second, circled in blue are instances when the cooling coil valve closes, and supply air temperature subsequently rises in spite of the fact that the heating coil valve % open status remains at 0%. The only possible explanation for this behavior is a leaking hot water coil. Third, circled in orange we see that the supply air temperature actually surpasses the air temperature reading after passing the hot water coil. Because there is no additional heat source present the only explanation for this behavior is a faulty hot water coil thermostat.

To simulate the leaking HW valve in the model, a "dummy" hot water coil is included in each air handler that heats the air by a set temperature throughout the year in the baseline model. To simulate the savings resulting from fixing the faulty valves, or adjusting the controls on the valves to function properly, the dummy coils are removed and a simulation is run. The predicted energy savings resulting from ECM #2 are taken to be the difference in consumption between the two simulations and are summarized in Figure Table 16.

Table 16: MB ECM #2: Hot water coil valve fix energy savings

	CHW [ton-hr]	Electricity [kWh]	Steam [lbs]	Total Energy Saved [kBtu]
Annual Energy Saved	4,705	2,400	994,556	1,252,145
% Reduction	1%	>1%	8%	3.8%

6.2.4 MB ECM #3 Ultra-low-temperature Freezer Consolidation

A number of aging ultra-low-temperature freezers was observed. Inquiries of occupants familiar with the equipment revealed that many of the freezers were old or aging and others' contents were entirely unknown. A brief literature review revealed a linear correlation between typical energy consumption of an ultra-low-temperature freezer and its age (Doyle & Gumapas, 2013).

The correlation is:

$$E_m = 17 * A + 502$$

Where:
E_m is the freezer's monthly electricity consumption in kWh
A is the age of the freezer in years.

It's recommended that the four oldest freezers be removed and their contents consolidated. A summary of energy and cost savings calculations are shown in Table 17. Though the savings are relatively small, their payback is immediate and the incentives for space savings make their implementation attractive.

Table 17: MB ECM #3 Savings Calculation

						EEM #3 Savings	
Age Range of Freezer	**Assumed Average Age of Freezer**	**Monthly Electricity Consumption per Freezer [kWh]**	**Number of Freezers In Age Range**	**Annual Energy Consumption [kWh]**	**Total Utility Cost**	**Electricity Savings [kWh/yr]**	**Utility Savings [$/yr]**
0-5	2.5	544.5	2	13,068	$ 1,490		
5-10	7.5	629.5	3	22,662	$ 2,583		
10-15	12.5	714.5	2	17,148	$ 1,955		
15-20	17.5	799.5	2	19,188	$ 2,187	(19,188)	$ (2,187.43)
20+	22.5	884.5	2	21,228	$ 2,420	(21,228)	$ (2,419.99)
		Total	11	93,294	$ 10,636	(40,416)	$ (4,607.42)

6.2.6 As-Designed Energy Model Summary

Energy modeling using comprehensive simulation engines has the capability of capturing the effect on building energy consumption caused by multiple energy conservation measures that may not be independent. In this case, the aggregate effect on predicted energy savings by modeling ECM #1 and ECM #2 simultaneously is not equal to the sum of the savings when each ECM is modeled separately. The as-designed energy model predicts the energy savings resulting from following the implementation of all three ECM's. Heating and cooling energy consumption savings are calculated relative to the building's actual average utility consumption, while electricity savings are calculated by taking the relative percentage difference of "As-designed" energy consumption to the baseline simulation consumption, and applying this to the average utility consumption. The final electricity savings result from adding the savings calculated in ECM #3. Figure 40 illustrates the energy savings proposed by the "As-designed" model.

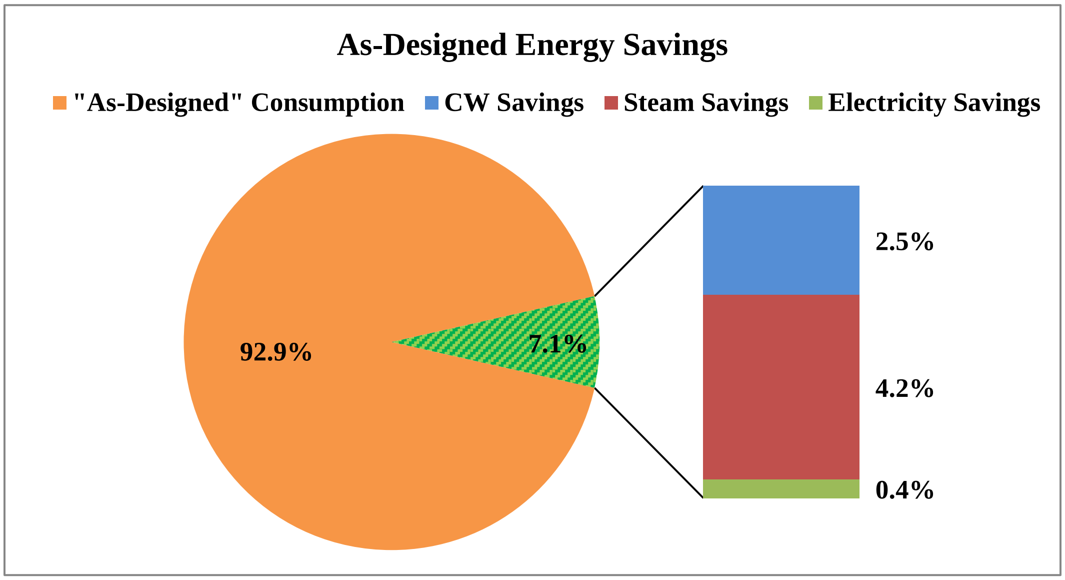

Figure 40: MB As-Designed Energy Model Savings Summary

6.3 Microbiology Building Energy Efficient Model

6.3.1 MB EEM #1 – Zone Temperature Setback

At present, there exists no zone temperature scheduling of any kind. In commercial buildings, its common practice during nighttime hours to either turn off HVAC systems entirely, or reduce heating setpoints during the winter and increase cooling setpoints during the summer via programmable thermostats located within spaces. However because MB's ventilation requirements and schemes to condition 100% outside air, turning off HVAC systems violates safety codes, and the practice of increasing summer temperature setpoints would actually *increase* energy consumption in summer months, as terminal heating units consume additional hot water (derived from campus steam) to meet the raised thermostat temperature.

Five setback schedules varying by the space types in which the setback is implemented were simulated. The space types affected by each setback schedule are summarized in Table 18. Note that the animal care unit is intentionally left unaffected by each set back schedule.

Table 18: MB zone temperature setback schedules

	Sch 1		Sch 2		Sch 3		Sch 4		Sch 5	
	Night	Wkd	Night	Wkd	Night	Wkd	Night	Wkd	Night	Wkd
Lecture Hall	X		X	X	X		X	X	X	X
Teaching Labs	X		X	X	X		X	X	X	X
Offices	X		X	X	X		X	X	X	X
General Purpose Labs					X		X		X	X
BSL-3 Lab					X		X		X	X
Animal Care Unit										

Pacific Northwest National Laboratory advises that 5-10°F is an acceptable range of temperature setbacks (PNNL, 2017). To model this EEM, zone temperatures of the "As-designed model" will be set back to 64°F from 12 a.m. to 6 a.m. In this manner, savings are accurately accumulated and there is no "double-counting." These savings are illustrated in Table 19 and Figure 41.

Table 19: EEM #1 – Zone Temperature Setback Savings Summary

	Sch 1	**Sch 2**	**Sch 3**	**Sch 4**	**Sch 5**
CHW Savings [Ton-Hrs]	2,105	4,333	3,714	5,571	6,190
Electricity Savings [kWh]	9,400	15,700	14,900	21,500	27,000
Steam Savings [kBtu]	287,500	525,000	2,037,500	2,262,500	3,487,500
Total Savings [kBtu]	344,830	630,568	2,132,910	2,402,715	3,653,909
Percent Energy Savings	1.1%	2.0%	6.7%	7.5%	11.4%
Dollar Savings	$10,006	$18,200	$63,068	$70,854	$108,087
Percent Dollar Savings	1.2%	2.2%	7.8%	8.7%	13.3%

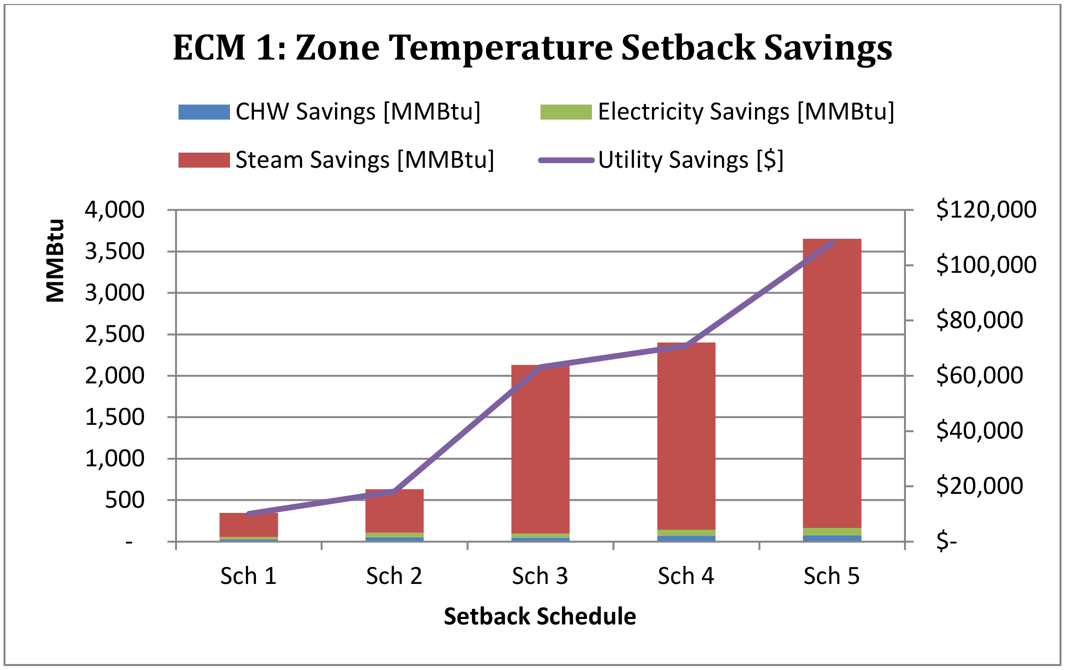

Figure 41: MB EEM #1 - Zone Temperature Setback Savings

One challenge in implementing this EEM is the sparse BAS coverage throughout the building as mentioned in Chapter 3. Cost estimates for BAS implementation vary widely; however, if the cost of implementation can be kept below \$1.29/ft^2-NASF (or \$0.80/ ft^2-GSF), then the simple payback period of EEM -1 using Schedule 4 will be 1 year or less.

6.3.2 MB EEM #2.1 – Variable Air Volume Fume Hood Retrofit

Consideration is often given to variable air volume (VAV) versus constant volume (CV) fume hoods when retrofitting laboratories. As mentioned in the literature review chapter, VAV fume hoods were a "featured technology" in 12 of the 13 Labs21 laboratory retrofit case studies, and are given significant attention in numerous other case studies and design handbooks (TSI Incorporated, 2014). The use of VAV fume hoods has two distinct advantages over CV hoods: increased safety due to having a constant face velocity that provides optimal containment, and energy savings resulting from a reduced quantity of exhausted conditioned air. A CV hood exhausts the same volume of air regardless of sash position, while a VAV hood only exhausts the amount of air required to maintain a specified face velocity, typically 100 feet per minute. Figure 42 illustrates basic exhaust principles of CV vs. VAV fume hoods. Figures were modified from (Oregonstate.edu/vent/bypass, 2014).

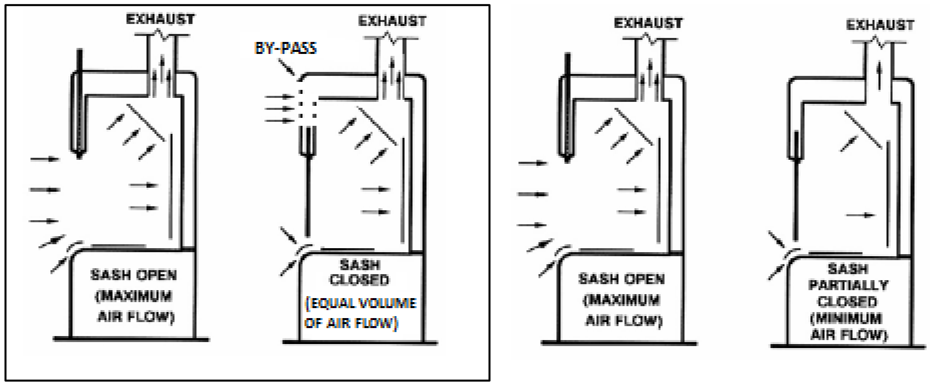

Figure 42: CV Fume Hood w/ By-Pass (left) vs. VAV Fume Hood (right)

There are a total of 21 fume hoods operating in MB. Air from 20 of the 21 fume hoods is exhausted from the building through the central manifold exhaust system. A detailed survey of the existing fume hoods was conducted to determine their configuration, exhaust CFM, and ratio of fume hood exhaust to total room exhaust. The ratio of fume hood exhaust to total room exhaust is crucial in choosing replacement candidates. Multiple case studies of VAV fume hood retrofits show that energy savings may only be achieved in zones that have open or CV fume hoods and whose exhaust air is "fume hood dominated (Gevelber, Choate, Sheehan, & Lo, 2015)." 12 fume hoods were identified as candidates for VAV replacement and are detailed Table 20.

Table 20: VAV Fume Hood Retrofit Specifications

Room Number	Total Exhaust [CFM]	Fume Hood Exhaust [CFM]	Design Supply Air [CFM]	Room Area [sq. ft.]	Ratio of Fume Hood Exhaust to eQUEST Zone Exhaust
0107L	920	920	870	207	0.0953
1104	1700	1420	1600	652	0.625
1106	920	920	870	266	
1107	1700	1420	1600	942	
1135	1420	1420	1600	951	0.354
1143	1700	1420	1600	965	
2103	2500	2500	2400	974	0.945
2105A	1420	1420	1370	286	
2131	1420	1420	1370	195	0.252
2201	1420	1420	650	908	0.271
2201E	1720	1720	1680	185	
3144B	920	920	800	138	0.209

To calculate the energy and cost savings resulting from a VAV fume hood retrofit, custom exhaust flow schedules specific to each applicable eQUEST thermal zone were created using a MATLAB script and a simulation was run using the "Track Exhaust and Supply" feature. When utilizing this feature, both the hourly exhaust flow and the supply flow are tracked, and both are set to the greater of the two. eQUEST documentation states that "this mode is useful simulating a laboratory with variable-flow fume hoods, where no supply should return to the air handler."[7]

The MATLAB script takes a value of the proportion of zone exhaust air due to fume hoods to total zone exhaust air as input, and by using a predefined "sash-opening schedule," described further in the next section, writes the exhaust schedules formatted to a Building Description Language (BDL) text file. These are then easily copy-pasted into the eQUEST .pd2 input file. This script saved many hours of labor

[7] See native DOE-2 Help Documentation: Dictionary > HVAC Components > ZONE > Airflow > Exhaust Airflow and Fans

by avoiding the tedious schedule-creation process built into the eQUEST GUI, and can be found in Appendix A1.

Numerous commercially available solutions exist to achieve this energy efficiency measure. One solution is to replace entirely the existing CAV fume hoods with new or used VAV fume hoods. However, this solution would likely be expensive and unnecessary as multiple companies and firms offer retrofit components individually or in "kits." As an example, Figure 43 displays the components of a retrofit kit from Accutrol that includes an exhaust valve, a face velocity sensor, a sash sensor, and relevant software (Accutrol LLC). Not pictured are the requisite VAV terminal supply air units that would also be necessary in rooms containing fume hoods for safe air balance levels. An estimate of $4,891 estimate for a VAV terminal supply air unit retro-fit kit is considered reasonable; however additional costs for labor and controls adjustments will be necessary (WattMaster VAV Control Systems, 2012).

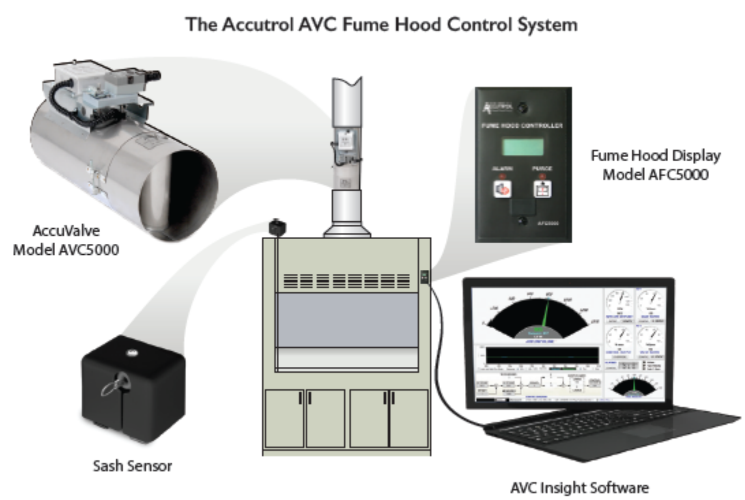

Figure 43: Components of a CAV to VAV Retrofit kit (Accutrol LLC)

Estimates for purchase and installation of BAS-integrated VAV fume hoods are typically around $5,000 per fume hood (ECT, Inc., 2017). Using this figure, the required capital investment for a whole-building VAV fume hood retrofit is estimated at $124,629.

Simulation results and savings estimates for a whole-building retrofit project are presented in the next section after a brief discussion on the potential impact of occupant behavior.

6.3.3 MB EEM #2.2 – VAV Fume Hoods: "Shut the Sash" Campaign

Variable occupant behavior is a primary source of error in any building energy model. When estimating the savings resulting from a VAV fume hood retrofit project, this is particularly the case. If occupants neglect to shut fume hood sashes when they are not in use, then no savings can be achieved.

In a case study on the average position of fume hood sashes conducted by the Department of Energy and California State University (CSU), researchers conducted a "shut-the-sash" campaign to educate laboratory occupants on the benefits of being mindful of closing fume hood sashes when appropriate and document the effects of the campaign on building-wide average sash height (Bell, 2012). During the campaign, a sticker was placed on each fume hood that simply and clearly illustrated that lowering the sash saved energy. Surveys were conducted to measure the average sash height of fume hoods in two CSU buildings before and after the installation of the stickers. Figure 44 shows the results of these surveys, with red lines showing the average sash height prior to the campaign, and the blue lines showing the average sash height after the campaign finished. In this figure a sash height of 24 inches is considered fully open. It's clear by comparing the time plots of average sash height, that the extra effort to increase awareness had a dramatic effect on occupant behavior and improved compliance in keeping sashes closed when not in use.

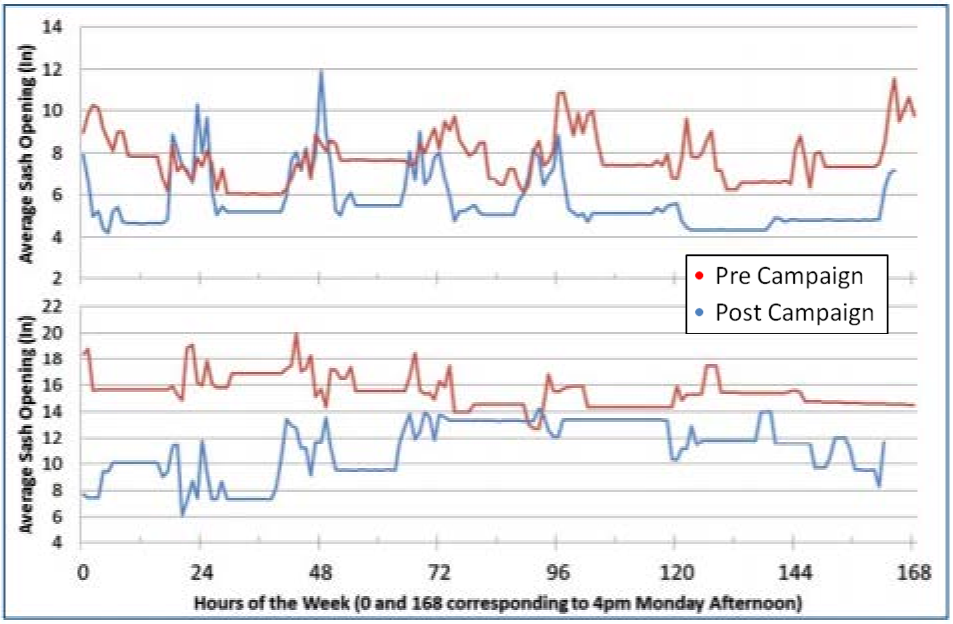

Figure 44: CSU "Shut-the-Sash" Survey Results from Two Campus Labs

The above figure also illustrates how a building can be generally "compliant" or non-compliant in keeping sash heights to a minimum; the building surveyed in the bottom chart consistently recorded average sash heights much larger than those displayed in the top chart.

As mentioned in the previous section, savings estimates resulting from a VAV fume hood retrofit were determined by, among other factors, a "sash-opening schedule." Using the above figure as a close reference, two sets of sash-opening schedules were created: one set mimicking a non-compliant building prior to a "shut-the-sash" campaign is conducted, and one set mimicking a compliant building after such a campaign. In this manner the two schedules cover a measured but wide range of occupant behavior, were respectively used to estimate savings for EEM #2.1 and #2.2. These schedules have unique weekday (WD) and weekend/holiday (WEH) patterns and are displayed in Figure 45 and Figure 46.

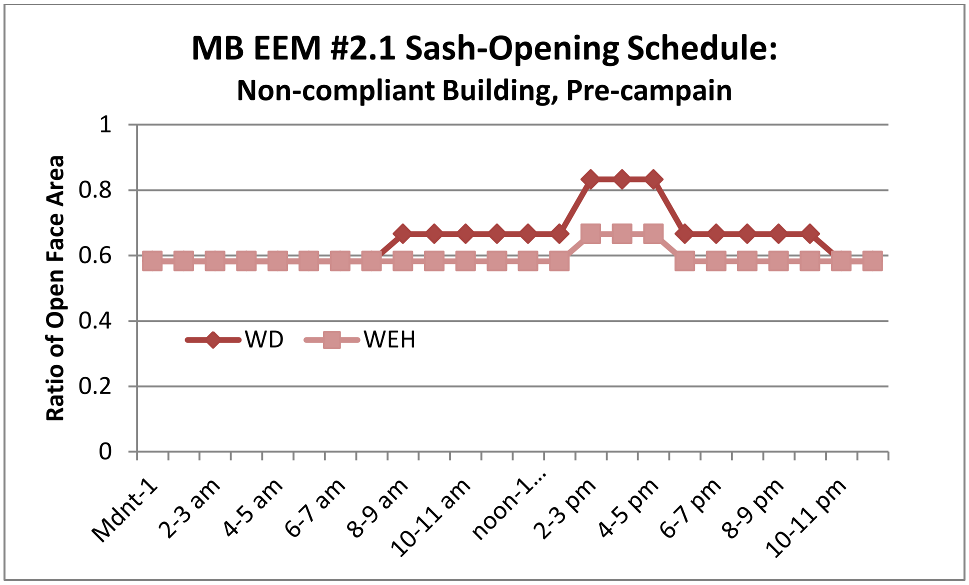

Figure 45: Sash-Opening Schedules for EEM #2.1

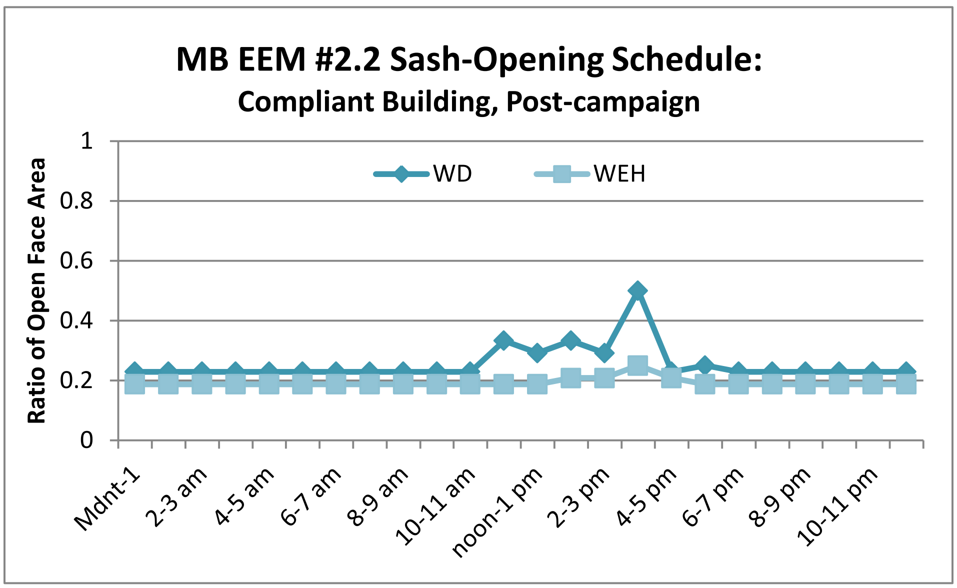

Figure 46: Sash-Opening Schedules for EEM# 2.2

To restate the function of these schedules as applies to the simulations of EEM #2.1 and 2.2, each schedule is applied to the unique proportion of air exhausted through fume hoods in each eQUEST zone containing at least one fume hood. These proportions were derived through examining original mechanical drawings and documenting the existing fume hoods throughout MB.

Figure 47 shows the predicted annual energy and cost savings for the low and high estimate sash-opening schedules, i.e. EEM #'s 2.1 and 2.2 respectively.

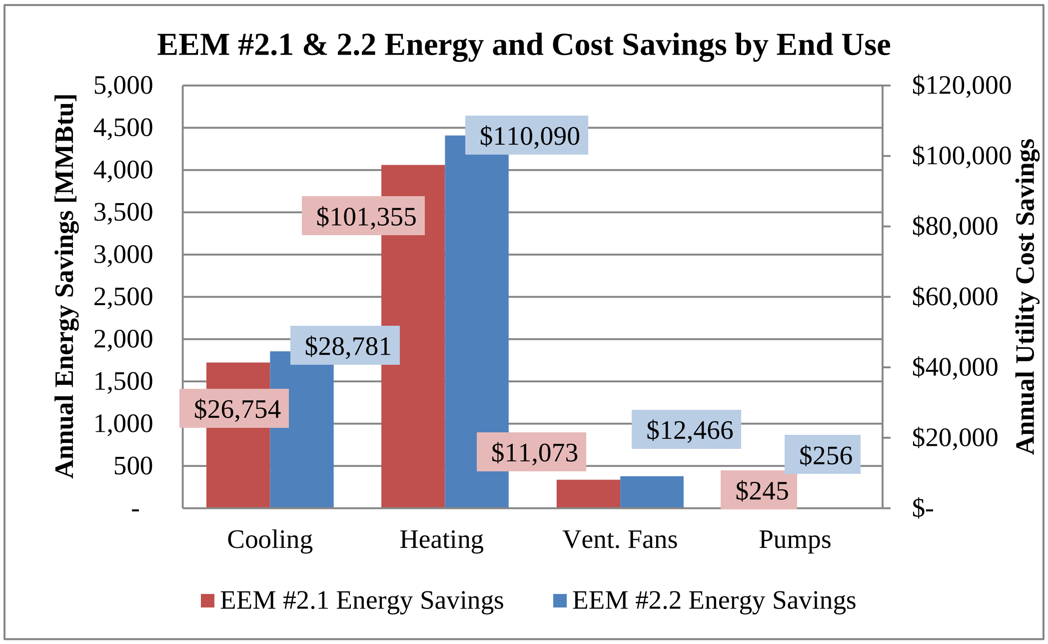

Figure 47: Energy and Utility Cost Savings by End Use for EEM #2.2 and 2.2

From Figure 47 it's clear that occupant compliance can have a significant impact on the efficacy of installing VAV fume hoods. Cost savings from steam could be negatively affected by nearly $10,000 annually, if occupants neglect to keep sashes closed when they are not in use. However according to the simulations, utility cost savings of over $140,000 per year are likely even with relatively low occupant compliance.

6.3.44 Energy-Efficient Model Savings Summary

The MB Energy-Efficient model combines the energy savings of the "As-Designed" model with EEM #1 – Schedule 4, and EEM #2.2. Figure 48 illustrates the predicted savings and Table 21 neatly summaries all ECM's and EEM's.

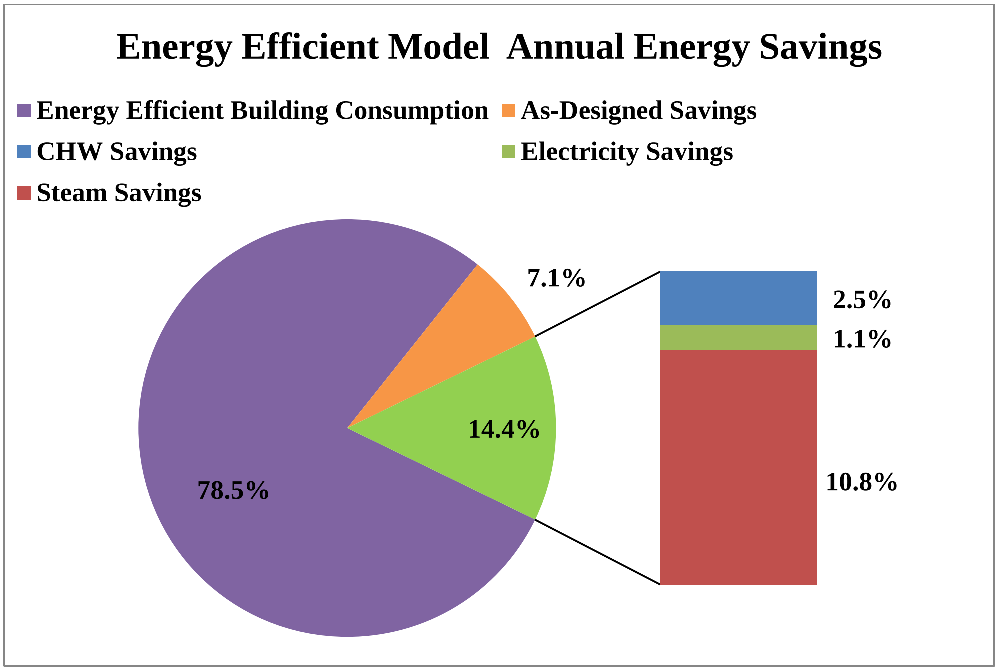

Figure 48: MB Energy Efficient Model Annual Energy Savings

Table 21: MB ECM and EEM Savings Summary

EEM / ECM Summary	CHW [Ton-hrs]	Steam [lbs]	Electricity [kWh]	Total [MMBtu]	Energy Savings [%]	Utility Savings [$]
ECM #1 - Sensors and Controls Audit	67,078	344,213	-	1,215.9	3.5%	22,734
ECM #2 - AHU-2 HW Coil Fix	4,705	994,556	2,400	1,252.1	3.6%	30,780
ECM #3 - ULT Freezer Consolidation	-	-	40,416	137.9	0.4%	4,502
As-Designed Model	71,783	1,223,610	42,712	2,468.1	7.1%	54,573
EEM #1 - Zone Temperature Setback	97,411	2,909,121	95,190	4,971.4	14.2%	115,415
EEM #2.1 - VAV Fume Hood Retrofit	143,840	3,401,164	143,275	6,275.9	18.0%	144,070
EEM #2.2 - VAV Fume Hood Retrofit w/ Shut-the-Sash Campaign	154,735	3,694,297	156,212	6,800.8	19.5%	156,273
Energy Efficient Model	144,211	4,385,252	158,897	7,508.7	21.5%	175,205

While wider BAS coverage and the installation of select CAV control units and VAV supply air terminal units are necessary for a full implementation of the Energy Efficient Model, an estimated simple-payback period of approximately 2 years is reasonable. Furthermore, with a comprehensive installation of a full-scale BAS, the resulting substantial amounts of additional data are likely to reveal new opportunities for energy savings and fine-tuning building operations.

6.5 The Hornbake Library Baseline Energy Model

The energy model for HBL was created using significantly more versatile building energy simulation software: EnergyPlus. As discussed in previous chapters, this allows for more accurate and detailed building descriptions, but can take substantially more time and effort. In spite of the additional effort required of this model, the following sections are written with brevity in mind, so as not to repeat some of the background information already discussed in section 6.4.

Figure 42 shows the physical representation of HBL as viewed in SketchUp with the OpenStudio plug-in. Surfaces colored purple in this figure represent shading surfaces, and include the faces of adjacent buildings nearest HBL. Using the built-in SketchUp image import, trace, and scale features, individual floor plans were drawn using the most up-to-date floor plan layouts digitally available to FM. During the course of this project, however, at least one major renovation to the floor plan layout was underway and thus neglected in the model floor plan layout.

As with the energy model of MB certain features were omitted to reduce simulation time or because they were understood not to have major effects on model results. Such features include internal doors, and aesthetic architectural components.

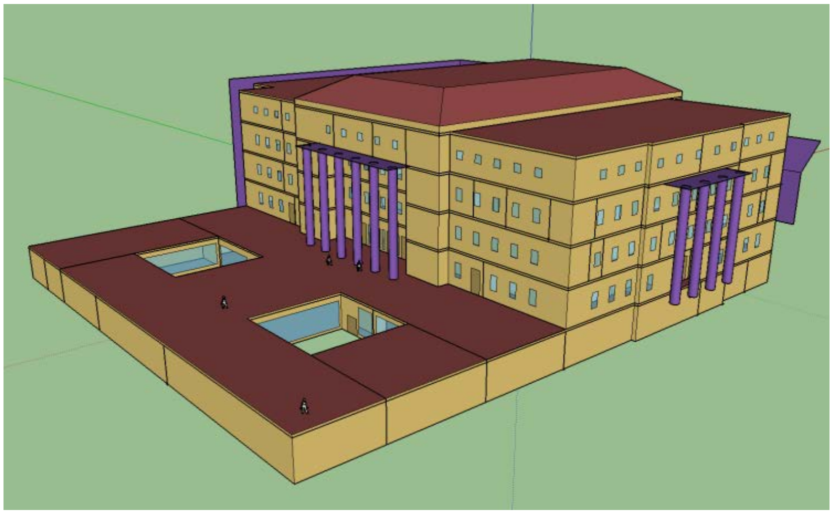

Figure 49: HBL energy model viewed in SketchUp

Figures 49 through 52 show three different renderings of the HBL model in SketchUp. The three main boundary conditions displayed in Figure 43 are internally exposed (green), exposed to sun and wind (blue), and in contact with the ground (tan). In total, 170 spaces were assigned to one of 10 space type definitions describing a major function served throughout the building. As with MB, each space type has unique lighting, plug loads, and occupancy definitions and associated schedules.

Spaces served by identical AHU's and in close proximity of one another were combined for simplicity. 86 total thermal zones were each assigned unique thermostat, humidistat, reheat coil capacity, and flow specification concordant with the data obtained during the building comprehension phase. Data obtained through frequent observation of HBL's library side BAS and historical BAS data provided by FM of the library's school-side were of crucial importance in determining the operation of the building's mechanical systems and schedules.

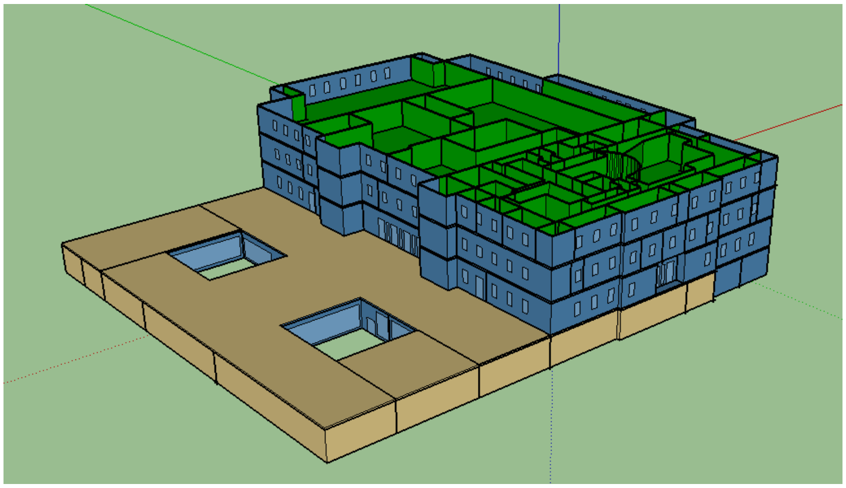

Figure 50: HBL energy model rendered by boundary condition

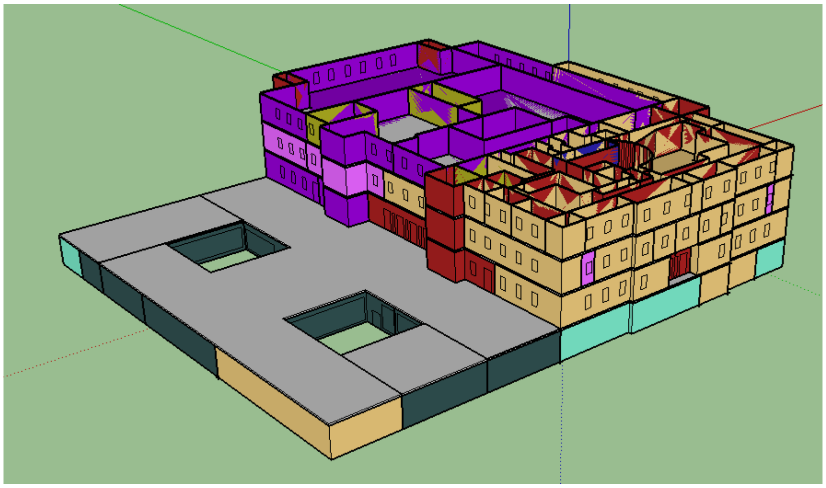

Figure 51: HBL energy model rendered by space type

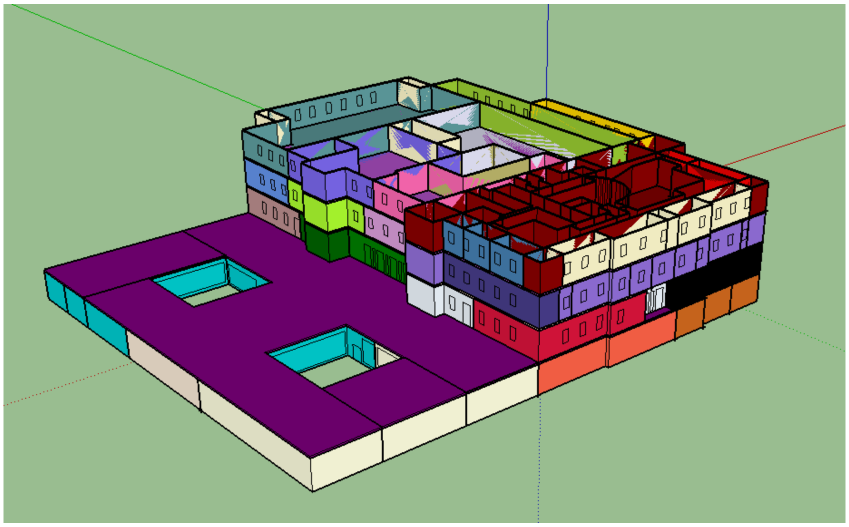

Figure 52: HBL energy model rendered by thermal zone

6.5.2 Building Energy Model Results

As with the energy model for MB, calibration and validation of the HBL energy model is the most important and time consuming task. Also similar to MB, once the model was properly calibrated, simulating most energy efficiency measures followed relatively rapidly. However, achieving accurate results for HBL's baseline energy model faced more numerous and difficult barriers than in the case of MB. These barriers included acquisition of occupant schedules, determining when the operation of mechanical equipment had been manually changed, simulating lighting schedules, and most significantly, simulating HBL's advanced desiccant dehumidification system.

Monthly consumption of the three utilities serving HBL (steam, chilled water, and electricity) was compared to the monthly usage reported in the E+ simulation results. Figure 53 displays the comparison between the actual utility consumption and the baseline energy model monthly steam consumption. Model steam consumption results deviated the most substantially from actual utility data as compared to the other two utilities. The baseline simulation overestimates steam consumption by 5.7% annually. Two factors likely contributed to this discrepancy. First, the model uses TMY3 weather data as opposed to on-site weather data to generate heat balance equations. Second, many of the building's HW fan coils must be switched on and off manually at varying unscheduled dates each year by facilities personnel. The baseline model was calibrated to switch the respective simulation objects coils on and off at estimated specific dates in the fall and spring, that could have been off by as much as 45 days according to persons interviewed.

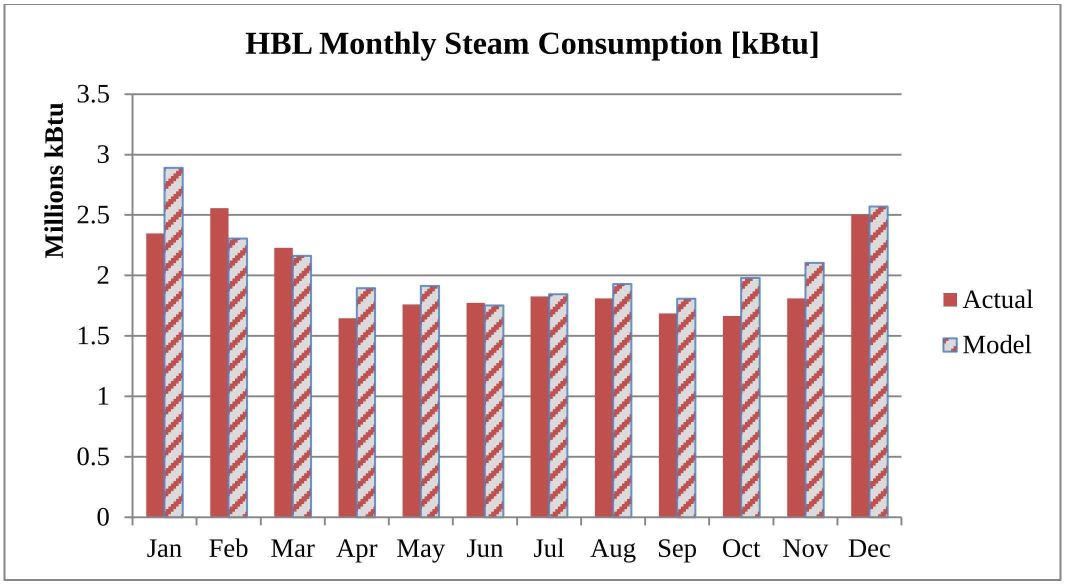

Figure 53: HBL monthly steam consumption - utility vs. baseline simulation

Results for baseline model cooling energy consumption *underestimate* utility data of CHW consumption by 2.1%. As seen in Figure 54, this is due mainly to the model's large underestimations in the milder months of April and October (approximately 18% each month.) This can also likely be attributed to the manual hot water coil switch discussed in the previous paragraph. Another trend visible in the figure is a consistent overestimation of CHW consumption during summer months, (approximately 9% per month).

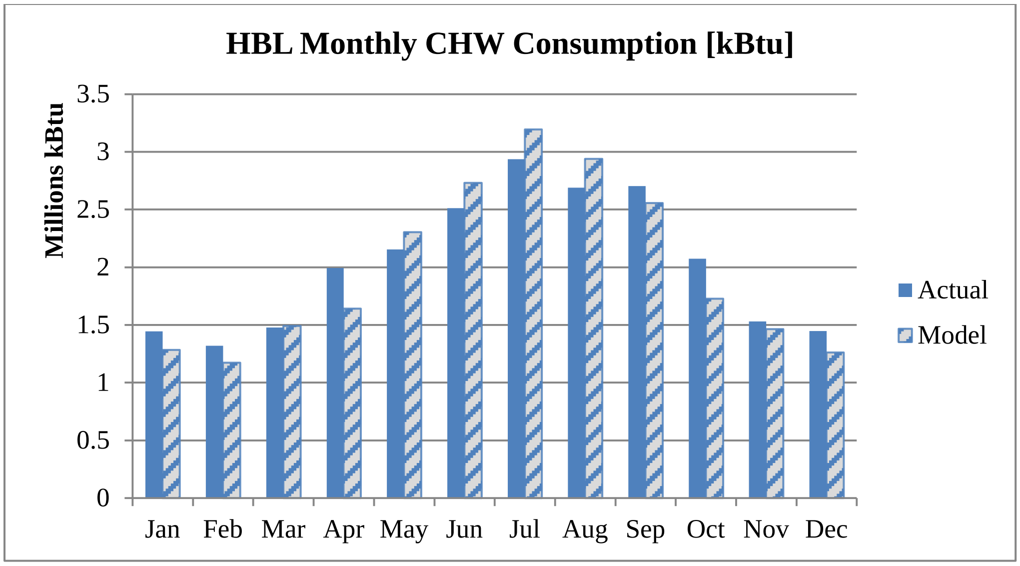

Figure 54: HBL CW consumption - utility vs. baseline simulation

Figure 55 compares monthly utility data for HBL's actual electricity consumption to the results given by the baseline energy model. Overall, the model deviates by only 1.2%. Lighting densities and schedules, some of the parameters more difficult to acquire, were the two variables adjusted to achieve such accurate results.

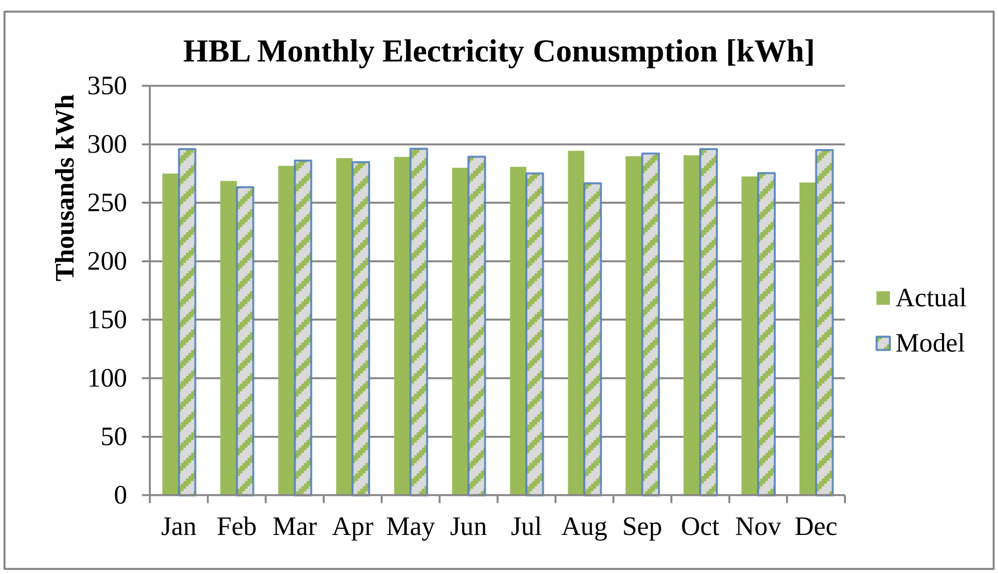

Figure 55: HBL electricity consumption - utility vs. baseline simulation

After completing the monthly comparison, simulation energy consumption was broken down by reported end-use for further analysis and can be seen in Figure 56: HBL baseline model energy consumption by end use. Electricity and steam consumption end uses are respectively shown in shades of red and green while the sole end use of CHW consumption is for cooling, shown in blue. Recall from Figure 27: HBL Utility Cost vs Energy Consumption by Energy Commodity and the utility analyses chapter, that the contributions of steam, CHW, and electricity to total building energy consumption were respectively, 39%, 41%, and 21%. The model's distributions are very close in this regard as well.

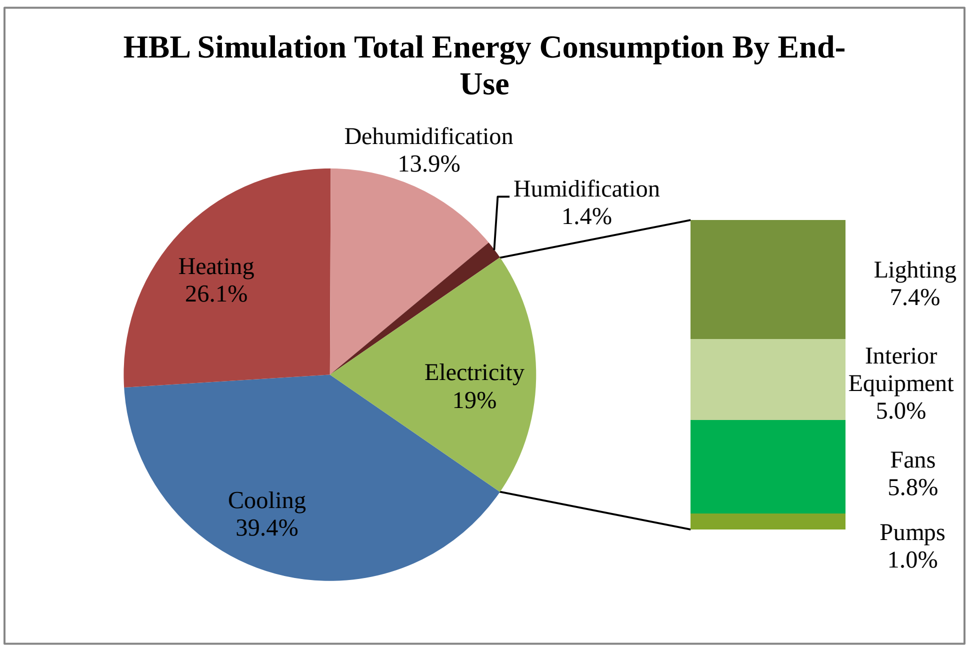

Figure 56: HBL baseline model energy consumption by end use

In summary, baseline energy model results were highly satisfactory. Predictions for overall annual energy consumption deviated by 1.6% from utility data and monthly trends closely match those seen in historical utility consumption for all three energy commodities.

6.5.3 Desiccant Dehumidification System

To simulate the energy consumption of HBL's desiccant dehumidification wheels (DDW's), it was necessary to leave the friendly graphical user interface of OpenStudio and make edits through other, more cumbersome means. The EnergyPlus object *Dehumidifier:Desiccant:System* (DDS) was utilized to simulate the Munters desiccant dehumidification wheels present in HBL. It was necessary to use EnergyPlus' native user interface (IDF Editor), as well as an open-source text editor (NotePad++), in order to implement this crucial aspect of the baseline energy model because this type of heat exchanger was only available in the OpenStudio Application Program Interface (API) and not the interface. Figure 57 shows a schematic of the desiccant dehumidifier as given in the EnergyPlus Input-Output Reference.

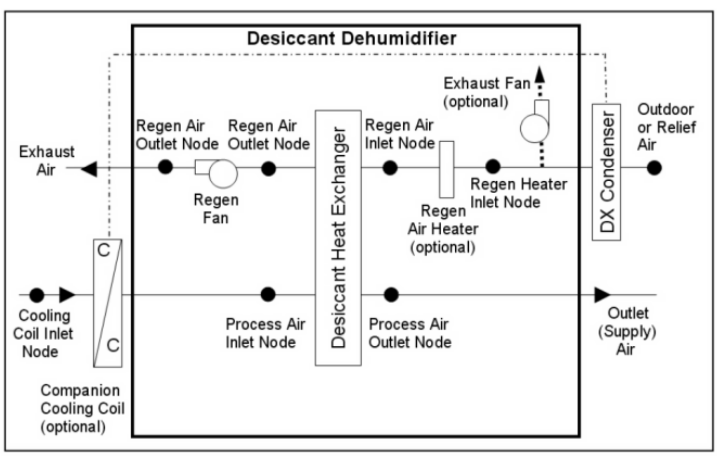

Figure 57: Schematic of the E+ Object Dehumidifier:Desiccant:System

The simulation DDS is schematically identical to both DDW's present in AHU-9 and AHU-10. Both the simulation and the building system contain a companion cooling coil, a regen air heater and fan, and a desiccant heat exchanger. The E+ object *HeatExchanger:Desiccant:BalancedFlow* models a balanced flow desiccant heat exchanger by predicting the regeneration air stream outlet temperature and humidity ratio values based on the entering regeneration and process air stream temperature, humidity ratio and face velocity.[8] The dry-bulb temperature of the regeneration outlet air is defined using the following equation:

$$RTO = B_1 + B_2 * RWI + B_3 * RTI + B_4 * \left(\frac{RWI}{RTI}\right) + B_5 * PWI + B_6 * PTI + B_7 * \left(\frac{PWI}{PTI}\right) + B_8 * RFV \quad \text{Eqn. 1)}$$

Where,

RTO = regeneration outlet air dry-bulb temperature (°C)
RWI = regeneration inlet air humidity ration (kgWater/kgDryAir)
RTI = regeneration inlet air dry-bulb temperature (°C)
PWI = process inlet air humidity ratio (kgWater/kgDryAir)
PTI = process inlet air dry-bulb temperature (°C)
RFV =regeneration (and process) face velocity (m/s)

The humidity ratio of the regeneration outlet air, *RWO*, is defined using the same equation form; however, different coefficients are used:

$$RWO = C_1 + C_2 * RWI + C_3 * RTI + C_4 * \left(\frac{RWI}{RTI}\right) + C_5 * PWI + C_6 * PTI + C_7 * \left(\frac{PWI}{PTI}\right) + C_8 * RFV \quad \text{Eqn. 2)}$$

A requisite *HeatExchanger:Desiccant:BalancedFlow:PerformanceDataType1* E+ data object specifies the 16 coefficients (B_1 through B_8 and C_1 through C_8) in the previous equations, and establishes valid ranges for the dependent and independent variables in the aforementioned equations. These coefficients are defined only through empirical testing and data fitting.

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[8] See native EnergyPlus™ Version 8.7 Documentation: Input Output Reference > Group Heat Recovery > *HeatExchanger:desiccant:BalancedFlow:PerformanceDataType1*

EnergyPlus provides two representative inputs for this data object that contain predefined values for each of the 32 coefficients as well as valid variable ranges. Together, the model coefficients, temperature and humidity ranges define a 4 inch deep rotary desiccant wheel having a rotational speed of 12 revolutions per hour with the desiccant material performance based on a Brunauer Type 3 isotherm shape with a maximum uptake of 30% (Kosar, 2007). The specifications for the model HX performance coefficients and operative ranges can be found in the EnergyPlus Performance Curves Data Set.

Figure 58 shows the monthly energy consumption of the steam regeneration coils in context with the model's steam consumption for space heating and dehumidification. As expected, humidification energy peaks in the summer months when ambient humidity levels are high. More surprisingly, this energy constitutes a very significant percentage of total annual steam energy consumption (28.1%).

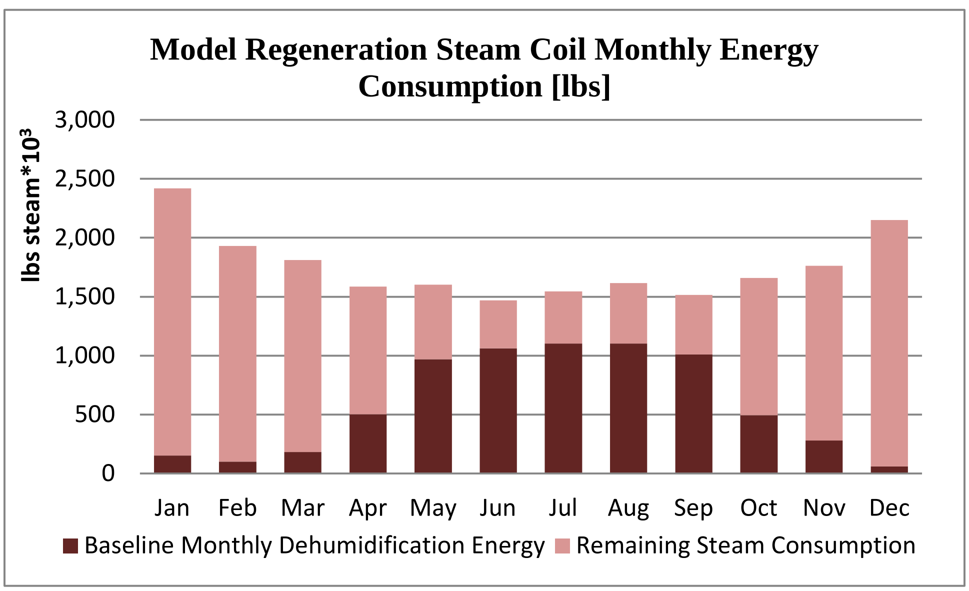

Figure 58: HBL model monthly steam consumption for dehumidification

A beneficial future task would be to install a steam consumption sub-meter for each of HBL's actual steam regeneration coils and compare collected data to these model results. Another approach would be to use existing data temperature and humidity data collected by the existing BAS and employ curve-fitting software such as MATLAB to approximate the aforementioned parameters defining the EnergyPlus desiccant performance. Existing BAS data points are sufficient to curve fit for EnergyPlus coefficients B_1 through B_8, however an additional humidistat would need to be installed to determine coefficients C_1 through C_8.

6.5.4 Uncertainty Analysis

An uncertainty analysis was again performed on HBL's baseline energy model to determine the effect that certain parameters have on overall annual energy consumption. Since the baseline model's included the E+ object for the desiccant wheels explicitly rather than with the use of an OpenStudio Measure, it was necessary to make textual edits to the baseline .idf file to perform the analysis. The E+ Group utilized in the analysis is called "Parametrics," and the accompanying Input Output Reference documentation guided the development and implementation of each Parametric:SetValueForRun object. Table 22 details the seven parameters that were selected for HBL's uncertainty analysis and Figure 59 shows the effect each parameter had on total annual energy consumption as compared to baseline model predictions. Note that the baseline energy model for HBL is far more sensitive than that of MB. Somewhat surprisingly, the zone relative humidity set point is the second least sensitive parameter of those examined.

Table 22: High and low parameter values used in HBL uncertainty analysis

Parameter	Unit	Baseline Value	Low Value	High Value
Wall Thermal Resistance	ft^2-hr-F/Btu	4.59	-50%	50%
Infiltration	cfm/ft^2	0.2232	0.1116	0.4464
Lighting Density	W/ft^2	1.2	1.0	1.4
Zone Thermostat Set Point	°F	71	67	74
AHU's 1,2,4,8 Discharge Temp	°F	50	45	55
Occupant Density	People/ft2	N/A	-50%	100%
Zone Relative Humidity Set Point	Percent	40	35	45

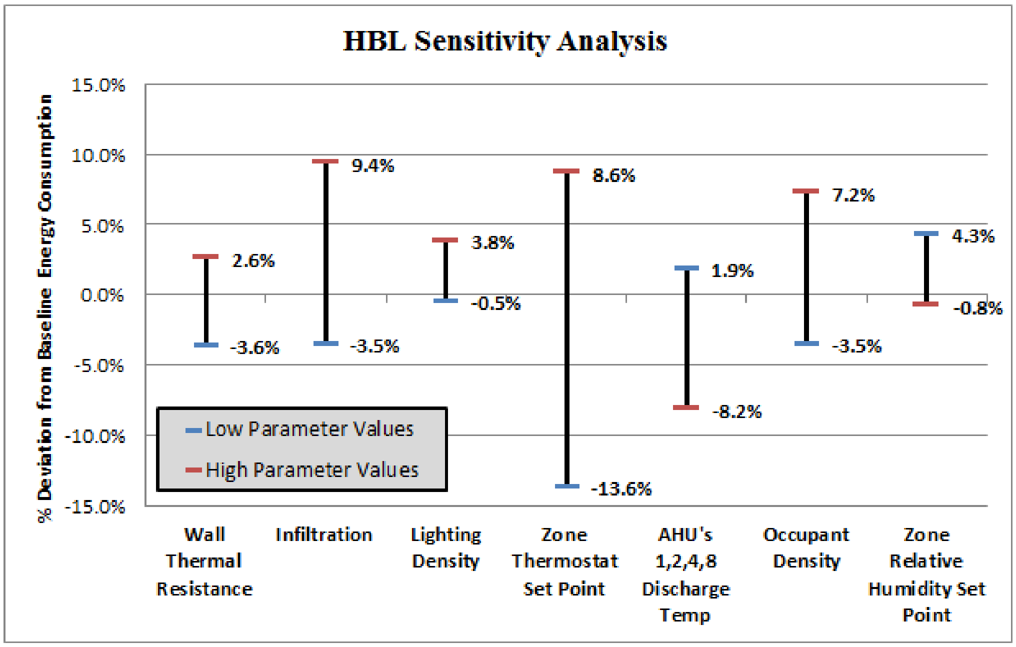

Figure 59: HBL energy model uncertainty results

In addition to the HBL uncertainty analysis, the effect of varying the simulation engine calculation frequency was also examined. E+ documentation recommends that at least four steps per hour, i.e. 15 minute time steps, be used in energy simulations. More frequent time steps per hour may improve the accuracy of model results; however, computational time increases substantially with diminishing effects on model energy consumption. Figure 60 displays the effect that different time step frequencies have on annual energy consumption and elapsed simulation time. The relation between simulation step size and elapsed simulation run time approximates the reciprocal function (blue, right axis) and similar to the findings of Levy '14, there is a positive correlation between simulation step size and model energy consumption (red, left axis).

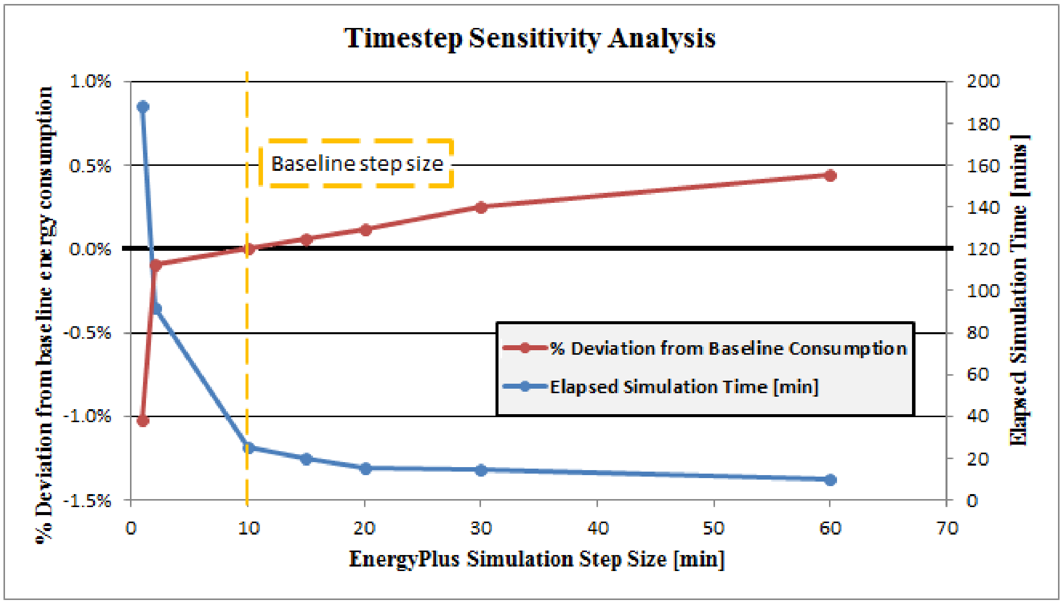

Figure 60: HBL Time step sensitivity analysis

<u>*6.6 As-designed Hornbake Library Energy Model*</u>

The As-designed HBL energy model has similar aims as compared to those of MB. Four energy conservation measures (ECM's) are evaluated at the individual level for energy and utility cost savings. These measures are reported in order of impact on energy and utility savings from most significant to least significant.

6.6.1 HBL ECM #1 – AHU Discharge Temperature Setpoint Adjustment

With the help of FM personnel, temporary access to the legacy MS-1800 BAS showed that the discharge temperature setpoints for AHU's-1, 2, and 8 were a constant 50°F. A closer look at the BAS data points revealed that the actual discharge air temperatures were consistently 1-3 °F higher than this setpoint. Furthermore, this was occurring in-spite of the fact that CHW coil control valves read as 100% open. In other words, CHW cooling coils were unable to meet supply air temperature set points, even when operating at full capacity. FM reported that the setpoints had likely been manually adjusted to meet the strict temperature and RH zone conditions discussed previously in the building description section; refer to Figure 14.

Furthermore, recall that AHU's 1, 2, and 8 are served, in other words receive pre-conditioned make-up air from, the advanced humid/de-humidification AHU's 9 and 10 and do not condition any outside air. As such, the latent cooling load on AHU's 1, 2, and 8 was reasoned to be negligible. Therefore a discharge setpoint of 50°F would be unnecessary, and only serve to increase cooling and re-heating energy consumption in these very large spaces. Finally, discharge air temperature setpoints of the make-up units (9 and 10) were consistently *above* those to which they served (1, 2, and 8).

To illustrate this sequence of heating and cooling, we refer to Figure 61 and Figure 62, hereto referred as "first" and "second". The first figure shows a schematic of the sequence of operations to condition and deliver outside air to the library side of HBL during a dehumidification cycle. The second figure shows psychrometric conditions corresponding to the numbers in the first figure. Data for Points 1, 2, 3, 4, and 8 (colored orange) are conditions taken from BAS recorded data, while conditions 5, 6, and 7 (colored grey) are set points observed in the MS-1800 BAS system, though their precise value could not be determined in the instance known. Point 5 (the return air temperature of AHU's- 1, 2, and 8) can be assumed to have similar conditions as point 7, with slightly higher moisture content due to occupant perspiration and infiltration. Finally, Point 8 in the first figure corresponds to the green shaded region in the second figure. This region represents the zone conditions that will not trigger a BAS alarm and is defined by the table included in the second figure.

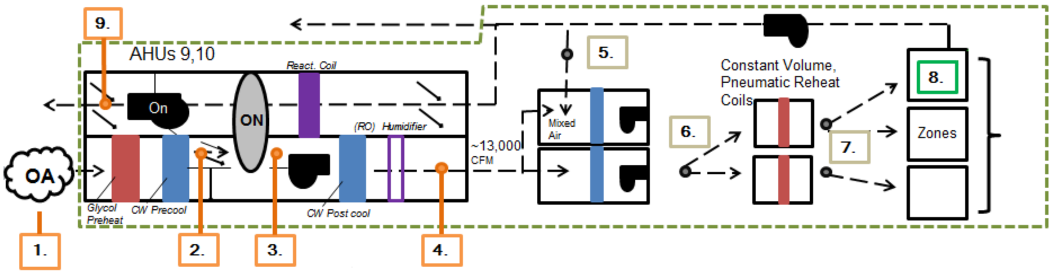

Figure 61: Sequence of operations of conditioned air in HBL's Library Side

HBL Library BAS Alarms		
Zone Alarm	Low Limit	High Limit
Dew Point	36°F	46°F
Temp.	50°F	75°F
RH	30%	50%

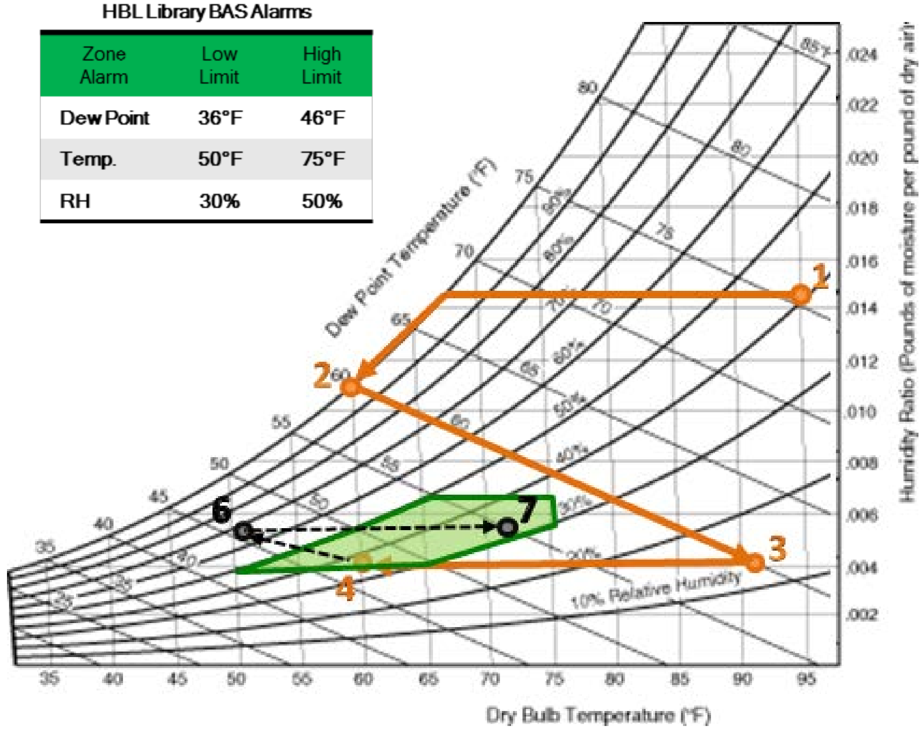

Figure 62: Psychrometric conditions corresponding to Figure 61

It's clear from examining these figures, that the process moving conditions from point 4 to point 6 is unnecessary and expends additional cooling energy, leading to additional heating energy in the processes from 6 to 7. Ideally, point 6 would be immediately above point 4 – having the same temperature and slightly higher though still acceptable moisture content.

After a discussion regarding these inefficiencies between AHU's 9 and 10, and with the consent of the FM staff present, the discharge temperature setpoint was raised by 5°F to better meet the discharge temperature setpoints of AHU's 9 and 10 and cause point 6 to better approach point 4. At this time FM staff reiterated that close attention should be paid to building conditions since the integrity of various aspects of the building's mechanical systems (e.g. fans, ductwork) as well as the tightness of the building's envelope were known to be questionable.

Three days after the set point adjustment was made, a high temperature alarm was triggered by an instance of space temperatures exceeding 75°F in room 4210T. FM staff rapidly responded by manually closing hot water valves controlling reheat coils serving the space and temperatures receded to acceptable levels. No other alarms were reported by the BAS as a result of these actions and library tenants initially concerned by the alarm reported being satisfied with zonal conditions in the three months following the alarm.

In a response to the cautions issued by FM staff regarding the questionable integrity of the building's envelope additional methods and means were sought to gather more data. Ph.D. student, Matthew Mauriello of the University of Maryland's Department of Computer Science and Human-Computer Interaction Lab was independently consulted for his novel work in state-of-the-art thermographic energy auditing practices as a part of the ongoing "Scalable Thermography" project led by Mr. Mauriello (Froehlich, 2017). Under his direction, two deployments of a sensor kit were conducted in room 4210T to investigate the thermal irregularities mentioned above. Table 23 details the date, time, duration and a description of the two deployments.

Table 23: HBL sensor kit deployment descriptions

Date	Time	Duration [hrs.]	Environmental Conditions
3/12/2017	2:53 p.m.	53.78	Cold, mostly overcast; light rain and some snow
3/24/2017	9:57 a.m.	76.32	Warm, mostly sunny; some wind

The sensor system automatically collected half-hour, temporal snapshots of internal temperature, internal humidity, external temperature, external weather conditions, and thermal imagery. Answers to three questions were sought in this deployment:

1. What are the average discharge air temperatures to room 4210T?
2. Are there patterns of surface temperatures that may indicate degradation in the exterior envelope?
3. Are there temporal patterns resulting from the heating and cooling of the room (e.g. solar loading) that might contribute to thermal instability?

Here we briefly answer all three questions, however a full copy of the summary report provided by Mr. Mauriello can be found in Appendix A2. The respective answers to the above questions were concluded as follows:

1. Discharge air temperatures averaged between 57.07°F and 60.42°F
2. No significant patterns could be discerned; average wall surface temperatures range from 59.5°F to 62.2°F; while external temperatures varied between 32°F and 72°F
3. Windows (shaded with heavy opaque cloth) were impacted by changes in solar loading; however average wall temperatures remained stable throughout both deployments

Figures 63 and 64 respectively show a sample thermal image and its associated plot of wall surface temperatures. These images were collected during the second deployment, and they directly inform the answers to questions 2 and 3. In the second figure the external temperature (green), and the window cover temperatures (purple) are seen to vary significantly across the deployment period while internal temperature (red) and wall element temperatures (black) remain stable.

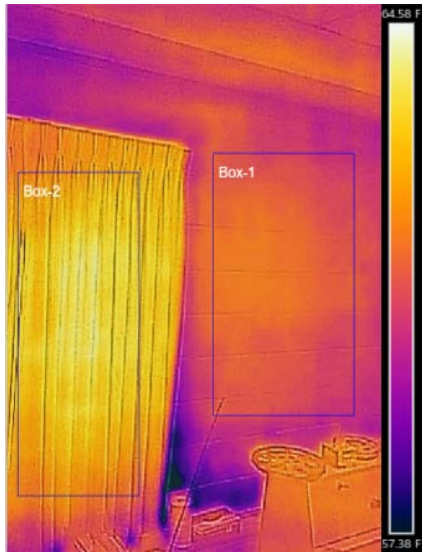

Figure 63: Sample thermal image from deployment 2

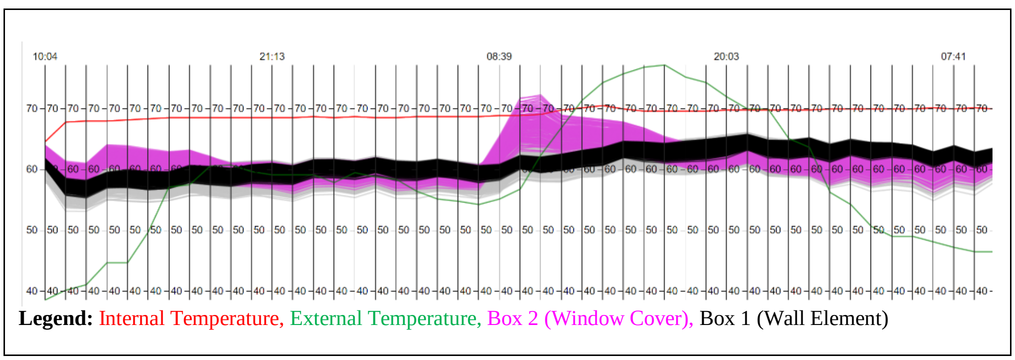

Figure 64: Associated plot of sensor data

The deployments demonstrated the versatility of the novel thermographic tool kit to examine multiple temperatures across long periods of time and contributed substantially to answering multiple questions posed by FM staff. Future deployments to other thermally unstable rooms or mechanical equipment with unknown effectiveness would offer unique and illustrative perspectives and likely answer questions that may be difficult to answer by other means.

After affirming that no anomalous sources of thermal instability were present in the space, baseline model parameters could be confidently altered to simulate the savings resulting from the above actions. A simulation was run in which the discharge temperatures of AHU's 1, 2, and 8 were changed from baseline values of 50°F to 55°F and the maximum flow rate of the simulation reheat coils serving the model zone 4210T was set to 0.

Additional simulations were run to determine HBL's sensitivity to further increases in AHU discharge air temperature. Figure 65 displays the results of this analysis. Note that additional 3ºF increase in discharge temperature setpoint may result in energy savings of nearly double those achieved by the 5ºF adjustment made in this ECM.

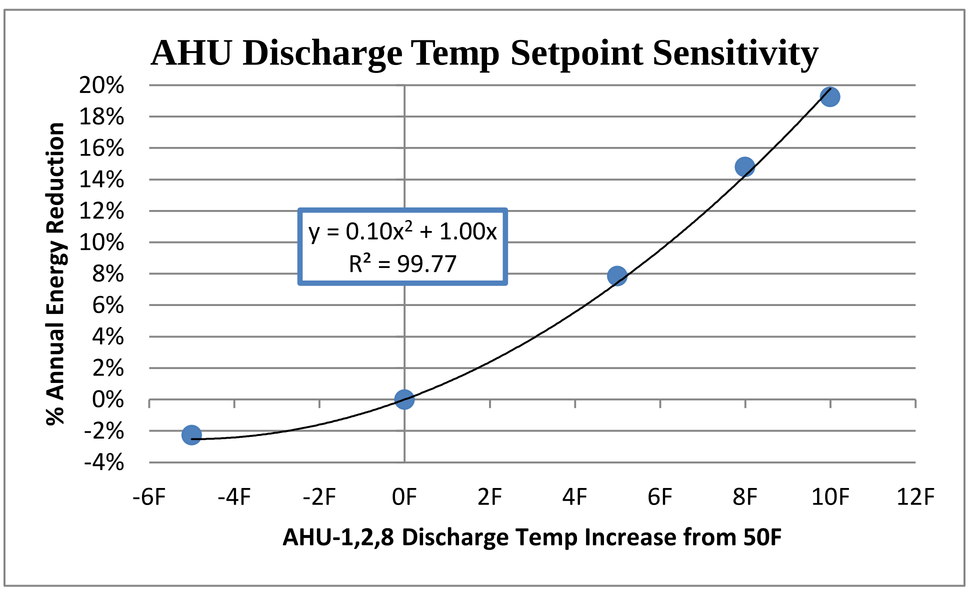

Figure 65: AHU discharge temperature setpoint savings potential

In summary, Figure 66 illustrates the annual energy savings resulting from the implementation of the original ECM, a discharge temperature increase from 50ºF to 55ºF.

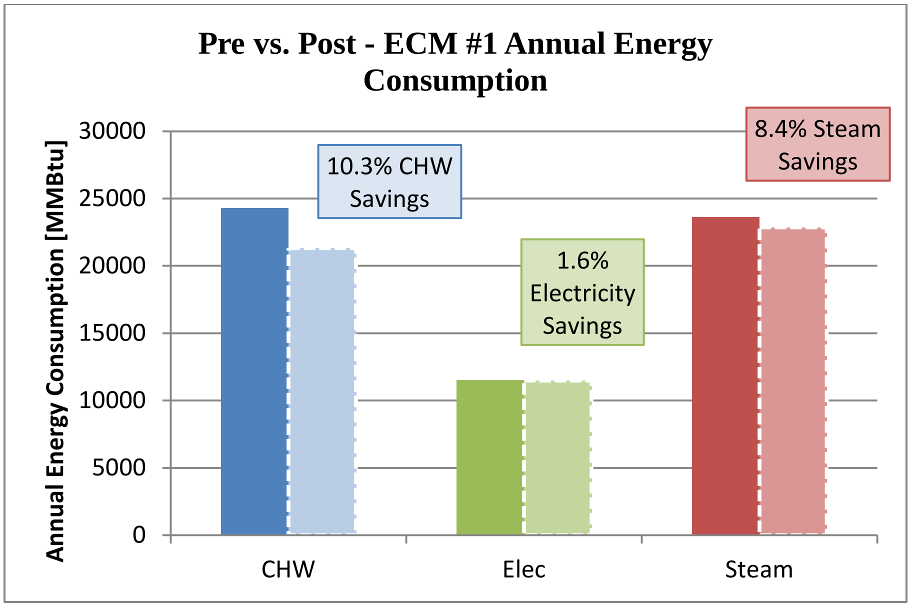

Figure 66: HBL ECM #1 annual energy consumption comparison

6.6.2 HBL ECM #2 – Glycol Pre-heat Valve Reset

Through observation of the Talon Tridium Niagra BAS, it was found that the glycol pre-heat coil valves on AHU's 9 and 10 read as 20% open regardless of outside temperature, or discharge temperature set points. This issue was brought to the attention of FM, who explained that the valves had been manually set to remain open in order to meet space heating loads in the winter. Action was taken to return the preheating coil valve controls to their original state after it was shown that the CHW precooling coils were subsequently and simultaneously operating. Figure 67 shows a screen grab taken from the Talon BAS that was the primary source for concern leading to the investigation described in this ECM.

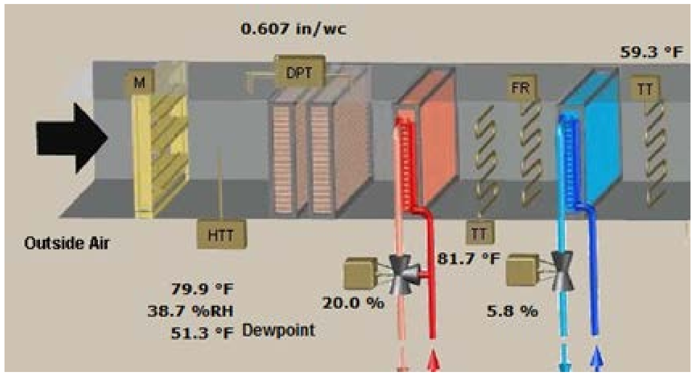

Figure 67: Simultaneous heating and cooling observed in the Talon BAS in HBL AHU-9

To model the savings resulting from this ECM, baseline simulations were run in which the Energy+ objects that control the water flow rate of the modeled preheat coils were instructed to hold a minimum water flow rate 20% of the auto-sized maximum water flow rate. Then, a simulation was run in which these controllers are allowed to operate normally. The energy and utility cost savings resulting from ECM #2 are displayed in Table 24.

Table 24: HBL ECM #2 Annual energy and utility savings

	CHW [ton-hr]	Electricity [kWh]	Steam [lbs]	Total Energy Saved [kBtu]	Utility Cost Saved [$]
Annual Savings	33,535	4,957	526,673	1,048,177	$22,484
% Reduction	1.7%	>1%	2.3%	1.8%	1.7%

6.6.3 HBL ECM #3 – CHW Pump Pressure Differential Isolation Valve Fix

During the on-site implementation of ECM #1, another related problem was discovered through observation of the Tridium Niagra BAS. Sensor readings of the CHW pump pressure differential displayed negative values close to 0 contrary to the programed set point of 12 psi. After locating the sensor a picture of which is shown in Figure 68, the cause of the problem was made clear by fact that the senor's isolation valve was closed. A simple twist of the hand opened the valve, and the sensor immediately began displaying correct pressure differential readings. The CHW pumps driven by variable speed motors responded by decreasing their operating speed from 100% to 60%. The pumps had been operating at 100% in an attempt to reach the differential pressure set point. The action results in immediate electricity savings and also reduces wear on valves, pipes, and CHW cooling coils, increasing the time between servicing and/or replacement.

Figure 68: CHW Pump Pressure Differential Isolation Valve

To model the energy savings resulting from this remedial action, a free Variable Speed Drive (VSD) Calculator for Pumps tool provided by the Department of Energy was utilized.[9] The tool's estimated electricity savings for reducing the load factor of 40 HP VSD pump from 100% to 80% was 10,845.5 kWh per year. This amounts to annual utility savings of $1,208 per year.

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[9] Available at https://ecenter.ee.doe.gov/EM/tools/Pages/VSDCalcPumps.aspx

6.6.4 HBL ECM #4 – AHU Envelope Integrity Repairs

All but three of the AHU's in HBL were installed during original construction and may be described as in fair to poor condition. The two main factors contributing to this assessment are loud fan and fan motor bearings indicative of extensive wear, and visible AHU envelope degradation as pictured in Figure 69. This picture, taken during a building walk-through from within the AHU-7, shows multiple holes in the air handler's fabric, allowing substantial leakage of conditioned air into the unoccupied penthouse mechanical room. AHU-6 and AHU-2 are the next two most prominent examples of this degradation.

Figure 69: Example of AHU Envelope Degradation (picture taken from within AHU-7)

While AHU-7 has been decommissioned for a number of years, it remains connected to AHU-8 via ductwork installed with AHU's-9 and 10 in 2001. AHU-8 is the second largest AHU by CFM in the building. It operates 24/7/365, and its 45,860 CFM accounts for 22% of all supply air in the building as a whole, and 32% of the air supply subject to strict temperature and humidity controls. Efforts were taken to isolate the two air handler's, but a significant amount of air-flow could still be felt from within decommissioned AHU-7 as well as leaking out of the tears in its fabric.

Two possible solutions exist: one is to better isolate AHU-8 and/or remove AHU-7 entirely; the other is to patch the tears in AHU-7. Because this project focuses on low or no cost ECM's, the latter option is recommended. It is important to note that DOE recommends avoiding cloth-back, rubber adhesive duct tape, and advises using mastic, butyl tape, foil tape, or other heat-approved tape. One indication that a tape meets these specifications is that it is sold with the Underwriters Laboratories (UL) logo (Energy.gov, 2017).

To estimate the energy savings of patching the tears in AHU-7, baseline energy simulations were run with a custom reporting measure. This measure created a virtual energy meter for each simulated AHU and included the results in the general results report. Assuming that patching the leaks in AHU-7 (effectively AHU-8) reduce by 0.1% the amount of CHW consumed by the cooling coil and 1.0% the amount of electricity consumed by the supply fans; the building would save at least 5,100 Ton-Hrs of CHW energy and 8,631 kWh of electricity. This amounts to a $1,910.22 reduction in annual utility costs.

6.6.5 As-Designed Energy Model Summary

The HBL As-Designed model predicts the energy consumption of HBL once all four ECM's have been implemented. At the time of writing (July 2017) ECM's 1-3 have been implemented. Energy consumption savings are calculated as the difference between baseline consumption and an adjusted model incorporating the adjusted parameters specified by ECM's 1 and 2. Additional electricity and cooling savings resulting from ECM's 3 and 4 are then summed with the savings predicted by the adjusted model. In total, the As-designed model is predicted to result in a 5,920 MMBtu reduction in annual energy consumption and a $122,165 or 8.9% reduction in annual utility cost expenditures. Figure 70 illustrates the breakdown of energy savings proposed by the HBL "As-designed" model.

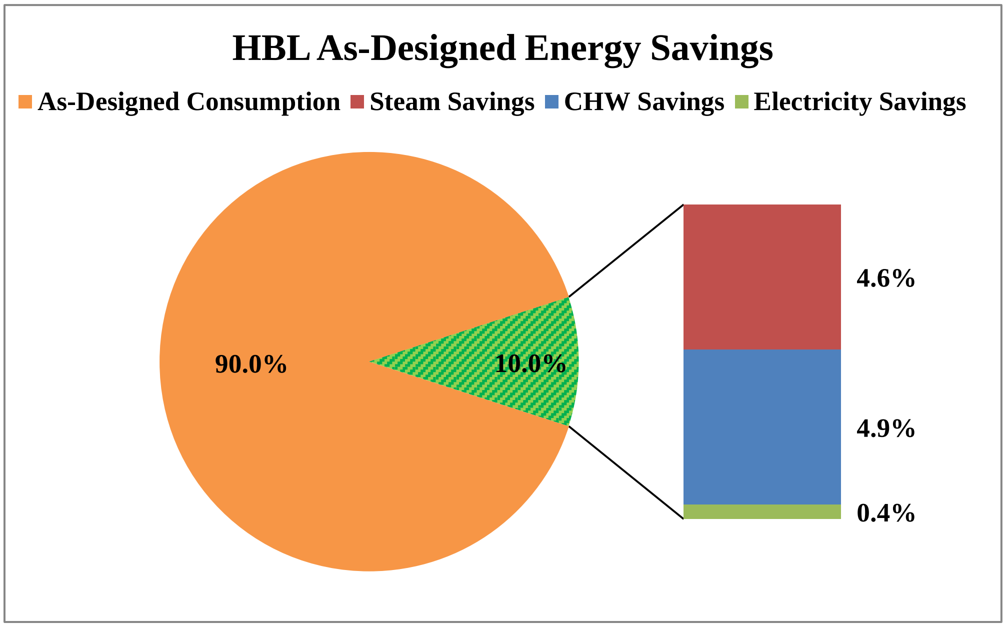


Figure 70: HBL As-Designed model energy savings break down

6.7 Energy Efficient Hornbake Library Energy Model

The HBL energy efficient model explores three additional energy efficiency measures (EEM's) aimed at further reducing both annual energy consumption and utility expenditures. EEM #1 was chosen based on its relative ease of implementation, and large return on investment. EEM's 2 and 3 were chosen for the high degree of urgency with which they likely should be addressed due to the existing need for repair or replacement. Fortunately, two of the three EEM's require minimal capital investment and have estimated simple payback periods of less than one year.

6.7.1 HBL EEM #1 – Zone Temperature Setback

The baseline energy model sensitivity analysis revealed that the zone thermostat set point had the greatest effect on annual energy consumption of the seven parameters examined. Referring back to Figure 52, one can see that reducing year-round building thermostat setpoints to 67°F resulted in a reduction in model energy consumption of over 13%. This result clearly indicates that a reduction in thermostat setpoints should be seriously considered.

Crucially, the energy savings results found in the sensitivity analysis are likely due in large part to the caveat that zone relative humidity setpoints remained fixed while zone thermostat temperatures were varied. This was done solely because EnergyPlus exclusively allows schedules of percent relative humidity (RH) as inputs for zone humidistat setpoint schedules. However, fundamentals of psychrometric analysis dictate that a change in temperature of moist air with a fixed relative humidity results in a change in the air's dewpoint. Because actual building mechanical systems' control variable is zone dew point and not relative humidity, it's clear that the above method of simulation adjustment does not correctly model reality.

As such, additional simulations were run adjusting zone thermostat setpoints as well as adjusting zone humidistat setpoints to the value corresponding to the building setpoint for dewpoint, 41°F. Table 25 enumerates the adjusted psychrometric setpoints employed to model energy savings from EEM #1.

Table 25: HBL EEM #1 Model thermostat and humidistat setpoints

Zone Thermostat Set Point [°F]	Zone RH Setpoint [%]
65	41.44
67	38.66
69	36.09
70	34.88
71	33.71

Thermostat setpoints in all HBL spaces are not controlled by either of the building automation systems and only library side space temperatures are monitored by a

BAS. As such, space temperatures varying between 66-74°F have been observed simultaneously on multiple occasions. It's likely that new thermostats will need to be installed in spaces whose primary function is the storage of archival material, i.e. stacks.

Figure 71 shows the annual energy savings predicted by the adjusted model as compared to As-designed energy model consumption. It's recommended that thermostats be adjusted to 69 ºF in mixed-stack spaces and 67 ºF in dedicated storage spaces *year-round*. Both thermal conditions meet ASHRAE 90.1 standards, and though a setpoint of 67 ºF is relatively cool, building occupants have expressed a willingness to don warmer garb since cooler conditions improves the life expectancy of sensitive archival materials.

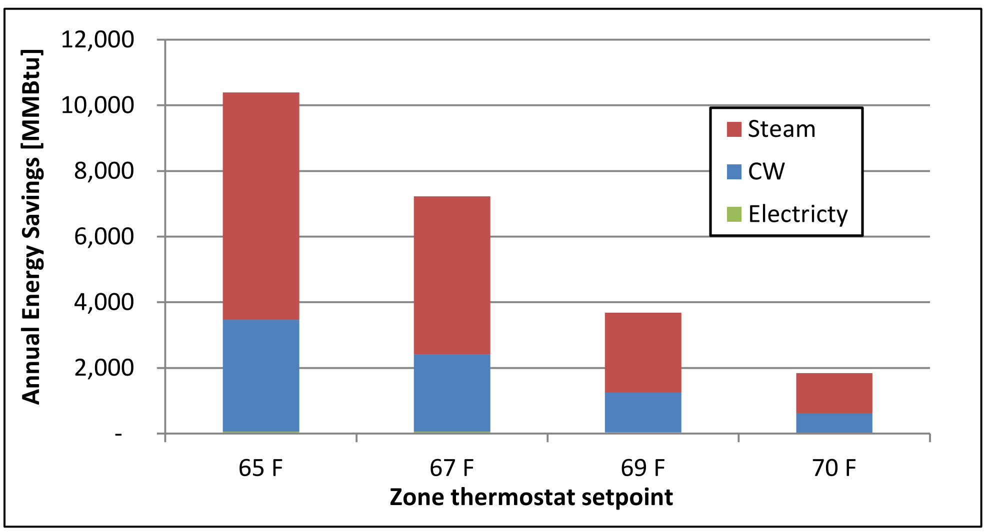


Figure 71: HBL EEM#1 Energy savings

6.7.2 HBL EEM #2 – Variable Frequency Drives for Fans

Fan motors for AHU's 1, 2, 3, and 4 are known to be from original construction (1972) and produced sounds considered to be audible signs of wear by

FM personnel. A motor failure would result in major problems for archival material integrity as well as severe inconvenience for occupants.

The ASHRAE reported 18 year median life expectancy of HVAC electric motors indicates these motors as likely candidates for replacement (Cullum Mechanical Construction, Inc., 2014). However, first note that motor breakdown can be the result of failed bearing, high amp draw, electrical failure in the windings, and anecdotally, “the most common cause [of motor breakdown] is dirt accumulation due to lack of maintenance” (Anesi, 2015). It’s recommended that FM management review existing equipment maintenance policies to ensure compliance with standards set by *ANSI/ASHRAE Std. 62.1-2010* regarding the minimum maintenance activity and frequency of equipment associated with acceptable indoor air quality.

To improve the energy efficiency of the supply fan motors mentioned above. This EEM consists of retaining existing motors, performing thorough maintenance, and installing variable frequency drives (VFDs).

A free online tool provided by the ABB Corporation called EnergySave Calculator for fans[10] was utilized to assess the energy savings resulting from EEM #2.1. Table 26 details the inputs used when evaluating this EEM through the calculator.

Table 26: ABB EnergySave Calculator inputs

[10] Available at http://energysave.abb-drives.com/#/main. Last accessed July, 2017

AHU #	HP	Flow [CFM]	Pressure Increase [in. H20]	Flow Control	Supply Voltage	Fan Type	Motor Efficiency Class
1	20	25310	3"	Inlet box damper	380-415 V	Centrifugal - FC	1970's
2	20	25310	3"	Inlet box damper	380-415 V	Centrifugal - FC	1970's
3	10	13185	2.75"	Inlet box damper	380-415 V	Centrifugal - FC	1970's
4	40	46840	3"	Inlet box damper	380-415 V	Centrifugal - FC	1970's
6	25	32475	3"	Inlet box damper	380-415 V	Centrifugal - FC	1970's

Of the required input variables, the "duration curve" is the most uncertain. The duration curve simply refers to the amount of time the fan is running at a particular load percentage. Therefore, two curves were tested: a normal curve and a constant 80% curve, i.e. the fan is operating at 80% load throughout the year. The energy and cost savings predicted by the EnergySave Calculator for fans is shown in Figure 72. The values displayed for energy utility cost savings are the average of the two duration curves tested, with error bars shown for cost savings estimates.

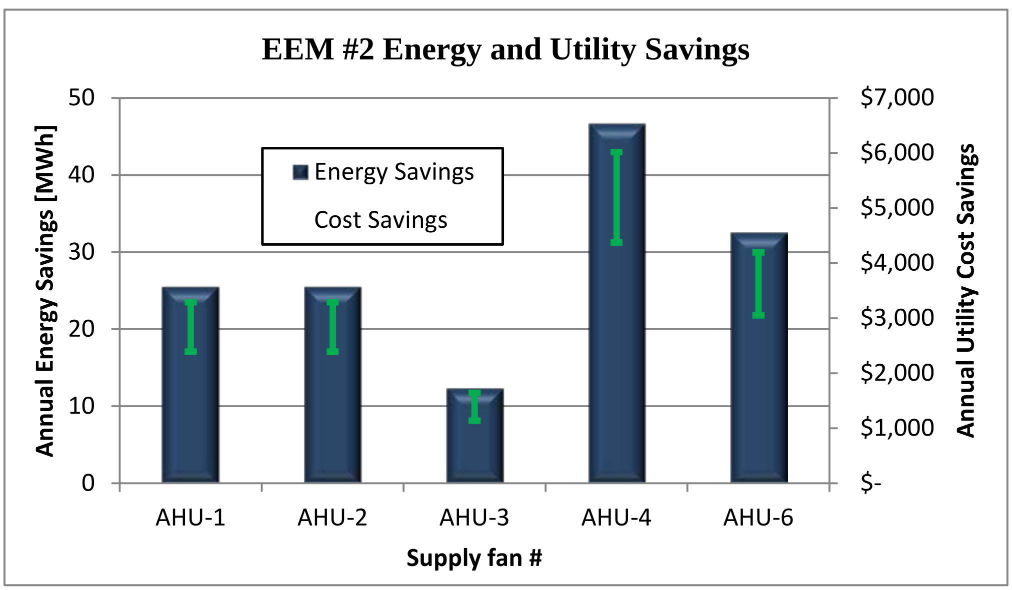


Figure 72: HBL EEM #2 energy and cost savings per AHU supply fan

From Figure 72 we see that AHU-4 and AHU-6 offer the best energy and cost savings opportunities. Capital expenditures to implement EEM #2 were surveyed to estimate the simple-pay back. Table 27 shows the results of the survey and includes the model of VFD recommended by the ABB EnergySave Calculator (Variable Frequncy Drives, 2017).[11]

Table 27: HBL EEM #2 Simple payback calculation summary

AHU #	ABB Drive Selection	Materials Cost	Labor Cost est.	Total Cost	Simple Payback Period [yrs.]
1	ACS880-01-32A0-3	$3,617	$3,000	$6,617	2.0 – 2.8
2	ACS880-01-32A0-3	$3,617	$3,000	$6,617	2.0 – 2.8
3	ACS880-01-017A-3	$1,300	$3,000	$4,300	2.6 – 3.8
4	ACS880-01-61A0-3	$5,367	$3,000	$8,367	1.6 – 1.9
6	ACS880-01-45A0-3	$4,167	$3,000	$7,167	2.0 – 2.3
Total		$18,068	$15,000	$33,068	2.1

Additional planning is necessary to ensure correct VFD selection, and consideration should also be given to replacing the aforementioned motors. If all five VFD drives were installed the estimated annual energy and cost savings would respectively total 142.6 MWh and $15,893 and the project would have a simple payback period of 2.1 years.

6.7.4 HBL EEM #3 – Steam System Maintenance

District steam received from the UMD Combined Heating and Power Plant is a highly efficient method of heating from a source-energy perspective. There are numerous advantages to using steam for space heating. Steam carries significantly more energy than hot water due to latent heat, it is easy to transport, and can be measured and controlled more precisely because its temperature is fixed with pressure. However, this dense energy commodity's demand continually grows with the increased space heating demands that accompany the ongoing construction

[11] http://www.vfds.org/abb-vfd-price-list-346980.html

projects on campus. Furthermore, if not carefully monitored and maintained, steam systems can lead to large energy losses and steam line failures can be potentially destructive and dangerous.

Many well-documented opportunities for energy savings exist in steam system operations, ranging from simple operating procedure modification to major retrofits requiring significant capital investment (Turner & Doty, 2006). This EEM examines the energy savings resulting from improved insulation of steam mains, flash tanks, and valves, as well as from fixing a number of identified leaks.

Mechanical drawings were red-lined to estimate the total length of high, medium, and low pressure steam lines. Table 28 displays the results of the mechanical drawings survey.

Table 28: HBL mechanical drawings' steam line lengths

	Mechanical drawing pipe length [ft.]		
Line Gauge Pressure [psig]	**Basement**	**Penthouse**	**Total**
125	142.83	20.67	163.50
40	302.58	312.25	614.83
15	-	99.75	99.75

After mechanical drawings were reviewed a brief building walkthrough was conducted to survey various aspects of HBL's steam system including steam lines, control valves, pressure regulating valves, steam traps, as well as condensate lines and pumps. Using a thermal camera, the integrity and extent of insulation on steam mains and condensate lines were able to be efficiently surveyed in a qualitative manner.

Overall, insulation was found to be relatively robust with a few exceptions. Firstly, at least 7 large valves and the large penthouse flash steam tank were lacking insulation. Secondly, a small distance of steam line before and after most steam traps, valves and pressure reduction stations lacked insulation as well. Figure 73 shows two thermographic images of example uninsulated valves located in the penthouse mechanical room. The image on the left also features an example of a portion uninsulated low pressure steam line.

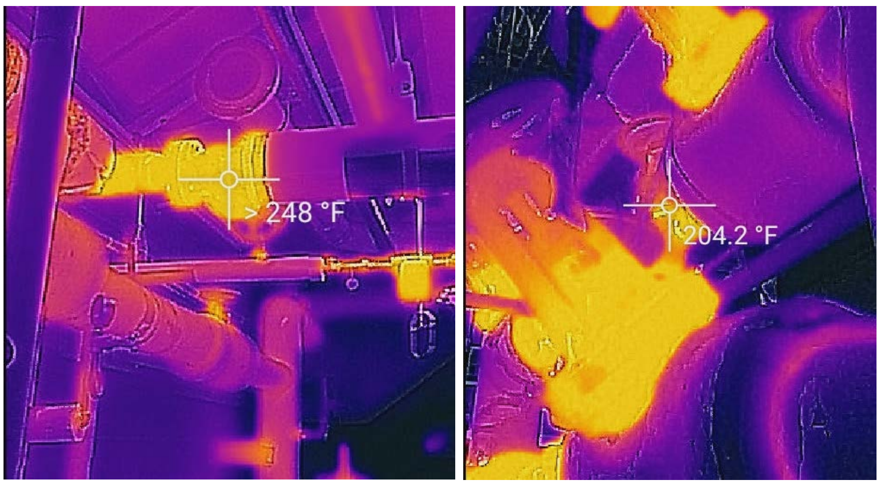


Figure 73: Two thermographic images of uninsulated steam system components located in HBL's penthouse mechanical room

To estimate the energy savings resulting from a campaign to survey and improve HBL's steam system insulation, the two system component categories previously discussed were assessed separately.

First between 1 and 5% of all steam line length measured in the mechanical drawings survey was assumed to be uninsulated. Heat loss estimations were then calculated as a function of pipe gauge pressure and diameter according to *Fig. 6.2 Heat loss from bare steam lines* found in The Energy Management Handbook (Turner & Doty, 2006). A summary of these calculations is shown in Table 29 and more detailed calculations can be found in A3.1: Bare steam line heat loss calculation.

Table 29: Heat loss and utility expenditures from uninsulated steam lines in HBL

% Piping Uninsulated	1%	2%	3%	4%	5%
Heat loss (MMBtu/yr)	74.56	149.13	223.69	298.25	372.82
Heat loss (lbs/yr)	62,448	124,896	187,344	249,793	312,241
Utility Cost [$/yr]	$ 1,860	$ 3,721	$ 5,582	$ 7,443	$ 9,304

Secondly, heat loss each of the large uninsulated valves is calculated as a function of surface area and temperature differential. From various temperature readings taken with thermographic images as seen in Figure 73, and by approximating each valve as a 20 inch long cylinder with a 14 inch diameter the rate heat loss from each of the seven valves was calculated to be 737.4 W.[12] Therefore the annual heat loss from all seven uninsulated valves is:

$$7 \times 737.4\,W \times 3.154 \times 10^{7}\,\frac{s}{yr} = 162.803\,\frac{GJ}{yr} = 154.31\,\frac{MMBtu}{yr}$$

which amounts to a loss of 129,263 lbs. steam or $3,851 in utility cost per year. This estimate can be considered very conservative due to the numerous other uninsulated steam system components which are easily identifiable with further thermographic surveying.

Insulation installation frequently results in energy loss reductions of at least 88%, and has simple pay-back periods of less than a year. And while bare piping is relatively simple to insulate, other components have convoluted shapes, which are more expensive to insulate and require periodic maintenance that involves removing existing insulation for access. Therefore, removable/reusable insulation blankets such as the one shown in Figure 74 are recommended for insulating other steam system components (Hart, 2011).

[12] See Appendix A3.2 Uninsulated steam valve heat loss calculation

Figure 74: A removable/reusable (R/R) insulation blanket for a steam gate valve

The final source of energy loss within HBL's steam system was the observed and reported existence of three visible steam leaks. A small leak was observed at each of the flanges connecting medium pressure steam lines to the two steam regeneration coil manifolds operating in AHU's 9 and 10. A larger leak was observed in the high pressure steam reduction station located in the penthouse mechanical room. This leak was also reported to have existed uninterrupted for at least 6 years. With estimated respective leak orifice diameters of 1/16 inch and 1/8 inch at a pressure differential of 40 psig the total steam energy lost from these three leaks is (Turner & Doty, 2006):

$$2 \times 13{,}300\frac{lbs}{month} + 52{,}200\frac{lbs}{month} = 78{,}800\frac{lbs}{month} \times \sqrt{\frac{40}{100}psig} \times 12 = 598{,}050\frac{lbs}{yr} = 714.1\frac{MMbtu}{yr}$$

This amounts to $17,821 in wasted steam utility costs per year. These losses in energy and utility costs can likely be fixed without significant capital investment by University Facilities Management, though additional training may be necessary. Furthermore, the proximity of the steam regeneration coil leaks to the desiccant dehumidification wheel motor and drive-belt likely exposes these parts to excessive heat and moisture reducing their lifetime. This is further evidenced by the fact that desiccant wheel drive-belts with life expectancies of 5 years have been replaced multiple times in a single year. Common causes of drive-belt failures include over-exposure to heat and moisture. The risk of both of these conditions is significantly increased by the presence of these steam leaks. A price quote obtained from Munters stated that a single drive belt costs $769.00, though FM reported a 50% discount when making their own purchases. If the 5 FM-reported belt replacements were a result of these steam leaks, fixing these leaks would have saved the university additional maintenance costs of at least $1,922.50.

A summary of the findings from the three components of this EEM is shown in Table 30. The energy and cost savings detailed are considered conservative by the writer as additional savings opportunities will undoubtedly present themselves with more robust surveying. Implementation of this EEM has an estimated simple payback of less than a year, will improve the life expectancy of other mechanical system components, and increase safety for facilities management staff.

Table 30: HBL EEM #3 Summary

Source of Wasted Energy	Annual Heat Loss [MMBtu]	Proposed Solution	Reduction in lost heat	Energy Saved [MMBtu]	Cost Saved	Simple Payback
Estimated 3% of uninsulated steam lines	223.69	Insulate with 1in. preformed fiberglass	88%	196.85	$4,913	< 1 year
Identified uninsulated steam system components	154.31	Insulate with R/R blanket	88%	135.79	$3,389	< 1 year
Three identified steam leaks	714.1	Seal jackets where leaks occur	100%	714.1	$17,820	Immediate
			Total	1,046.7	$26,122	< 1 year

6.8 HBL Energy Savings Summary

After implementing all of the suggested ECM's and EEM's HBL is expected to reduce its annual energy consumption by 18.7% and have an associated building

EUI of 202.11 kBtu/ft^2-yr. Auxiliary utility rates would indicate these energy savings would amount to a $244,933 reduction in annual utility bills. At the time of writing, ECM's #1-3 have already been implemented and are expected to reduce annual energy consumption and utility expenditures by 5,920 MMBtu and $122,165 respectively. Table 31 summarizes the energy and cost savings for each ECM and EEM evaluated in the HBL as-designed and energy efficient models. Figure 75 shows the breakdown of energy savings of the HBL energy efficient model by energy commodity.

Table 31: HBL Annual energy and utility cost savings summary

EEM / ECM Summary	CHW [ton-hrs]	Steam [lbs]	Electricity [kWh]	Total [MMBtu]	Energy Savings [%]	Utility Savings [$]
ECM #1 - AHU Discharge Air Temp Adjustment	204,749	1,763,689	53,146	4,744.2	8.0%	96,562
ECM #2 - Glycol Preheat Valve Reset	33,535	526,673	4,957	1,048.2	1.8%	22,485
ECM #3 - CHW Pump Pressure Valve Fix	5,103	-	8,631	90.7	0.2%	1,911
ECM #4 - AHU Envelope Repairs	-	-	10,846	37.0	0.1%	1,208
As Designed Model	243,386	2,290,362	77,580	5,920.0	10.0%	122,165
EEM #1 - Zone Temperature Setback	100,751	2,041,175	10,697	3,682.7	6.2%	80,758
EEM #2 - Variable Speed Fan Motors	-	-	142,600	486.6	0.8%	15,886
EEM #3 - Steam System Maintenance	-	876,633	-	1,046.7	1.8%	26,124
Energy Efficient Model	344,138	5,208,171	230,876	11,136.0	18.7%	244,933

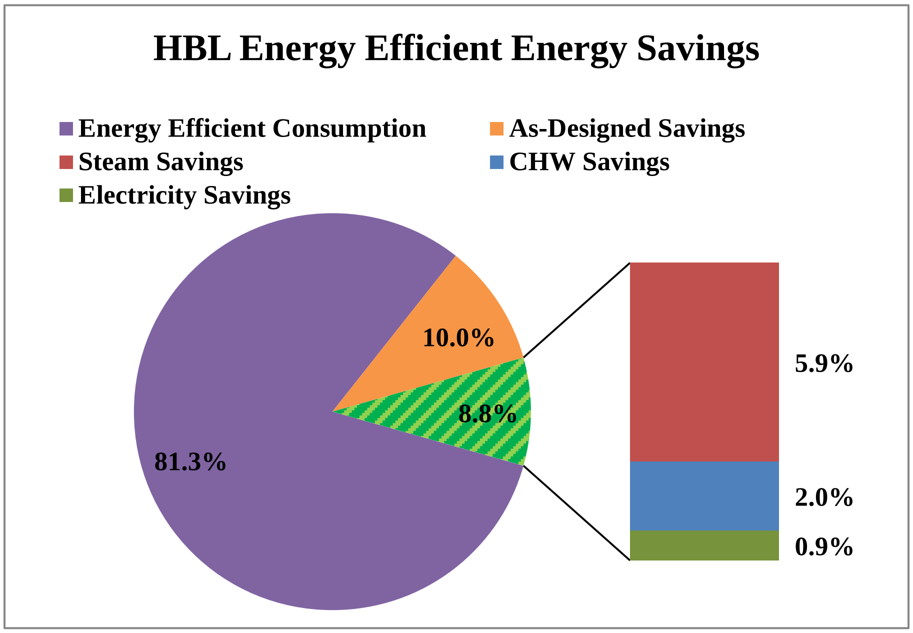


Figure 75: HBL energy efficient model savings breakdown

Chapter 7: Conclusions and Future Work Recommendations

7.1 Project Summary

Detailed and accurate building energy auditing and modeling are highly involved processes requiring substantial time, resources, and coordination. Buildings are complex systems whose behavior and energy consumption are often not understood without a thorough investigation of mechanical systems, electrical equipment loads, environmental conditions, and occupant behavior. Existing and retrofit campus building pose additional challenges to the modeling process. Renovation documentation may be incomplete and can be difficult to acquire, and the questionable integrity of a building's envelope, mechanical systems and schedules, require additional investigative resources to produce accurate simulation results. Finally, while the open-source building energy modeling tools used in this project are relatively robust and accessible, simulation development of complex systems, such as MB's ventilation energy recovery system and HBL's desiccant wheels, require experience with and a deep understanding of the software.

In spite of the challenges associated with energy modeling, an accurate baseline energy model can provide a number of powerful tools to a diverse and complex community of buildings on campus. Engineers and Facility Managers are enabled to identify under-performing systems, make better informed decisions on retrofit options, predict the savings resulting from energy conservation measures, while also avoiding potential impacts on occupants' thermal comfort. University faculty and staff implementing sustainability programs can more effectively communicate wasteful practices and propose simple energy-saving solutions with convincing visual aids, as well as evaluate and show case successful projects.

Finally, students can become intimately engaged with campus-wide efforts to save energy and are provided with a platform to test the feasibility of innovative ideas that may otherwise interfere with actual building operations at no cost.

Predicted monthly energy consumption of both baseline energy models closely matched averaged annual energy reported by utility bills between 2011 and 2015. Table 32 shows both baseline models' percent deviation from utility averages for each energy commodity as well as their respective coefficients of variation of the root-mean-square-error: CV (RSME) and normal mean bias error (NMBE) evaluated on a monthly basis. Both models meet ASHRAE calibration requirements as given by Guideline 14-2002.

Table 32: Baseline model percent deviations from average utility bills

	Utility Data	**Electricity**	**CHW**	**Steam**	**Total Energy Consumption**	**Monthly CV (RSME)**	**Monthly NMBE**
Microbiology	2012-2015	4.5%	-7.2%	-2.7%	-2.4%	8.63	2.60
Hornbake Library	2011-2015	1.2%	-2.1%	5.7%	1.9%	7.04	2.12
ASHRAE Calibration Requirements	3 years	-	-	-	-	< 15	< 5

These baseline models were used to simulate the expected energy savings resulting from the implementation of a series of actions aimed at reducing the buildings' annual energy consumption. This report divided these actions into two categories: energy conservation measures (ECM's) focus on no or low-cost corrective actions, and energy efficiency measures (EEM's) focus primarily on more proactive retro-fit projects tended to require greater investments in cost and labor.

In both buildings, measures requiring significant capital investments were not considered despite the fact that they can result in significant energy and operational cost savings. The "as-designed" energy models summarize the ECM's of each building and together are estimated to save the university 8,388 MMBtu in energy and $176,738 in utility cost each year. These ECM's rely primarily on a shift towards "best-practice" building operation and targeted auditing of HVAC controls logic and hardware.

Measures requiring more significant investments summarized in the "energy efficient" building models are estimated to save an additional 10,256 MMBtu and $243,400 per year for the two buildings. Simple payback periods for these measures in the Microbiology Building (MB) and Hornbake Library (HBL) are both expected to be less than 2 years.

7.2 MB Project Conclusions and Recommendations

According to the baseline energy model, ventilation fans account for 13% of total building energy consumption in spite of a recent major renovation. Furthermore, based on the utility analysis and the energy model, space conditioning (heating and cooling) accounts for approximately 74% of the building's energy consumption. Due to the large proportion these end uses have in total annual energy consumption, all ECM's and EEM's (excluding ECM #3) were targeted to address the ventilation and space condition systems and their control schemes.

The sensors and controls audit as discussed in ECM #1 indicates that a significant portion of heating and cooling energy is a result of uncalibrated HVAC control systems and sensors. Simultaneous heating and cooling within MB AHUs was observed to be relatively common and controls sequence logic relating to an improperly installed outside air temperature is likely to be the primary cause. An additional existing outside air stat connected to the energy recovery system could also be used to control air handlers and forego the installation of a replacement thermostat.

ECM #2 – AHU-2 HW coil fix is only one example of controls hardware in need of maintenance. Further monitoring and reviewing of historical BAS trend data will likely present additional examples of temperature stats, valves, dampers, etc. in need of recalibration and/or maintenance. It's highly recommended that persons intimately involved with the implementation of MB's controls system design and perform a thorough audit of these systems.

ECM #3 – Ultra Low Temperature (ULT) Freezer Consolidation is an excellent example of an opportunity to engage building occupants with the task of reducing energy consumption. While the predicted energy and cost savings are not as significant as other measures, the wider goal of achieving a sustainable campus necessitates an increase in mindful energy practices and a broader shift in culture. A simple and inexpensive study to monitor current ULT freezer electricity consumption before and after occupants review and consolidate stored contents would serve as an illustrative profile of the campus' commitment to reduce energy consumption and increase awareness at the local level. Numerous other laboratory buildings such as the Chemistry Building should be included in the study that could easily be carried out by an undergraduate student with the support of the University's Office of Sustainability and Facilities Management.

The two EEM's that comprise MB's energy efficient model can and should be implemented simultaneously. EEM #1 – Zone Temperature Setback could be implemented with AHU discharge setpoint adjustments, however it would be better implemented with the installation of variable air volume (VAV) re-heat terminal units. The installation of these terminal units is also a prerequisite to the full implementation of EEM #2 – VAV Fume Hood Retrofit. The most effective way of saving energy in MB is to reduce the amount of conditioned air whenever safe and possible. And while the multimillion dollar manifold exhaust system retrofit, completed in 2015, has all the equipment necessary for implementing variable exhaust air schedules, no energy savings have been realized to date because the requisite exhaust air dampers are not present within MB's spaces. Existing constant volume fume hoods account for more than 30% of all exhaust air in the building. A simple and relatively inexpensive retrofit kit such as the one discussed in this report would take full advantage of existing systems to reduce energy as well as improve worker safety by properly modulating fume-hood face velocity.

7.3 HBL Project Conclusions and Recommendations

In the case of HBL, there were sufficient existing operational problems so as to render most high-investment energy conservation measures unnecessary until the low cost/no cost measures were addressed. Of the 7 energy reduction measures proposed for implementation in HBL, all but one are recommended for implementation, and three have already been implement at the time of writing.

ECM's 1 through 3, (AHU discharge air temperature adjustment, glycol preheat valve reset and CHW pump pressure valve fix), were completed in the course of approximately three hours by FM engineers and staff and are expected to reduce the building's annual energy consumption by nearly 10%. These adjustments were done almost entirely by using the existing building's BAS. Additional increases in AHU discharge air temperature, up to 60ºF, are also recommended for implementation in the following manner: an increase of 1ºF per week with continual BAS monitoring and regular occupant interviewing. Spaces in which temperatures rise above alarm setpoints should have the associated reheat coils disconnected and spaces in which relative humidity levels rise above alarm setpoints should have the discharge temperature of its associated AHU reduced to the setpoint of the previous week. The incentive for such an action is incredibly high. Referring back to Figure 65, we see that up to 12% of additional energy savings can be realized through implementation of these increased discharge setpoints. The existence of the advanced Munters humid/dehumidification units also minimizes the risk of temperature and relative humidity destabilization. It should be noted that occupants have expressed a willingness to tolerate lower temperatures in areas not consistently occupied due to the increases in life-expectancy of archival materials associated with lower storage temperatures.

Repairing leaks in the envelope of AHU-7 is one of the most simple an inexpensive ways to reduce energy waste in HBL. Unfortunately, the prevalence of these leaks likely indicates the existence of other leaks in AHU envelopes and ductwork throughout the building. It's recommended that further analysis be done through pressurization testing and thermographic surveys to identify other source of conditioned air waste.

Of the EEM's proposed in the HBL's energy efficient model, EEM #3 – Steam System Maintenance is the most pressing, and least expensive to implement. Through improved insulation of bare steam lines and other equipment heat losses can be reduced by a minimum of 88% with very little cost. Identified steam leaks, especially ones seen at the steam regeneration coil inlets on AHU's 9 and 10, should be fixed as soon as possible to eliminate energy loss, increase worker safety, and improve the life expectancy of air handler equipment such as desiccant wheel drive-belts. A thorough survey would be greatly aided with the use of thermographic imaging technology.

EEM #2 – Variable Speed Fan Motors is the only measure not recommended for implementation. This is due to the multiple complications that come with retrofitting variable frequency drives to existing motors. If, however, the existing motors are to be replaced, VFDs are highly recommended as an accompanying purchase.

Many of HBL's operational issues stem mainly from the act of repurposing the building from a typical university library to a research and storage facility for sensitive archival materials. Implementation of HBL EEM #1 – Zone temperature setback is likely the most cost-intensive measure recommended due to this repurposing as well. The transition required the installation and application of energy-intensive humidification and dehumidification systems for the vast majority of the exceptionally large facility. HBL was originally designed without consideration for the purpose of long-term storage of sensitive archival media and its large open-space layout is not conducive to maintaining narrow bands of acceptable temperature and humidity conditions. As such, a large scale operation may be necessary to determine a more appropriate research and storage facility for many if not all of the materials currently housed in HBL.

7.4 Project Comparisons and Lessons Learned

This project contained energy analyses and models of two unique buildings that from one another in numerous ways. From a building comprehension standpoint, each building's size, age, general function, HVAC design, as well as respective occupants varied substantially. For example, MB is primarily a biochemical research and teaching laboratory employing a dedicated outdoor air and exhaust energy recovery system, while HBL is primarily an archival storage facility with a desiccant dehumidification system for precise humidity control.

From the energy modeling perspective, the two building energy modeling environments, eQUEST and EnergyPlus, have unique benefits and drawbacks. Most notably, eQUEST lacks the ability to model certain mechanical systems (e.g. a desiccant heat-exchanger), as well as the ability to customize and fine-tune building controls to mimic actual building behavior. However, early model development in EnergyPlus is far more time-consuming and current open source graphical user interfaces still contain numerous bugs (e.g. in OpenStudio's "surface matching" algorithm.)

In spite of these differences two key similarities emerged during the course of the projects. First, both buildings endured complete transformations with respect to their primary function. Furthermore, these transformations contributed substantially to their status as among the most energy-intensive buildings on UMD campus. MB, originally built as The United States Bureau of Mines Building, did not employ even common sustainability practices of modern laboratory buildings when first designed. Similarly, the repurposing of a majority of HBL's floor space from use as a graduate student library to an archival storage facility for sensitive materials means best practices normally considered during the design phase of such a dedicated storage facility would be difficult if not impossible to implement during the building's transition.

As a result in MB, laboratory spaces are not properly isolated, leading to HVAC systems that provide air change rates in office spaces that match ASHRAE requirements of laboratories and thus far exceed office space requirements. In HBL, building occupants and archival materials are in close proximity and thus the thermal conditions of both must be met simultaneously. Furthermore, archival materials are housed in large, open spaces with high ceilings not originally intended for such sensitive media. Spaces having smaller volume would require less energy to maintain and are satisfactory for storage purposes.

The second similarity between the two projects is that in both cases, access to building data could be difficult to acquire for long periods of time. Digital copies of mechanical, electrical, architectural, and plumbing drawings at times did not exsit, and were always somewhat difficult to find. Also, on-demand access to view the MS-1800 building automation system and to the buildings' mechanical rooms housing AHU's, pumps, etc. was never made available. The author believes greater and more open student access to these resources- given a certain level of confidence in the student conducting a similar project - could expedite future projects' completion time and may lead to additional insights for energy conservation measures.

7.5 Future Work

Although a comprehensive energy model and energy reduction study was completed for both MB and HBL, additional energy-saving opportunities undoubtedly can be identified and analyzed for their feasibility and payback analysis.

For the most part, many of the opportunities not discussed in this thesis are capital-intensive EEM's, and rely on cutting-edge technologies that may not yet be well established. For example, Microbiology and other campus laboratories should examine lab space HVAC isolation, whole building demand-controlled ventilation, and radiant cooling panels; while Hornbake Library can give serious thought to a thorough sensitive materials audit and isolation, a thorough steam trap audit and replacement program, as well as replacing many if not all of the aging AHU's entirely. These technologies and the possible savings resulting from their implementation can be simulated using the models developed herein.

The OpenStudio (OS) GUI for E+ is incredibly user-friendly and was of great help in the early stages of development for HBL's energy model. However, an OS measure written specifically to allow the implementation of a desiccant dehumidification wheel would have saved many hours of work in this project. A student with patience and knowledge of both the Ruby code language and E+ could create such a measure that would greatly benefit the building energy modeling community.

The next phase of these projects would include implementation of the recommended ECM's and EEM's with suitable planning and further development. Afterwards, building energy consumption should be monitored, and the resultant savings should be compared to the values predicted in this report. The data collected for the two major buildings reported here can be used to verify the energy simulation models.

Perhaps an important future work can be development of energy audit tools which can substantially automate the energy audit, thus decrease the amount time required to perform the audit. This can include utilization of a combination of both software and hardware tools.

Appendices

A1: Matlab Schedule Generator for eQUEST

Table # shows the table of values taken as input for the Matlab Schedule Generator used to create zone-specific exhaust flow schedules for the Microbiology eQUEST model. This table was developed from the results found in (Bell, 2012). Shaded columns refer to those used in EEM #2.1 and 2.2 as seen in **Error! Reference source not found.** Note that the table must be in the format of exclusively values and in a .csv file format for the Matlab script to function.

Table 33: Schedule Generator Input Matrix

	Building Average Ratio of Sash Opening (UC Study Pre-Campaign)				Building Average Ratio of Sash Opening (UC Study Post-Campaign)			
	Non-compliant		Complaint		Non-compliant		Complaint	
	WD	WEH	WD	WEH	WD	WEH	WD	WEH
Mdnt-1	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
1-2 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
2-3 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
3-4 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
4-5 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
5-6 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
6-7 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
7-8 am	0.583	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
8-9 am	0.666	0.583	0.2916	0.25	0.333	0.333	0.2291	0.18745
9-10 am	0.666	0.583	0.2916	0.25	0.4166	0.4166	0.2291	0.18745
10-11 am	0.666	0.583	0.333	0.25	0.4166	0.4166	0.2291	0.18745
11-noon	0.666	0.583	0.333	0.25	0.4166	0.50	0.333	0.18745
noon-1 pm	0.666	0.583	0.333	0.2916	0.5833	0.50	0.2916	0.18745
1-2 pm	0.666	0.583	0.333	0.2916	0.5833	0.50	0.333	0.2083
2-3 pm	0.833	0.666	0.50	0.40	0.50	0.50	0.2916	0.2083
3-4 pm	0.833	0.666	0.333	0.2916	0.375	0.4166	0.5	0.25
4-5 pm	0.833	0.666	0.50	0.40	0.50	0.4166	0.2291	0.2083
5-6 pm	0.666	0.583	0.333	0.2916	0.5833	0.4166	0.25	0.18745
6-7 pm	0.666	0.583	0.333	0.2916	0.5833	0.4166	0.2291	0.18745
7-8 pm	0.666	0.583	0.333	0.2916	0.4166	0.4166	0.2291	0.18745
8-9 pm	0.666	0.583	0.333	0.2916	0.4166	0.4166	0.2291	0.18745
9-10 pm	0.666	0.583	0.333	0.2916	0.4166	0.4166	0.2291	0.18745
10-11 pm	0.583	0.583	0.2916	0.25	0.4166	0.4166	0.2291	0.18745
11-Mdnt	0.583	0.583	0.2916	0.25	0.4166	0.4166	0.2291	0.18745

```
% Read Fume hood Schedules Matrix into Script
M = csvread('FumeHood_Schedules.csv');

% Create questdlg for compliance status of building
choice1 = questdlg('Select Compliance Status of Building:
','Building Compliance Selection','Compliant','Non-
compliant','Compliant');

% Handle choice of compliance
comp = 0;
switch choice1
    case 'Compliant'
        disp([choice1 ' That''s good to hear!'])
        comp = 2;
    case 'Non-compliant'
        disp([choice1 ' We''ll have to work on that...'])
        comp = 0;
end

% Create questdlg for campaign status of building
choice2 = questdlg('Has your building undergone a "Shut-the-sash"
campaign? ','Pre/Post Campaign Selection','Yes','Not yet','Yes');

% Handle choice of campaign status
camp = 1;
switch choice2
    case 'Yes'
        disp([choice2 ' Wonderful! You must really care about
energy savings!'])
        camp = 5;
    case 'No'
        disp([choice2 ' That''s okay! It''s very simple and
inexpensive to do!'])
        camp = 1;
end

% Select associated columns from fumehood flow matrix
choicef = camp+comp;
choicef1 = choicef+1;
disp([choicef choicef1]);


% List of fumehood exhaust in zone to total exhaust in zone
ratios
A = [0.0953 0.625 0.354 0.945 0.271];
B = zeros(24,2);

% Create total zone exhuast flow matricies
for i = 1:length(A)
    B(:,2*i-1) = 1-A(i)+M(:,choicef)*A(i);
    B(:,2*i) = 1-A(i)+M(:,choicef1)*A(i);
end
C = transpose(B);
C = round(C,4);
```

```
index = length(C)-1;
fileID = fopen('Testtext1.txt','w');


% Write daily schedules in eQUEST format
for i = 1:length(A)
    strWD = string(C(i,:));
    strWD = reshape(strWD,2,12);
    strWEH = string(C(i+1,:));
    strWEH = reshape(strWEH,2,12);
    formatSpecDay = '"FuHd Exh %g WD" = DAY-SCHEDULE-PD\n   TYPE
= FRACTION \n   VALUES           = (%s,%s,%s,%s,%s,%s,\n
%s,%s,%s,%s,%s,%s,%s,%s\n         ,%s,%s,%s,%s,%s,%s,%s,%s,%s,%s)
\n   ..\n"FuHd Exh %g WEH" = DAY-SCHEDULE-PD\n   TYPE
= FRACTION \n   VALUES           = (%s,%s,%s,%s,%s,%s,\n
%s,%s,%s,%s,%s,%s,%s,%s,\n         %s,%s,%s,%s,%s,%s,%s,%s,%s,%s)
\n   ..\n';
    strfDay = sprintf(formatSpecDay,A(i),strWD,A(i),strWEH);
    fprintf(fileID,strfDay);
end
% Write weekly schedules in eQUEST format
for i = 1:length(A)
    formatSpecWk = '"FuHd Exh %g Wk" = WEEK-SCHEDULE-PD\n   TYPE
= FRACTION \n   DAY-SCHEDULES    = ( "FuHd Exh %g WD", &D, &D,
&D, &D, \n         "FuHd Exh %g WEH" )\n   ..\n';
    strfWk = sprintf(formatSpecWk,A(i),A(i),A(i));
    fprintf(fileID,strfWk);
end
% Write annual scheduels in eQuest format
for i = 1:length(A)
    formatSpecYr = '"FuHd Exh %g Sch" = SCHEDULE-PD\n   TYPE
= FRACTION\n   MONTH            = ( 12 )\n   DAY              = (
31 )\n   WEEK-SCHEDULES   = ( "FuHd Exh %g Wk" )\n   ..\n';
    strfYr = sprintf(formatSpecYr,A(i),A(i));
    fprintf(fileID,strfYr);
end

fclose(fileID);
```

After this script was run, the schedules were copied from text file ‘Testtext1.txt’ and pasted in the appropriate locations within an eQUEST .inp file to automatically incorporate annual, weekly, and daily exhaust flow schedules into the energy model. This method saved substantial time by circumnavigating the cumbersome process associated with entering each flow schedule into eQUEST manually and individually through the native graphical user interface.

<u>*A2: HBL Thermography and Sensor Kit Deployment Summary Report*</u>

Dana M. Savage and Matthew L. Mauriello, Summary of Temporal Thermography Session Notes, May 11, 2017

DEPLOYMENT

To investigate potential thermal irregularities reported in Hornbake 4210T, a sensor kit was deployed to augment the building's BAS system and supply additional data for the energy auditing activities being conducted. The sensor system automatically collected half-hour, temporal snapshots of internal temperature, internal humidity, external temperature, external weather conditions, and thermal imagery; two deployments were conducted.

OVERVIEW

Descriptions of the two deployments are as followed:

Date	Time	Duration (hrs.)	Description
2017-03-12	02:53 PM	53.78	Cold, mostly overcast; light rain and some snow.
2017-03-24	09:57 AM	76.32	Warm, mostly sunny; some wind.

AUDIT QUESTIONS

Specific questions that this deployment seeks to address are:

1. Is the air discharge into the room by the HVAC system operating effectively/efficiently?
2. Are there patterns of surface temperatures that might indicate the presences of degradation in exterior walls?
3. Are there any temporal patterns resulting from the heating and cooling of the room itself or exterior wall (e.g., from solar loading) that might contribute to the reported thermal instability?

HVAC FINDINGS (QUESTION 1)

When evaluating the HVAC system in the first dataset via (i) proxy of the surface temperatures around the air discharge vents and (ii) the internal temperatures recorded by the air temperature sensor, all recorded temperatures appear stable (i.e., average exit temperature between 57.07 F to 60.42 F) with only minor fluctuations (Figure 1). These fluctuations can most likely be attributed to camera calibration/sensitivity.

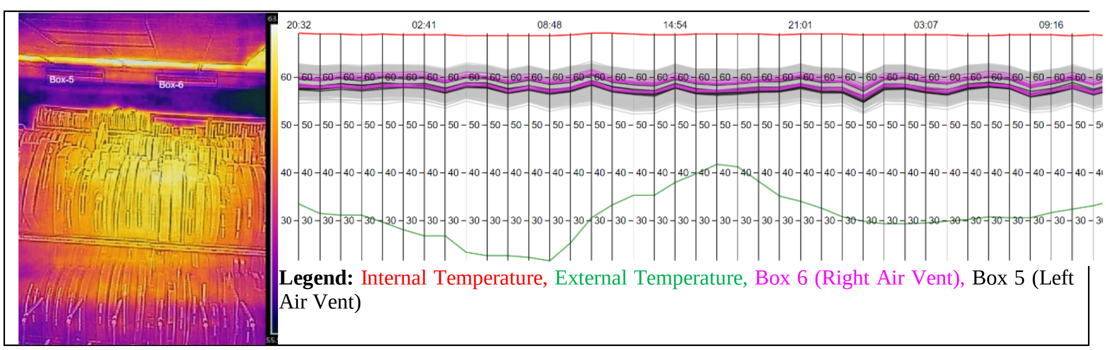
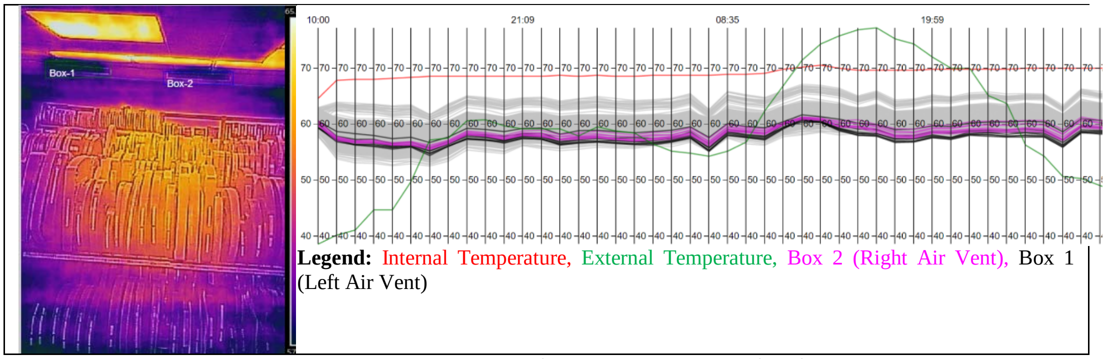


Figure 1: Sample thermal image collected in dataset 1 (left); the associated plot of surface temperatures and sensors data (right).

When evaluating the HVAC system in the second dataset using the same assumptions mentioned previously, all recorded temperatures again appear stable (i.e., average exit temperature between 57.48 F to 59.69 F). As expected, internal temperature rose slightly during the observed period due to external weather conditions potentially indicating solar loading and high external temperatures may result in some problems being observed in summer months (Figure 2).

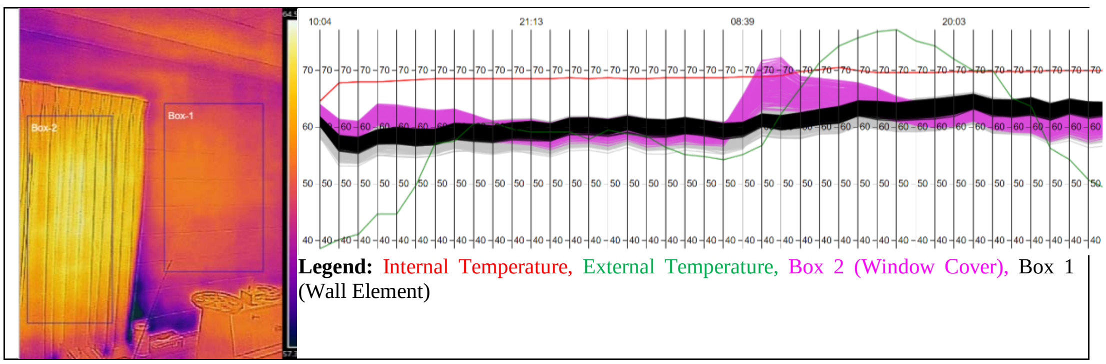


Legend: Internal Temperature, External Temperature, Box 2 (Right Air Vent), Box 1 (Left Air Vent)

Figure 2: Sample thermal image collected in dataset 2 (left); the associated plot of surface temperatures and sensors data (right).

WALL INSPECTION FINDINGS (QUESTION 2 & 3)

When evaluating the exterior walls, we could find no signs of degradation in either data collection periods. Sampling from several regions we can see the windows are impacted strongly by solar loading, while the exterior walls resist and retain the heat longer (as expected); however, no significant patterns were observed in the collected thermal data (Figure 3). Average wall surface temperatures range from 59.46 F to 62.24 F.



Legend: Internal Temperature, External Temperature, Box 2 (Window Cover), Box 1 (Wall Element)

Figure 3: Sample thermal imaged collected in dataset 2(left); the associated plot of surface temperatures and sensor data (right)

In the absences of any detectable areas of wall degradation, providing additional insulation or reflective covering around windows may reduce the influence of solar loading; however, without observing summer conditions directly these effects might not be significant.

CONCLUSION

No observable problems were found. The HVAC system appears to be operating efficiently given the current room settings, no wall degradation was observed, and the effects of solar loading given the current data is likely not significant enough to warrant improvements.

ABOUT

The "Scalable Thermography" project is an ongoing research initiative being conducted by lead graduate student Matthew Louis Mauriello (mattm401@umd.edu) and Dr. Jon E. Froehlich (jonf@umd.edu) of the Makeability Lab—a lablet of the Human-Computer Interaction Lab. The project explores new tools and methods to support thermographic energy auditing of the built environment. The temporal data was automatically collected using a new, easy-to-deploy sensor kit and then analyzed using a preliminary information visualization tool. For more information about the project, please visit: https://makeabilitylab.umiacs.umd.edu/projects/thermography/

A3: HBL Steam System Heat Loss Calculations

A3.1: Bare steam line heat loss calculation

Table 33: HBL Steam line heat loss potential

	Line diameter [in.] / Line gauge pressure [psig]	1"	1.5"	2"	2.5"	3"	4"	5"	6"	8"	10"	Total
Total Line Length [ft.]	**125**	-	-	-	-	-	-	163.5	-	-	-	163.50
	40	64.33	41.92	44.33	81.67	190.66	147.25	7.25	37.42	-	-	614.83
	15	-	-	-	-	-	-	-	-	34.92	64.83	99.75
Heat Loss Per Linear Foot [MMBtu/yr]	**125**	-	-	-	-	-	-	14	-	-	-	-
	40	2.4	3	5	5.62	6.25	8.75	9.38	10	-	-	-
	15	-	-	-	-	-	-	-	-	11.25	13.75	-
Total Heat Loss [MMBtu/yr]	125	-	-	-	-	-	-	2289	-	-	-	2289
	40	154.392	125.76	221.65	458.9854	1191.625	1288.4375	68.005	374.2	-	-	3883.0549
	15	-	-	-	-	-	-	-	-	392.85	891.4125	1284.2625
Grand Total [MMBtu/yr]												7456.3174

A3.2 Uninsulated steam valve heat loss calculation

Each valve is assumed to be an oxidized cast iron $\varepsilon = 0.78$ (Mikron, 2015) horizontal cylinder having diameter, D = 14 in = 0.3556 m and length, L = 20 in = 0.508 m. From **Error! Reference source not found.**, the valve surface temperature, T_s = 248ºF = 120ºC and T_∞ = T_{sur} = 74ºF = 22.22ºC.

Properties of air evaluated @ $T_f = (T_s+T_\infty)/2 \approx 350K$

$\nu = 2.056 \times 10^{-5} \frac{m^2}{s}$

$\alpha = 29.18 \times 10^{-6} \frac{m^2}{s}$

$g = 9.8 \frac{m}{s^2}$

$\rho_f = 1.009 \frac{kg}{m^3}$

$\rho_\infty = 1.177 \frac{kg}{m^3}$

Pr = 0.697

$k = 0.03003 \frac{W}{m \cdot K}$

$\beta = \frac{1}{T_f} = 2.857 \times 10^{-3} K^{-1}$

The total heat transfer from the valve is:

$$q' = q'_{conv} + q'_{rad}$$

From (Bergman & Incropera, 2006, p. 580) the Nussult correlation for a horizontal cylinder is:

$$\overline{Nu_D} = \frac{\bar{h}D}{k} = \left\{0.60 + \frac{0.387 Ra_D^{1/6}}{\left[1+\left(0.559/Pr\right)^{9/16}\right]^{8/27}}\right\}^2$$

$$Ra_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu\alpha}$$

$$= \frac{\left(9.8 \frac{m}{s^2}\right)(2.857 \times 10^{-3} K^{-1})(120 - 22.2)K(0.3356m)^3}{\left(2.056 \times 10^{-5} \frac{m^2}{s}\right)\left(29.18 \times 10^{-6} \frac{m^2}{s}\right)} = 2.0524 \times 10^8$$

Hence,

$$\overline{Nu_D} = \left\{0.60 + \frac{0.387(2.0524 \times 10^8)^{1/6}}{\left[1 + \left(0.559/(0.697)\right)^{9/16}\right]^{8/27}}\right\}^2 = 70.421$$

and

$$\bar{h} = \frac{k}{D}\overline{Nu_D} = \frac{\left(0.03003 \frac{W}{m \cdot K}\right)}{(0.3556m)}(70.421) = 5.947 \frac{W}{m^2 \cdot K}$$

So the total heat loss is:

$$q = Lq' = L(q'_{conv} + q'_{rad}) = L\left[\bar{h}\pi D(T_s - T_\infty) + \varepsilon\pi D\sigma(T_s^4 - T_{sur}^4)\right]$$

$$= (0.508m)[\left(5.947 \frac{W}{m^2 \cdot K}\right) \times \pi \times (0.3556m) \times (393 - 295)K$$

$$+(0.78) \times \pi \times (0.3556m) \times \left(5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4}\right)(393^4 - 295^4)K^4]$$

$$= (0.508m) \times [648 + 803]\frac{W}{m} = \boxed{737.4\, W}$$

■

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