Goddard Hall Air Audit

A Major Qualifying Project
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In
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By:

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Abstract

The goal of this project was to assess the current conditions of the heating, ventilation and air conditioning system in Goddard Hall and determine ways that it could be improved. Due to current conditions, Goddard Hall is overly negatively pressurized, resulting in uncomfortable classrooms and hallways as well as making the front door extremely difficult to open. After analysis of the mechanical drawings, as well as walkthroughs to observe current conditions and record temperature data and system deficiencies, the research team was able to determine multiple possible solutions of various scope and cost impact, to improve the overall building comfort.

Acknowledgements

I would like to thank Professor Robert Daniello for his unwavering support and advocacy which were crucial in completing this project. I would also like to thank Jack Price and Lou DiBerardinis for their help and expertise in the analysis of existing conditions and safety within the building. Additionally, Finally, I would like to thank the WPI Facilities staff, in particular Dan Sarachick and Bill Grudzinski for their in depth knowledge of the WPI Campus and its energy systems, as well as their willingness to show me the mechanical spaces within Goddard Hall.

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1.0 Introduction

College campus laboratories are important and complicated buildings. There is a wide range of experiments and research that can occur in laboratory buildings, ranging from simple introductory chemistry classes to research on potentially explosive or poisonous chemicals. The most crucial thing to consider when designing a laboratory building is the safety of building occupants, and of those who are walking by the building. Humanity never would progress if the health and safety of laboratory staff were jeopardized by dangerous conditions. Ensuring chemicals are ventilated properly is arguably the most important consideration during the design process of a laboratory. HVAC systems in particular are a vital line of defense for protecting building occupants, as they provide fresh outdoor air to the rooms and exhaust all contaminated air. Because HVAC systems are so crucial to the success and safety of the building, the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE), has come up with a set of standards for laboratory buildings to ensure consistency in safety, operation and maintenance. While not mandated everywhere, ASHRAE sets the standard for good engineering practices for all buildings and helps to ensure consistent safety. ASHRAE has a design guide pertaining specifically to laboratory buildings, called ASHRAE/ANSI 110 and ANSI Z9.5. A building that was built with this design guide in mind is Goddard Hall on Worcester Polytechnic Institute's campus. Goddard Hall, which was built in 1965, has been enlarged and updated a few times through the years to maintain relevant technology. Goddard Hall is home to the Chemical Engineering, Chemistry, Biomedical Engineering and Biochemistry departments, which required it to house many sophisticated experiments and processes. Despite the updates, the building has never had a cohesive supply air system, and it has an oversized exhaust system. This results in negative pressurization in the hallways and classrooms in the building, which should be positively pressurized. Negative pressurization is only ideal for laboratory spaces in buildings, as this avoids contamination between lab rooms, and ideally, the fumes exhausted to the outdoors, many other issues present themselves when the negative pressurization is overwhelming. It impacts the safety of the building and also results in office, classroom and hallway spaces being moderately uncomfortable, as well as causes drafty and noisy conditions around windows. The negative pressurization also results in excessive force being needed to open the entrances. The goal of this project is to investigate the causes of this, and provide cost analysis, feasibility and suggest new systems to improve the buildings overall comfort and safety.

2.0 Background

2.1 Introduction

In this chapter, the context surrounding the needs for HVAC systems, in particular in laboratory buildings will be discussed, and the issues that can arise when HVAC systems do not function properly. The design guidelines put forth by ASHRAE in order to help maintain standards in laboratory ventilation will be reviewed and their impact on Goddard Hall will be considered. Finally, the history of Goddard hall and what has been done to improve this HVAC system thus far will be presented.

2.2 Heating, Ventilating and Air-Conditioning

Heating, Ventilation and Air-Conditioning is a type of engineering focus in thermal comfort and indoor air quality in buildings and transportation. In this report, we will be focusing specifically on HVAC systems that are needed in buildings. Buildings have very specific requirements for air quality and thermal comfort, and it is up to engineers to design these systems in accordance with these considerations. When designing an HVAC system for a building, engineers take into account room use, occupancy type and duration, exterior wall and window area, door area, lighting, heat output from equipment and processes, and directional orientation, which all impact the amount of fresh air, heated air, cooled air, and exhaust needed by a space. HVAC Systems are particularly critical in a laboratory space as there are many chemical experiments that are occurring that can have negative effects on the building occupants.

It is crucial that fumes are exhausted and fresh air is being brought into the space to make up what is being exhausted.

HVAC systems utilize an abundance of specialized equipment in order to achieve thermal comfort. Typically, a complex run of ductwork is installed throughout the building. There are separate duct systems for supply air, return air and exhaust air, which are connected to fans that move the air throughout the building. These fans can be constant volume, variable volume, constant temperature or variable temperature depending on the needs of the space. In addition to the fans, there are also typically coils that utilize water or refrigerant to heat and cool the air based on occupant needs. The duct systems also utilize dampers to control airflow and ensure that the pressurization in the building is appropriate for the building usage. The entire system is carefully balanced by professional balancers after installation to adjust the systems and then commissioners ensure that the building is operating at peak condition.

2.3 ASHRAE

The American Society of Heating, Refrigeration and Air-Conditioning Engineers is a professional society that was founded in 1894 to focus on “building systems, energy efficiency, indoor air quality, refrigeration and sustainability within the industry” (ASHRAE, 2019).

Figure 1. ASHRAE Logo (ASHRAE.org, 2019)

ASHRAE members and committees develop standards and design guides to improve with

HVAC standards within many types of buildings. Many of their standards, in particular ASHRAE 90.1 and 55.2, are adopted by many local governments into their local building code. ASHRAE guidelines and standards are considered “engineering best practice” for most of the United States, and much of the world.

2.4 Laboratory Design Guidelines

A particularly relevant subcommittee to the issues that are examined in this MQP has created the “ASHRAE Laboratory Design Guide; Planning and Operations of Laboratory HVAC Systems.” This extensive book covers a range of topics from fume hoods and zone air distribution to energy recovery and stack effect. This guide will serve as a critical reference for the duration of this project. The section of primary importance is the Design Process chapter, which outlines the steps that are recommended to take in order to successfully design a laboratory HVAC system. It breaks down the creation of an HVAC system into three main phases; predesign, design and construction. During predesign, the engineer completes parametric analysis, simulates target energy metrics, and brainstorms ideas for appropriate solutions. The design phase is when all of the building drawings are created (architectural, structural, mechanical, electrical, etc) and are reviewed and revised by professional engineers. The construction phase is when the drawings are bid by contractors, who prepare and coordinate installation of all the building systems. This MQP will focus on the pre-design and design phases in order to analyze solutions to improve Goddard Hall.

2.5 Negative Pressurization

Experimental laboratories have existed since the days of Pythagoras and have had thousands of years to evolve. During this evolution, experiments have become increasingly more complicated and the importance of creating experiments that are capable of being replicated and peer reviewed has been prioritized. In response to this, laboratories have evolved to be incredibly complex spaces, with stringent guidelines and requirements for chemical disposal, personal protective equipment, laboratory practices and ventilation requirements. Modern laboratories have strict exhaust and supply air requirements and often implement fume hoods, which are enclosed tabletops with a dedicated exhaust system to minimize inhalation of fumes as much as possible. The exhaust requirements of laboratories and other spaces are generally called negative pressurization, which implies that more air is being removed from the space than is being introduced. While fresh, outdoor air is crucial in providing a safe laboratory space, it is equally as crucial to ensure that the fumes are exhausted quickly and thoroughly. This negative pressurization is typically not very noticeable and ensures that no fumes are accidentally pushed into the hallway; however, there is such a thing as too much negative pressurization, which can cause several issues such as inability to easily open doors, increased drafts through windows and general discomfort.

2.6 History of Goddard Hall

Goddard Hall was built in 1965 and was originally intended to house the expanding chemistry, biochemistry, and chemical engineering departments on Worcester Polytechnic Institute's campus. The building consists of four floors, totaling 21,300 square feet of area, including various lecture spaces, offices for faculty, conference rooms and laboratories performing a wide range of experiments. In an effort to modernize the building and keep up with a changing industry and growing campus population, Goddard Hall was majorly renovated in 2008 to keep up with new chemical engineering, biochemistry and biology equipment. Goddard Hall consists of a North section of the building and South side of the building, with one being the original and one being added in 2008.

Figure 2. Goddard Hall (WPI.edu)

For the last twelve years, professors and students have noticed various issues related to Goddard Hall. These issues include a front door requiring excessive force to open, windows that are unable to be opened due to the amount of outdoor air that is sucked into the building, laboratories that have inefficient and overwhelming fume hood performance, and spaces that have poor temperature control, an issue for temperature sensitive experiments. These issues result in a building that is uncomfortable to occupy, difficult to enter and potentially dangerous due to the fume hoods potentially pulling chemicals from other spaces, resulting in contaminated experiments.

Over the years, various groups have been brought into assess the issues within Goddard Hall and attempt to remedy them. A project that occurred about 5 years ago attempted to rebalance the North side HVAC system and provide additional makeup air to remedy the excessive exhaust issues. Another project about 5 years ago attempted to inspect and repair duct sealing in order to eliminate an excess of 30,000 cfm of exhaust from the building. Both of these projects were unsuccessful as they were unable to remedy the buildings issues. It is likely that the building issues were too encompassing to be fixed with these small patching jobs. Per the facilities department, the issue with these two attempts was that they only looked at half of the problem. The North and South sides of the building have two separate HVAC systems, and focusing on one or the other does not account for what the other half is doing. This year, a third party company called 3Flow was brought in to assess the existing conditions and do a thorough analysis of the entire building HVAC system (north and south), as well as the chemical reactions being researched within the building. The goal of this project is to have several feasible solutions to improve the building, which could range from small fixes to an entirely new building. The end of the 3Flow report is where this MQP begins.

3.0 Methodology

This project was aimed at investigating the existing HVAC building systems in Goddard Hall, determining operational conditions and outlining concrete recommendations to improve the negative pressurization and overall safety of the building. This methodology is inspired by the *Roadmap to High Performance Laboratories and Critical Control Environment,* a thorough procedure that focuses on the development of Smart Labs and is intended to help engineers develop a strategic plan for cost effective implementation of improved HVAC systems to improve safety and building maintenance costs. It is broken down into 4 phases: Plan, Assessment, Optimization and Manage, with an anticipated timeline of 5 to 10 years from start to finish. This project focuses on the planning and assessment portion of the procedure and was accomplished in two phases: Overall Qualitative Scope Study, and Quantitative Performance Audit. These phases were broken down further to attainable steps.

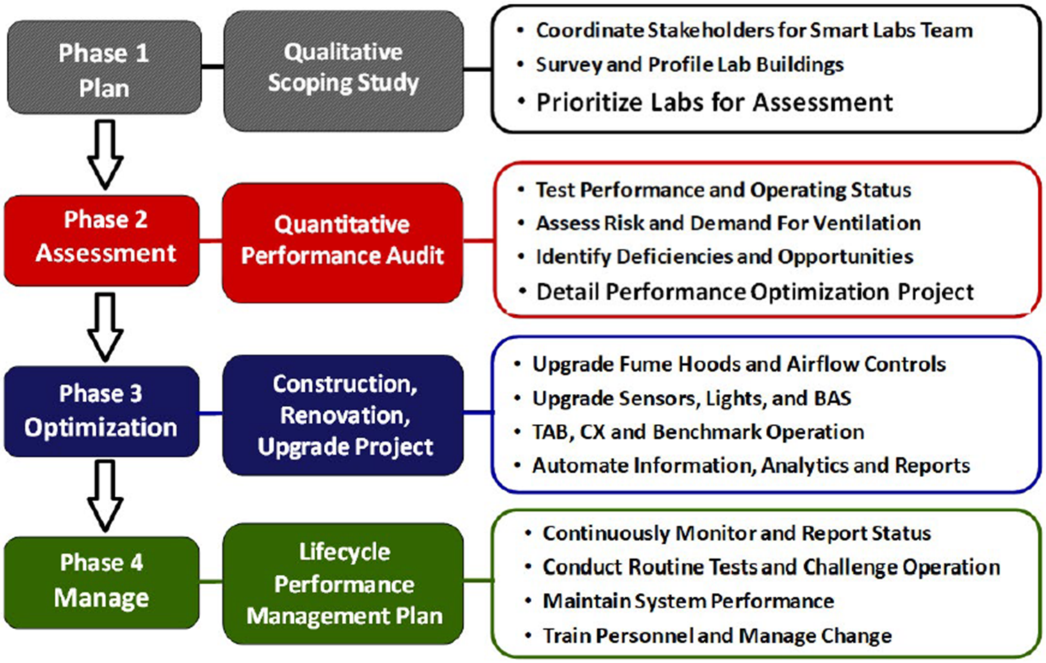

Figure 3. High Performance Lab Optimization Processes and Phases, from ROADMAP: To High Performance Laboratories and Critical Control Environments (2018.)

Overall Qualitative Scope Study

1. Laboratory Building Inventory
2. Lab Condition Status
3. Profile Lab Building Condition
4. Deliverable: Project Optimization Priority

Quantitative Performance Audit

1. Building Design and Operating Documents
2. Lab Ventilation Risk Assessment
3. Operation Specifications and Tests
4. Performance Improvement Measures
5. Deliverable: Scope of work for future improvements

Each of these steps were crucial in the overall determination of the condition of the building systems, operational capacity of the fume hoods, and supply air system and exhaust system. With this clear road map of necessary objectives, the project goals of improved building comfort and safety were accomplished and are explained further in this chapter.

3.1 Overall Qualitative Scope Study

The focus of this phase is to determine major issues within the lab building and determine where the major efforts of the investigation and renovation should be focused. In order to accomplish this, the Smart Labs procedure has broken down phase one into five steps, four of which are relevant to the Goddard Hall Air Audit. This first step, which encompasses Lab building inventory, lab condition status and the creating a lab building condition profile to determine which lab buildings should be upgraded, will take about four weeks.

3.1.1 Laboratory Building Inventory

This very first step in the procedure is critical for determining the scope and obtaining basic information about the building. The most important information gathered in this step includes the building age, size, uses, number of occupants, number and size of labs, type of

HVAC systems, number of temperature controls devices and number of floors. For this project, the second floor of Goddard was the main focus for quantitative tests, but the entire building was observed for a comprehensive picture of existing systems. This information was gathered through a walkthrough of the building and analysis of the building floor plans (see appendix A), as well as research about the history of the building.

3.1.2 Lab Condition Status

The objective of this step is to gather information about the condition of the labs and HVAC systems, in order to accurately determine issues. This was also accomplished with a walkthrough survey, focusing on operational status and building condition. This walkthrough included the mechanical rooms in Goddard Labs, as well as the mechanical space on the roof and behind the building. In particular, I looked for damage from weather, obvious differences in age of equipment, unusual noises indicating less than ideal operation, air intakes that were clogged with pollen, leaves or other detritus, and abandoned duct runs. This visual inspection is intended to give insight into cost, complexity and duration of a potential renovation project.

3.1.3 Profile Lab Building Condition

This step requires the synthesis of the information gathered in the previous two steps for a comprehensive look at the state of the building systems. This combined information showcased key performance indicators such as the overall state of the building systems, potential opportunities for improvement, potential benefits and payback if upgrades and renovations were to take place, as well as an idea of average energy cost per square foot, cost per cubic feet of air per minute. Energy cost per square foot was estimated by counting light fixtures and fume hoods in each room, and cost per cubic feet of air per minute can be estimated by adding the feet per minute from each fume hood in the lab spaces.

3.1.4 Deliverable: Project Optimization Priority Report

The final objective in Phase 1 is a complete report on the building condition as observed. This report describes the building history, current deficiencies and issues observed on the walkthrough and establishes possible solutions in their first stages of development that have the greatest potential for success and are the most valuable for renovation per organization budget. This detailed report was compiled as an “Existing Conditions Memo” and can be found in chapter 4 of this report. The next phase is based off of this existing conditions memo, and delves deeper into cost benefit analysis, occupant comfort and temperature swings, and outlines many solutions ranging in low to significant cost that could be taken by the WPI Facilities Department in an effort to improve the building comfort and safety.

3.2 Quantitative Performance Audit

The primary focus of this phase is looking at the current operating metrics of the building and comparing them to how the building could operate, if it were a perfectly designed, very efficient building. The difference between these two levels is the basis for potential improvements in the building. This phase is broken down into seven main steps with several sub steps, two of which have been eliminated due to limitations of the building monitoring system. The assessment phase, which encompasses building documents (lab floor plans, system descriptions and designs, controls sequences), lab risk assessments, systems operation tests, airflow and operating specifications and is summed up into an energy and operating cost analysis that the recommended performance improvement measures are based off.

3.2.1 Building Design and Operating Documents

This objective involves gathering relevant building documentation to base designs and assumptions. System descriptions, system components, mechanical floor plans, and description of control systems were collected and reviewed. This step proved difficult, as there are no current mechanical plans for the whole building due to the piecemeal upgrades. The most recent mechanical plans were at least eight years out of date, and significant upgrades have occurred since these drawings were issued. However, a few documents on the operation of some of the systems were located, which proved useful for obtaining a full building view of the systems and how they likely operate together.

3.2.2 Lab Ventilation Risk Assessment

This next step walks through an evaluation of hazard data, hazardous waste records and site surveys, as well as interior hazards that translate into risk matrices for Exposure Control Devices, Fume Hoods, lab spaces, exhaust systems and point towards recommended design, airflow and operating specifications for lab safety. Knowledge of what chemicals are used in the building are gathered by lab safety officials and used in the building is critical for determining exactly how many fume hoods are necessary and at what flow rate. Goddard Hall is primarily a teaching lab, with many novice scientists learning the basics of proper lab technique and exploration. There are no major toxic chemicals being utilized in the building that require significant exhausting and strict safety precautions at this time. Determining the type of chemical used also allows for the potential of ramping fume hoods exhaust air down when they are not being actively used as a measure to save money and decrease the excess exhaust airflow.

3.2.3 Operation Specifications and Tests

The next step in the assessment phase requires a survey to evaluate existing control systems to determine configuration and capabilities. This survey will determine modulation capabilities and assess how much individual control building occupants have on the temperature and overall comfort of their spaces. In addition to this, the ventilation effectiveness of supply and exhaust systems will be evaluated to determine ability to achieve desired air quality. It is very possible that the space is not able to receive the appropriate temperature air for what the occupants require, which would be seen in temperature trending. This temperature trending will also showcase the fluctuation of temperatures in spaces, which can have a significant impact on comfort as well. Finally, calculations will be performed to determine the demand for ventilation, airflow, heating and cooling in the lab spaces. This can be compared to the current performance of the system which gives an accurate picture of how well the systems are working and whether the labs are getting adequate supply and exhaust air.

3.2.4 Performance Improvement Measures

The last objective to accomplish requires significant research into possible solutions for the issues the previous steps have discovered. With this information, realistic solutions can be discussed and performance improvement measures will be determined that can lead to improved safety, more reliable operation and better energy efficiency. These solutions will be analyzed for cost impacts and potential money savings, as well as for how feasible the solutions are in the existing space. The school year schedule and summer research work can impact the ease of vacating the building to make way for construction improvements.

3.2.5 Deliverable: Scope of work for Phase 3

The culmination of phase 2 will be a report that describes how the systems are currently operating, compares current operation to the current demand for ventilation, identifies deficiencies, identifies applicable performance improvement measures and defines the scope of work in which the recommendations can be applied for success. This final report will also be presented to the WPI Facilities department for review and consideration in their plans to renovate and improve the building.

3.3 Methodology Conclusion

Following this comprehensive procedure, the project goal of determining deficiencies in the HVAC system of Goddard Hall and providing realistic recommendations to improve the building comfort and safety was accomplished. These steps also enabled accurate cost analysis of several of the recommendations, providing a substantial amount of information to the WPI Facilities department to aid their work in maintaining the safety and comfort of Worcester Polytechnic Institute's buildings.

4.0 Existing Conditions

4.1 Introduction

The scope of this project is to determine the issues with comfort and safety in the chemistry building at Worcester Polytechnic Institute, Goddard Hall. The prevalent issues include negative pressurization impacting building comfort, safety and energy usage.

As mentioned earlier in this report, Goddard Hall was originally built in 1965 and renovated in 2008. As the building was expanded and upgraded, the HVAC system was too. However, the two primary HVAC systems, in the north and south sections of the building, are not connected. Due to this, the amount of supply and exhaust air throughout the building is inconsistent, leading to potential safety and comfort issues. The goal of this chapter is to detail the main issues with the building. There are almost 60 years of compounding issues in this building. However, few documents were able to be procured on this building. There are no overall mechanical drawings, minimal systems data beyond a narrative describing some supply air systems, and there is no way to monitor Goddard Hall's energy usage, so energy metering was also unable to be reviewed. This made it very difficult to perform analyses on the building. The primary issues in the building are detailed in the next several paragraphs.

4.2 Primary Building Issues

Half of the building has a combined, new exhaust system. The other half of the building, which is older, has individual exhaust fans for each lab fume hood. Because these systems are so different in design and age, the systems are not compatible. Additionally, the systems are not balanced in relation to each other, they are not communicating with a centralized controls system and they do not modulate based on need. This results in the building having significantly more exhaust capacity than is needed. For instance, one exhaust fan is running at 1600 CFM, when one typical lab hood only needs between 500 CFM - 700 CFM. This is a large discrepancy in exhaust requirements. Many of the fume hoods are running at drastically different CFMs, despite the building lab sizes, hoods and needs being relatively consistent throughout. Goddard is primarily a teaching laboratory and includes several small individual research labs. There are no highly-toxic contaminants being used regularly in the building, therefore fume hoods ranging with between 500 CFM - 700 CFM are adequate for most needs. Many of the older fume hoods are running well above this, while some of the newer fume hoods are running in this range. This inconsistency is both energy inefficient and contributes heavily to the building's negative pressure issue. Speculating on the energy usage of Goddard Hall, university lab buildings typically use two to three times the energy than a university office building uses. If this type of building is uncontrolled, it will use much more energy than this.

4.3 Lacking Controls System

Another major issue in the building is with the controls system. Due to the quantity of upgrades that varied in scope and complexity, there is no centralized control system that allows for close monitoring and control of the systems. There are only localized thermostats for some rooms, and no control over the airflow in the fume hoods. As a result, many building occupants complain of uncomfortable temperatures and breezes and there is no way to adjust temperature or ramp down the exhaust capabilities, which causes excess exhaust and wasted energy. Several

Figure 4. Roof Photo of the new combined overall exhaust system for newer half of the building. (Andrews, 2020)

Figure 5. Roof Photo of the older, individual exhaust fans on older half of the building. (Andrews, 2020)

rooms were sampled for a week at the same time to determine the variation of building temperature these spaces experienced. The variation was

significant, in some rooms varying up to 20 degrees at the same time each day. This lack of consistency is evident in figure 6.

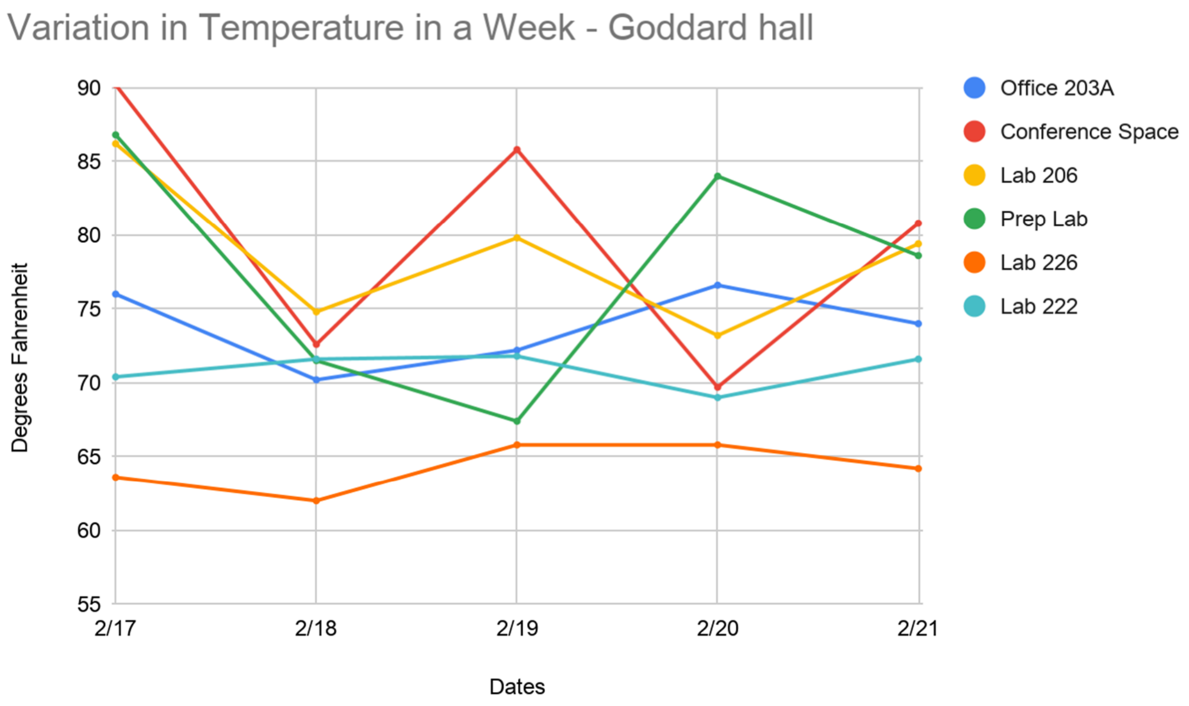

Figure 6. Recorded week of temperatures from 6 rooms on Second floor of Goddard Hall.

4.4 Years of Building Upgrades

Another issue that is evident upon walking the building is the various stages of upgrades that have occurred throughout the years. This is obvious on the roof, where the exhaust system for the two halves of the building is completely separate and different. This is also evident behind the building, where there are four separate brands of split system air conditioning units within 50 feet of each other. This demonstrates the “Frankenstein” nature of the building, and severely impacts efficiency as well as cost. Split systems are designed to work with their own parts and can be incredibly efficient when installed correctly. However, when a building has more than one system, efficiency and comfort are compromised. These units do not communicate with each other and thus do not account for occupancy and load changes. This can result in an uncomfortable and inefficient building. Additionally, as the building has been upgraded, various ducts have been connected, disconnected, and abandoned or reconnected for new purposes. This can be noted when walking through the building and feeling drafts, seeing disconnected and abandoned ducts with the dampers open and when entering rooms that are a significantly different temperature from the adjacent spaces.

Figure 8. Photo of outdoor Condensing Units. Several different brands are installed at this location (Andrews, 2020).

Figure 7. Photo of abandoned ducts in a second-floor research laboratory within Goddard (Andrews, 2020).

4.5 Lack of Overall Cooling

Additionally, many of the lab spaces have window air conditioning units due to the lack of centralized cooling in the overall HVAC system in the building. This is an issue as it impacts energy efficiency in the building, and these air conditioners provide many spaces for air to leak through. It also does not provide make up air to replace the air that is exhausted. These window air conditioners are also uninsulated and cause infiltration around all of their edges of the wall penetrations, an issue which is especially noticeable in the winter. Another major issue in this respect is the lack of heat recovery on the building. Heat recovery units have become standard on college campus laboratories, as they use the warm exhaust air as “free heat” to pre-heat the cooler supply air from outdoors. This method can result in major energy savings, which is something that Goddard Hall is missing.

4.6 Potential Solutions

These issues, while perhaps not major on a room by room basis, compound to be an uncomfortable, inefficient and potentially unsafe laboratory building. However, there are several potential solutions that can be beneficial in mitigating some of these issues. Some solutions include continuing to replace fume hoods with more energy efficient VAV fume hoods, which can lower exhaust CFM and improve energy efficiency. These existing constant volume fume hoods could also be converted to variable volume fume hoods, which would lower their exhaust output. Another type of fume hood that has recently come to the forefront is a standalone filter fume hood. These fume hoods are cheaper than standard fume hoods and are also not hard ducted to the building exhaust system. These fume hoods use charcoal filters and recirculate filtered air into the room. These fume hoods are well suited for teaching laboratories with relatively safe chemicals. A new overall controls system could be installed to modulate the existing equipment and enable it to work more efficiently and be more responsive to building changes. The older, separate fans exhaust system could be replaced with a large, overall combined centralized upblast VAV exhaust air handler that incorporates a heat recovery system that matches the other side of the building. This would decrease exhaust output and improve efficiency and control. Another potential solution includes installing a new overall supply air system with heat recovery to help mitigate the excessive amounts of exhaust that render the building uncomfortable. This new system has the potential to be very energy efficient and responsive to building and occupant demands, thus making the building more comfortable as well. Another solution could include ramping down the exhaust fan powers by turning off some of the fume hoods when they are not in use, or installing variable frequency drives, which allow fans to have a modulation operation to match load. The fans could be run on low speed when classes are out or at night to lower some of the exhaust capacity and need for make-up air. Finally, there is the potential for some of the issues to be mitigated by installing fire doors at the connection point of the north and south sides of the building, as the systems are separate and were balanced separately. All solutions to improve this building require significant investment, and engineering and will involve potentially disruptive construction during the school year. It is imperative all potential solutions are examined from all aspects to achieve the greatest amount of success from the least amount of money and disruption.

4.7 Existing Conditions Conclusion

After looking closely at the current state of Goddard Hall, it is evident there is much room for improvement, and that improving this building should be a priority for WPI. Between the inconsistent airflows keeping doors shut and potentially causing migration of chemical odors into areas that should be chemical-free, to just a general need of upgrading a crucial research laboratory building on campus, there are many ways that WPI can improve this building without needing to demolish it entirely and starting over. These improvements will go a long way in improving the energy efficiency of Goddard Hall as well. These improvements will be discussed at length in the next chapter.

5.0 Recommendations

5.1 Introduction

In this chapter, several of the proposed approaches mentioned in the previous chapter will be examined financially and their likelihood of success will be discussed. Due to the nature of this project and the closure of WPI's campus as a result of COVID-19, some important calculations were unable to be performed. Only the most realistic and cost-effective solutions will be discussed, as this report recommends investing in a legitimate, long-term solution to best benefit the students and faculty who rely on Goddard Hall's laboratory space.

5.2 Install new overall Controls System

One potential solution to remedy the issues outlined in chapter 5 is the installation of a new overall controls system in the building. One of the major reasons for the issues observed is that there are several different brands of heat pump, fume hoods, terminal boxes and exhaust fans in the building and none of them are communicating with each other or modulating in a way that anticipates air demand and reacts appropriately. While the installation of a new controls system would be costly, due to the controls company needing to engineer the system, obtain information on all of the equipment in the building as well as the demand in each room, and then purchase and install costly controls equipment and thermostats, as well as set up a Building Automation System (BAS), this would result in a huge improvement in the building comfort and energy savings, as well as eventual repayment of the investment, seen below in table 1. A BAS has the added benefits of efficiently controlling the air conditioning, heating and exhaust systems in a way that saves the building owner money. It will also lower building maintenance costs, as it monitors all energy and HVAC equipment in the building and allows it to work together on a schedule of operation while initiating alarms for equipment that is operating out of normal parameters, or in need of maintenance. Building Automation systems are also capable of load shedding, which prevents brownouts during days where the grid is hitting peak energy demand, and can alert the building operator to issues and system failures (High Performance HVAC, 2008). Installing a BAS also enables any new HVAC equipment to be tied into it, and relieves Goddard Hall of the issues caused by years of HVAC upgrades that do not communicate. The current market cost for installation of building controls is between $2.50 and $7.50 per square foot (Rawal, 2016). As Goddard Hall is a 21,300 square foot building, WPI is looking at a cost of potentially around $159,750 to install a BAS system and controls for all existing HVAC equipment. Low return on investment typically discourages most building owners from installing a Building Automation System. However, a new controls system has the potential for being a less invasive construction process than an entire new HVAC system. It could very easily be installed in a few months or so during WPI's summer or winter break, which lowers the impact the installation would have on students and faculty research. Possible savings from installing a

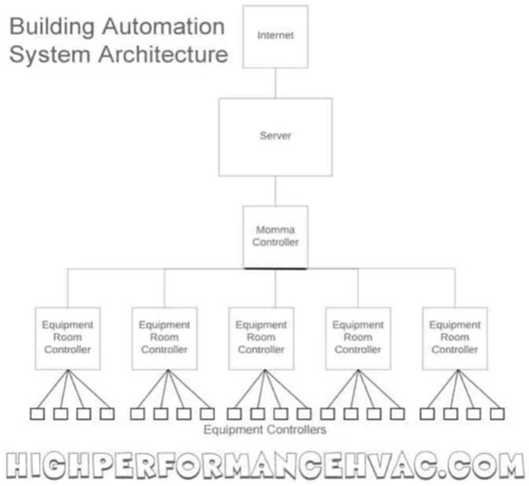

Figure 9. Depiction of communication structure for a BAS (HighperformanceHVAC.com, 2008).

Building Automation System are between 10 percent and 25 percent with HVAC, lighting and some electrical loads being monitored and modulated by the BAS (Rawal, 2016). WPI could potentially see a return on this investment within 5 years.

5.3 Replace fume hoods with energy efficient fume hoods

Another feasible solution to improve building conditions would be to replace all outdated, constant volume fume hoods in the building. Goddard Hall is currently home to 77 fume hoods and 23 ventilated storage cabinets, with 15 fume hoods being on the second floor alone. These vary from three feet wide to six feet wide, and are in various states of disrepair.

Figure 10. Image of Standard Lab Fume hoods that are replacing older models in Goddard Hall. (Labconco.com, 2020).

Some are totally non-operational and are turned off and used for glassware storage. Others are exhausting much more air than necessary for the type of chemicals and size of hoods that are used in Goddard, and others have been replaced with new energy efficient VAV fume hoods. This wide selection of fume hoods all use different energy amounts, exhaust different amounts of air and some are not necessary to have anymore. In speaking with WPI facilities, I learned that WPI has been slowly replacing the oldest fume hoods throughout the years in an attempt to minimize the extreme amounts of exhaust air in the building, causing the negative pressurization seen throughout the building. The cost to replace a fume hood is between $18,000 - $20,000, which includes the purchase of an equivalent size fume hood, demolition, installation and connection to existing HVAC ductwork, and then individualized safety controls for each fume hood. The return on investment that WPI has seen in doing this is roughly 4-5 years, saving money primarily due to the energy savings, as the new fume hoods are able to vary the amount of airflow they exhaust, as well as using less air than the older models. Another possibility in fume hood replacement is in the "ductless fume hoods" which have been growing in popularity due to their ease of installation and low energy costs. These fume hoods use activated charcoal filters to trap chemicals and then recirculate the filtered air back into the room. The installation of these is significantly easier than a normal ducted fume hood, and they can be great substitutions in buildings like Goddard Hall, which is used for teaching and does not use many highly dangerous chemicals. Ductless fume hoods range from $2,000 to $4,000, with charcoal filters costing around $400 per filter depending on the size of the fume hood. Standard fume hoods like labconco typically cost $5,000 to $10,000 depending on size, plus face velocity sensors. Replacing all 77 fume hoods in Goddard Hall with a new high-performance fume hood would cost around $1,540,000 for the hoods and installation. Replacing every fume hood in Goddard Hall with a ductless fume hood is closer to $231,000. While the ductless fume hoods are likely not a suitable fume hood substitution for every fume hood in the building, it is very possible to purchase some combination of standard fume hoods and ductless fume hoods, which would still be a significant energy and cost savings solution, as compared to just replacing every fume hood with an identical, newer, low FPM fume hood. One acceptable method of replacement is one ducted hood per research lab and one ducted fume hood per teaching lab, and the rest would be ductless fume hoods.

5.4 Install new overall supply air system with Phoenix Valves

The last potential solution for mitigating the issues found throughout Goddard Hall is to install a new overall supply air system with chilled water cooling, steam and hot water heating and glycol heat recovery that uses Phoenix Air Valves. Phoenix Air Valves are highly engineered venturi valves that are designed for complex and critical airflow control, like a laboratory building. They are hourglass shaped tubes that contain a moveable cone which regulates flow. Venturi valves can maintain airflow regardless of duct pressure, are capable of operating in constant volume or variable volume, and come with sophisticated controls that allow for modulation based on changing room conditions. These are used in place of traditional Variable Air Volume (VAV) boxes, which a less complicated building such as an office building may use to distribute air, as precise control of airflow, temperature and humidity is less

Figure 12. Ductless Filter Fume Hood (Grainger.com, 2020).

Figure 11. Charcoal Filter for Ductless Filter Fume hood (Grainger.com, 2020).

critical. VAV boxes have heating coils inside which alters the air temperature as it flows through and can change how much air flow it pushes through based on room conditions. Venturi valves have significantly more control and accuracy over these factors and, once initially balanced, require no periodic balancing or maintenance. Standard VAV boxes used in laboratory buildings can create many issues, such as slow response to changing room conditions, instability due to duct pressure variations, unbalanced systems which require additional maintenance and balancing services. VAV boxes in laboratory buildings also tend to be very inefficient. These are remedied with the installation of a venturi valve system, which are more precise, quicker to adjust, and do not rely on pressure within the duct. Venturi valves are also able to modulate airflow much quicker than VAV boxes, so when a fume hood is opened fully, the exhaust venturi valve can respond quickly to the need for more exhaust air, while the supply venturi valve can response to the need for increase make-up airflow to the room immediately, protecting the scientists from exposure to high concentrations of chemicals.

Figure 14. Image of Phoenix Venturi Valve (Phoenixcontrols.com, 2020)

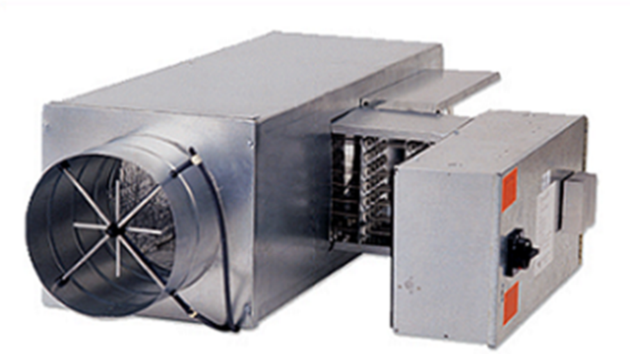

Figure 13. Typical VAV Box (york.com, 2020)

When looking at the cost of Phoenix Valves, it is difficult to pinpoint how much the installation of this kind of system would be in a building like Goddard Hall. As noted previously, there are no updated mechanical plans for this building, however a safe assumption would be that two venturi valves are necessary for every room in the building, one supply and one exhaust. Some smaller storage rooms may not end up needing a valve, some larger rooms will need more than one. Each ducted fume hood would also have a dedicated valve, as they come with complicated controllers that can monitor sash height, temperature and CFM of each fume hood. There are 86 rooms in the building and 77 ducted fume hoods so at least 172 venturi valves are needed. With venturi valves, you also need to factor in the cost of installation of the valve as well as the cost of controls installation. The approximate cost for purchasing venturi valves and controls would be $2,500 for a supply or exhaust valve, and closer to $7,000 for a fume hood dedicated valve. This does not include the cost of demolition and disposal of the existing system components, reworking of duct and engineering required to make this possible. This is by far the most invasive solution for the issues that Goddard Hall is facing, however it would also be the most comprehensive and beneficial overall. The HVAC control capability would be significantly more precise and sophisticated compared to what the building currently can do. Additionally, it would increase the supply air in the building, helping mitigate the excessive exhaust air. This solution would take several months of design and purchasing, and likely would be phased to avoid a total building shutdown. A budget cost for purchasing the venturi valves and controllers is around $430,000 for supply and exhaust valves, with an additional $539,000 for the 77 ducted fume hoods. However, money can be saved if there were fewer ducted fume hoods, and ductless filter fume hoods were implemented. While an initially costly improvement, the savings in the long run are astronomical. From discussions with practicing engineers, a similar upgrade on a similar college laboratory, cost roughly $350 per square foot with $10 per square foot for engineering. This building saw savings over $1.5 million dollars per year in energy costs alone and had a return on investment of 7% and would see the total return on investment in about 5 years. Using these metrics, this upgrade would cost WPI around $7,668,00. While this approach is the costlier than the others presented, it also leaves the most room for savings.

5.5 Recommendations Conclusion

While there are many other solutions possible to fix the problems seen in Goddard Hall, I have brought up and analyzed those that are the most cost effective and comprehensive solutions. For years, Goddard Hall has seen patchwork fixes that are intended to be temporary and quick solutions, and these have compounded and made the air control and negative pressure problems in the buildings worse and worse. By choosing a reasonable solution with a fair return on investment, WPI has the potential to make a serious impact in mitigating the issues in Goddard, making the building more updated, safer and comfortable for all the faculty and students who use it every day.

Solution	**Cost**	**Return on Investment**
New Controls System	~$100,000	5 - 6 Years
New High Performance VAV Fume Hoods	~$1,540,000	4 - 5 Years
New Combination of Ductless and High Performance Fume Hoods (1 Ducted per lab, rest Ductless)	High Performance: 27 * $20,000 = $540,000 Ductless: 50 * $3,000 = $150,000 Total Cost: $690,000	3 - 5 Years, due to much lower energy usage of Ductless Fume Hoods
New Venturi Valve Supply Air System	$7,665,000 ($969,000 for venturi valves alone)	Approximately 5 years in energy cost savings

Table 1. Cost analysis of proposed HVAC approaches.

6.0 Conclusions

The goal of this project was to perform a comprehensive review of the Goddard Hall HVAC systems and their insufficiencies as well as present reasonable solutions that WPI could pursue to remedy the problems noted in this report. From negative pressurization to patchwork repairs and equipment installation, Goddard Hall has suffered from a variety of issues for over 20 years. These existing conditions have compounded and left the building uncomfortable and potentially unsafe. Solutions like installing a new sophisticated supply air system, a new overall controls system or replacing fume hoods are potentially costly, but comprehensive and reasonable updates that could be funded and would make a significant impact on the HVAC systems overall control and effectiveness in the building. While funding and prioritization of multiple projects will always be an issue at institutions like WPI, it is time for a significant and comprehensive fix for the Goddard Hall HVAC system, which this report analyzes in depth. Further research on possible solutions, analysis of updated mechanical drawings and consultation of professional engineers are likely needed before any major movement on the institutes part but this report serves as an introductory look at the entire building, and at solutions that would positively impact the building and its occupants.

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Appendix A

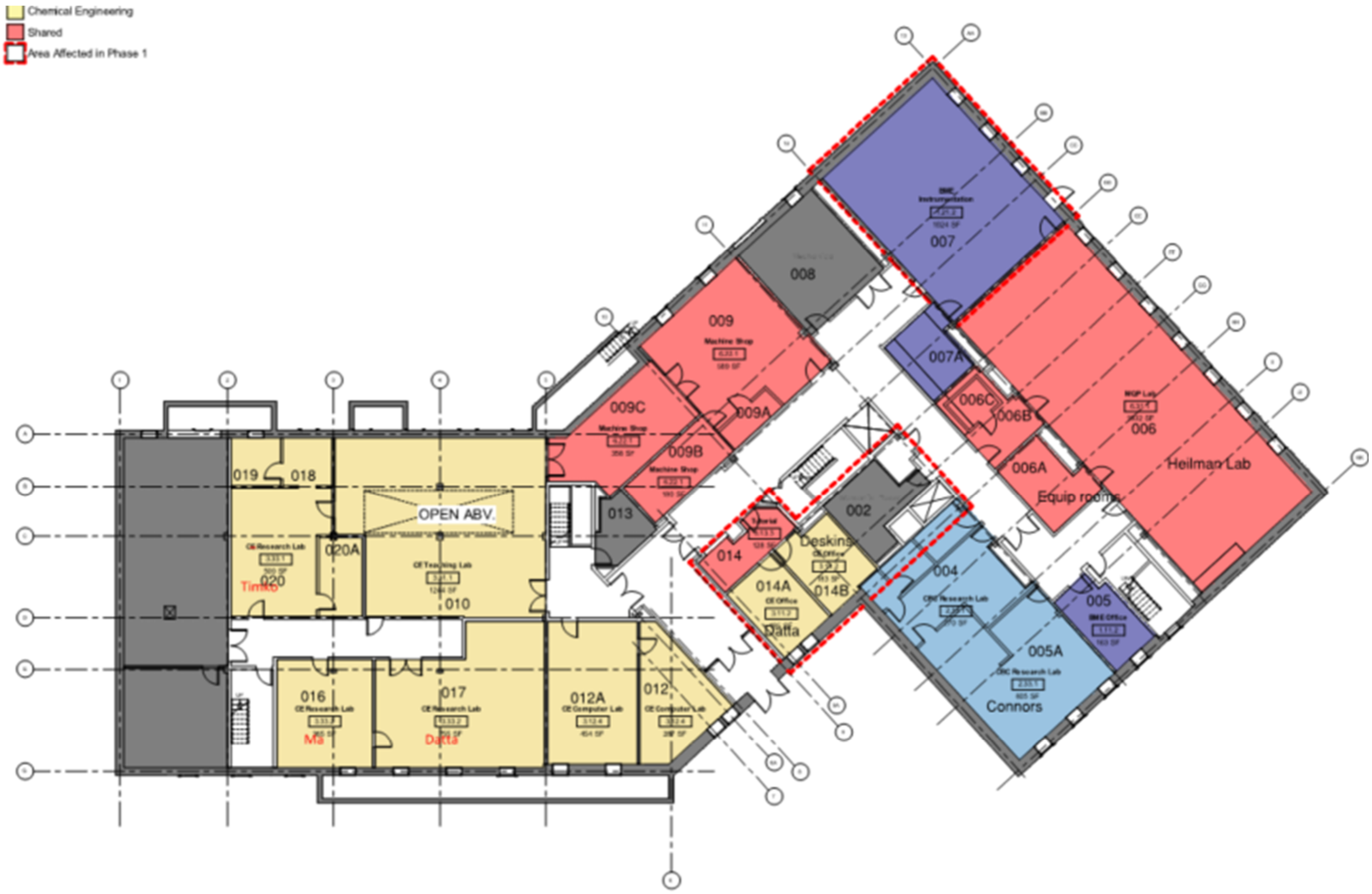

Figure 15. Ground Floor of Goddard Hall

Figure 16. First Floor of Goddard Hall

Figure 17. Second Floor of Goddard Hall

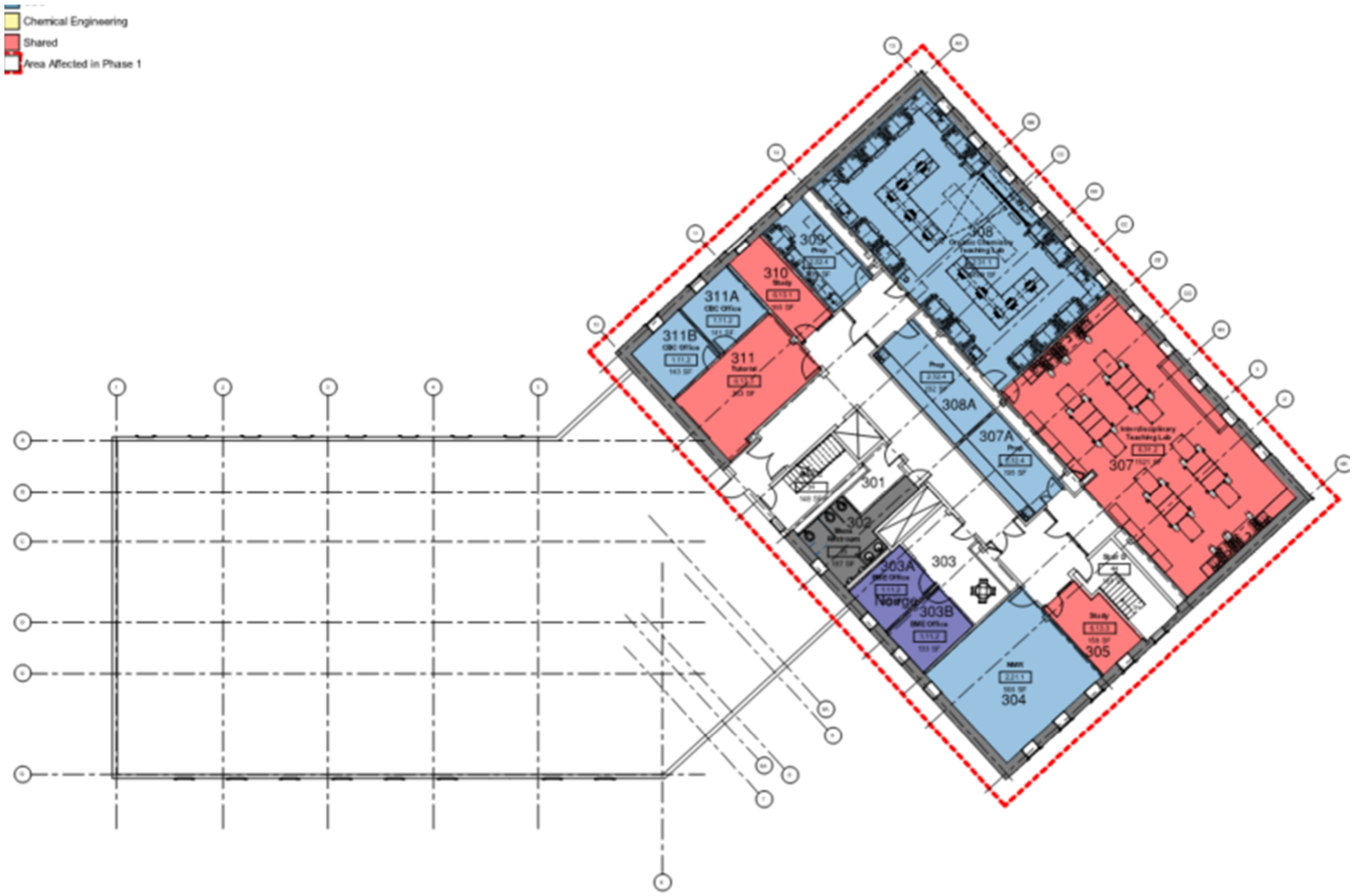

Figure 18. Third Floor of Goddard Hall