Energy Management Lighting & HVAC

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Executive Summary

The Chestnut Residence building at 89 Chestnut St., a University of Toronto (UofT) building, has poor energy efficiency on the 27th and 28th floors. The redesign scope is limited to the outdated glass walls from 1971, HVAC, and lighting systems, which have been identified as the major contributors towards energy loss through research and client communication. Notably, this goes against the UofT's sustainability goals. That is why our client, Isaias Franco, the manager of building operations, proposed a project to optimize the systems of these floors within a $500,000 budget.

Key stakeholders in this project include the UofT Sustainability Office, government bodies, and the many building managers. These groups hold influence and impact over the project, as it will help solidify UofT's reputation as the most sustainable university in the world.

The redesign will be carried out on the top 2 floors of the 28-story building in downtown Toronto. Factors such as temperature, wind, and sunlight are therefore taken into consideration for the service environment. The 27th floor is used as a student gathering space with sofas and vending machines, while the 28th floor is for quiet study, with an open area and bookable study rooms.

The redesign's primary function will be to maintain the indoor environment. Secondary functions include providing adjustable heating/cooling and lighting and insulating. Therefore, the main objectives involve reducing total energy consumption by 1% monthly and maintaining a uniform floor temperature within the range of $\pm$ 1℃. The main constraints involve abiding by government building codes, ensuring sufficient air quality, and implementing an appropriate temperature.

The proposed solution is a Heat Recovery Ventilation Integrated Smart Glass System, selected out of 56 potential full solutions and 3 alternative designs. Using daylight harvesting systems, electrochromic glass, and smart ventilation with CO_2 monitoring, it effectively integrates multiple robust energy-saving technologies. The system actively adapts to and harnesses the potential of its ever-changing environment, while the 2 alternatives take a more passive approach. It is also a practical and convenient design, requiring less major infrastructure changes than the alternatives but providing better results.

Success will be measured using Building Energy Modeling (BEM) software, which simulates energy use under various climate conditions. By comparing the baseline model of the current layout against the proposed design, the team can quantify reductions in HVAC load and lighting consumption. Specifically, the team will assess if monthly energy usage (measured in gigajoules per month) is reduced by at least 1% the new design solution to conclude that it is sufficient in solving the design problem.

1.0 Introduction

The 27th and 28th floors of the Chestnut Residence building require an improved energy management system due to existing HVAC, glass walls, and lighting systems. The current design does not align with UofT's sustainability goals and contributes to high operating costs. Isaias Franco, the Manager of Building Operations, has proposed a redesign to modernize the building.

This report analyzes the problem's key aspects, including the problem statement, stakeholder interests, the service environment, detailed requirements, the idea generation process, alternative design selections, the final proposed conceptual design specification, and measures of success.

2.0 Problem Statement

The Chestnut Residence building's 27th and 28th floors have large, outdated glass walls around the perimeter which cause significant heat loss in the winter and cooling loss in the summer. The HVAC system operates continuously to compensate, resulting in higher energy consumption (Appendix D). Additionally, the lighting system operates 24/7, using electricity when natural daylight is available or spaces are unoccupied. Figure 1 shows the dimensions of the floors [1].

The gap is a lack of an energy conserving design on the 27th and 28th floors of Chestnut Residence.

The need is a means to conserve energy year-round that follows UofT's sustainability goals. Specifically, there needs to be a means to retain heat in the winter, cool air in the summer, and to reduce lighting energy consumption.

The scope includes the glass walls [2], the HVAC system [3], and the lighting system [4]. These three items were found to be key factors to improving energy efficiency based on research and our client meeting. They are located on the 27th floor, a student study/socializing area, and the 28th floor, which is a quiet study space with an open area and bookable study rooms. The floors are connected by a stairway and escalator which are not in scope. The lighting in that space is also not in scope. The design must not exceed $500,000.

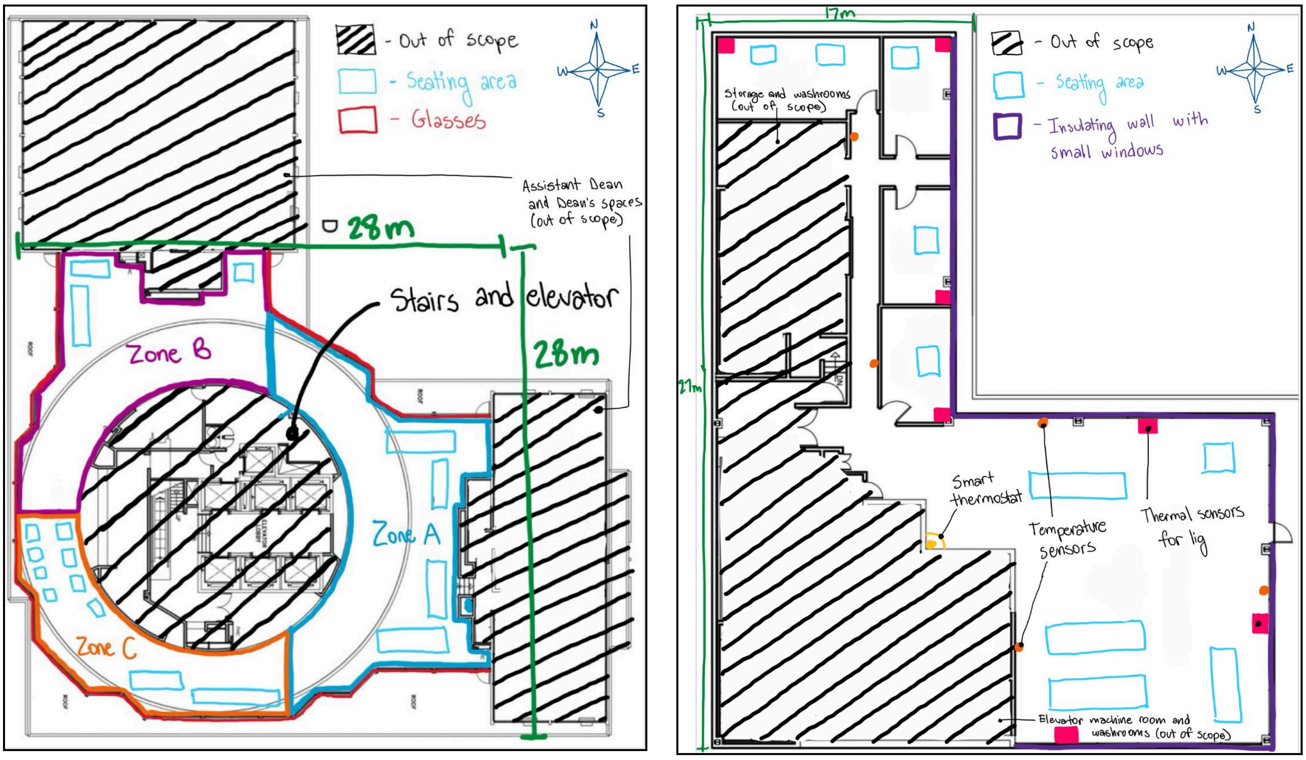

Figure 1. Floor Plans for the 27th (left) and 28th (right) floor.

3.0 Service Environment

The two floors are the highest of the university residence at 89 Chestnut St, in downtown Toronto.

3.1 Physical Environment

The year-round effectiveness of a design requires addressing the challenges posed by climate. Toronto's temperature and wind speed are characterized in the following figures.

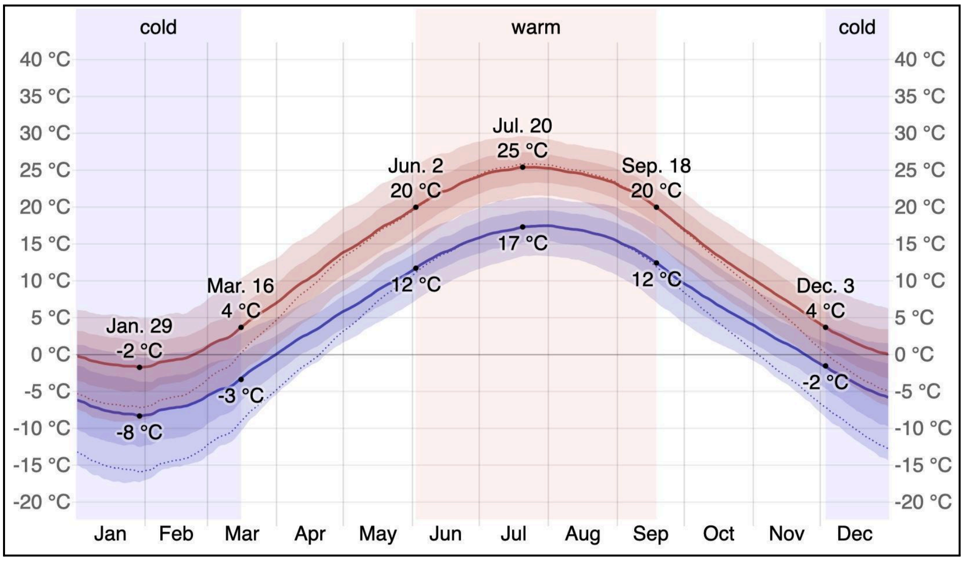

Figure 2. Average Weather Year-Round in Toronto 2017 - 2024. [5]

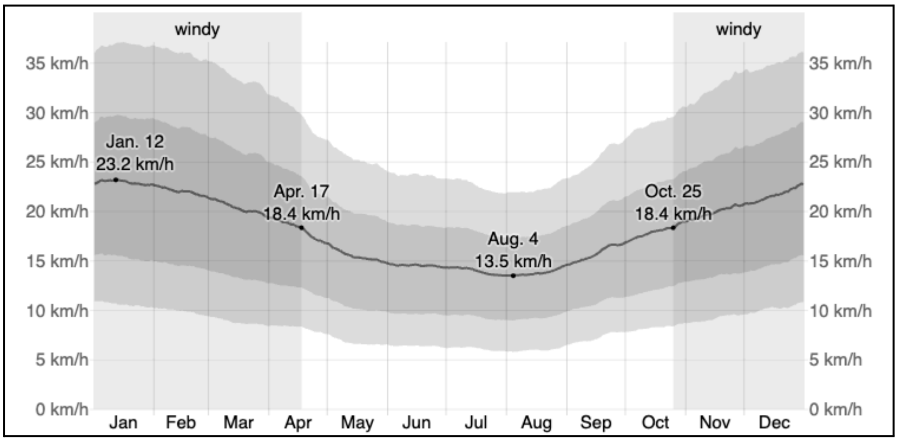

Figure 3. Year-round Environment Wind Speed in Toronto 2017 - 2024. [5]

Additionally, the current state of the glass walls, HVAC, and lighting system are examined below.

3.1.1 Glass Analysis

The current glass walls are dual-layered insulating glass units (IGU), the earliest from 1971. IGU's have an expected lifespan of 20-30 years. Past this, there will be thermal bridging and other frame effects in the glass that reduce insulating properties [6]. Figure 5 shows the types of glass according to the color scheme in Figure 4.

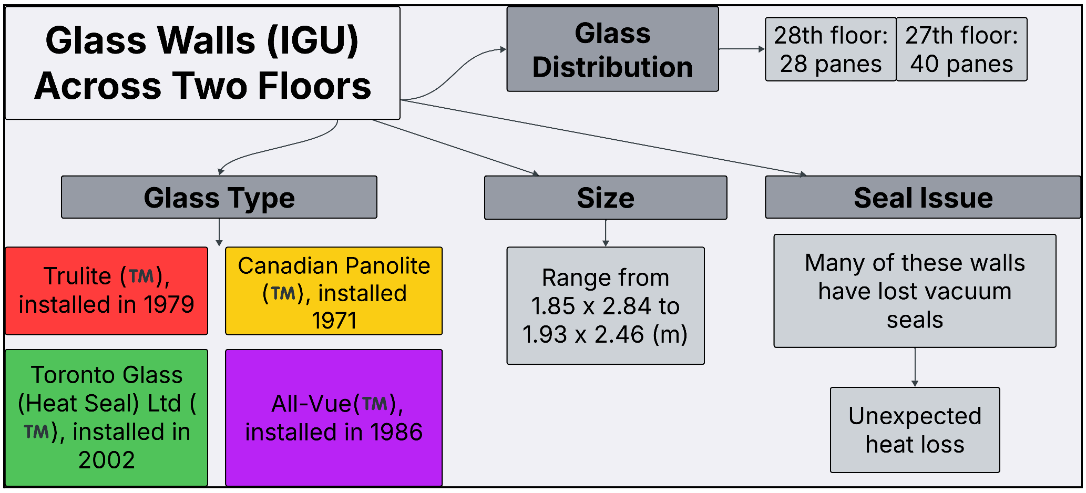

Figure 4. Breakdown of current glass walls. [7]

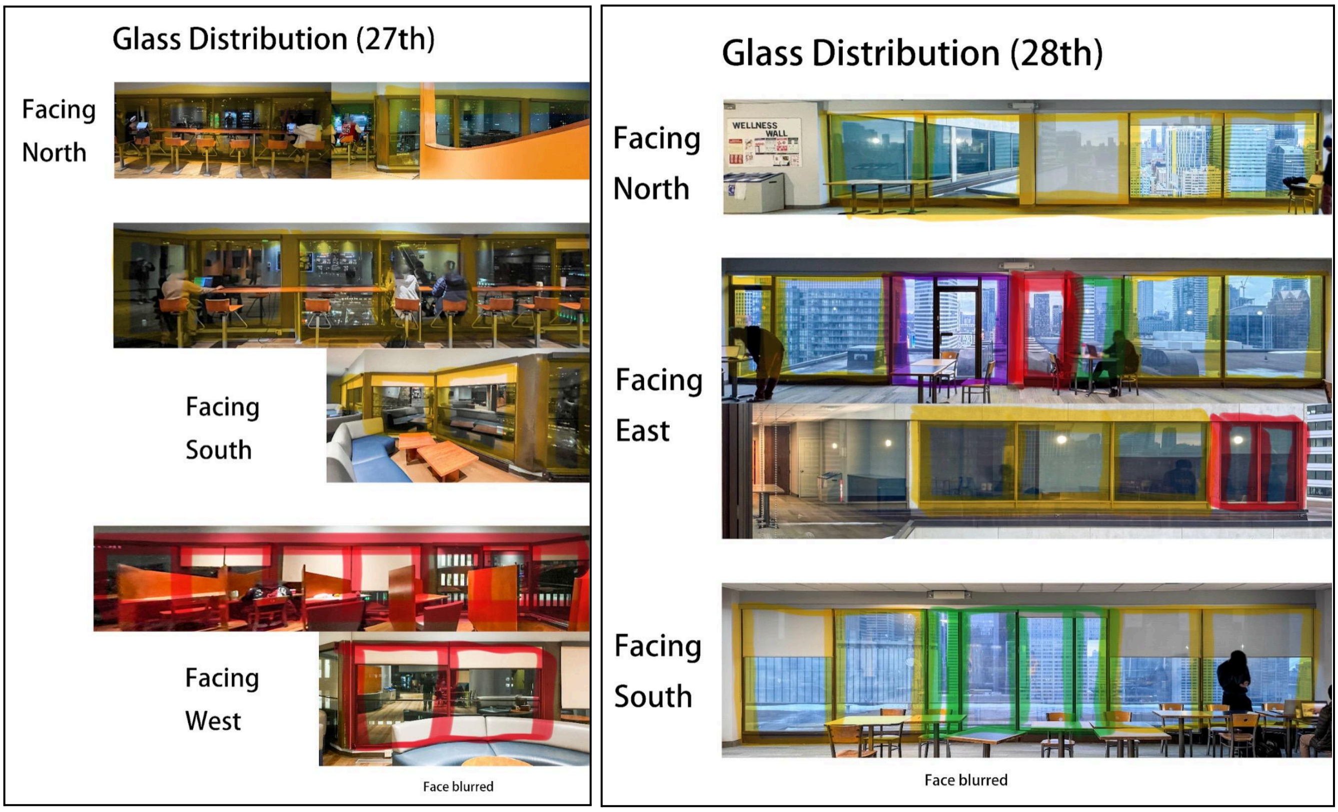

Figure 5. Types of glass on the 27th and 28th floor (colored as shown in Figure 4).

3.1.2 HVAC System

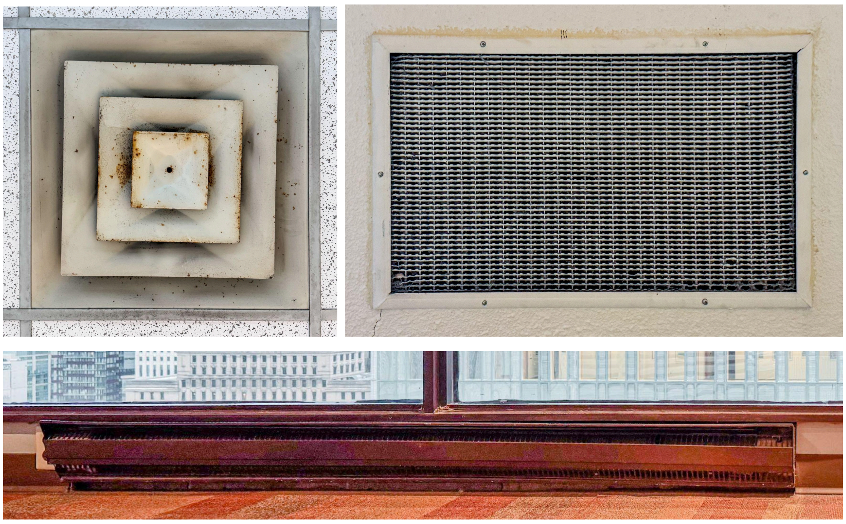

Figure 6. Square Ceiling Diffuser (28th); Return Air Grille, Baseboard Heater (27th).

The HVAC system utilizes vents on the ceiling and radiators that line the bottom of the walls. It is evident the system is fully operational on both floors.

3.2 Lighting System and Evaluation

The lights are perpetually running. The current types of electrical lights are shown in Figures 7 and 8.

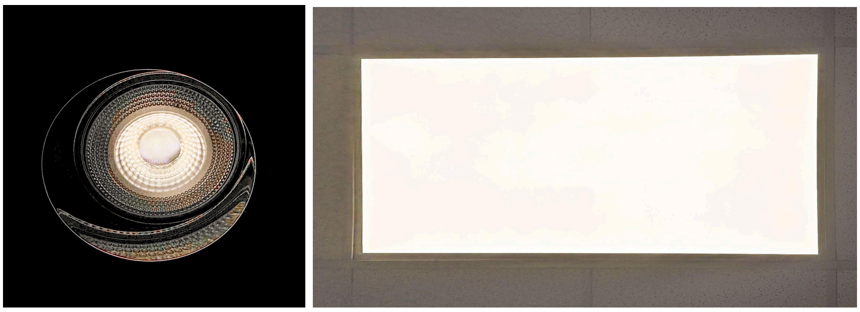

Figure 7. Recessed Spotlights and LED Ceiling Panel Lights on 27th floor.

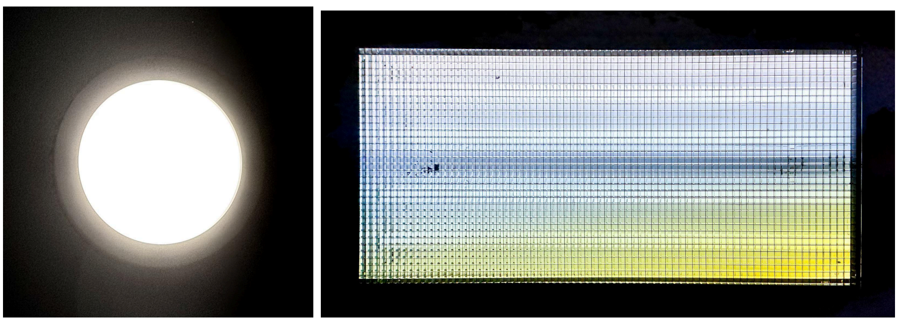

Figure 8. LED Slim Panel Light and Fluorescent Troffer on 28th floor.

The floors include lights that provide different levels of illumination (measured by Light Meter app [8]).

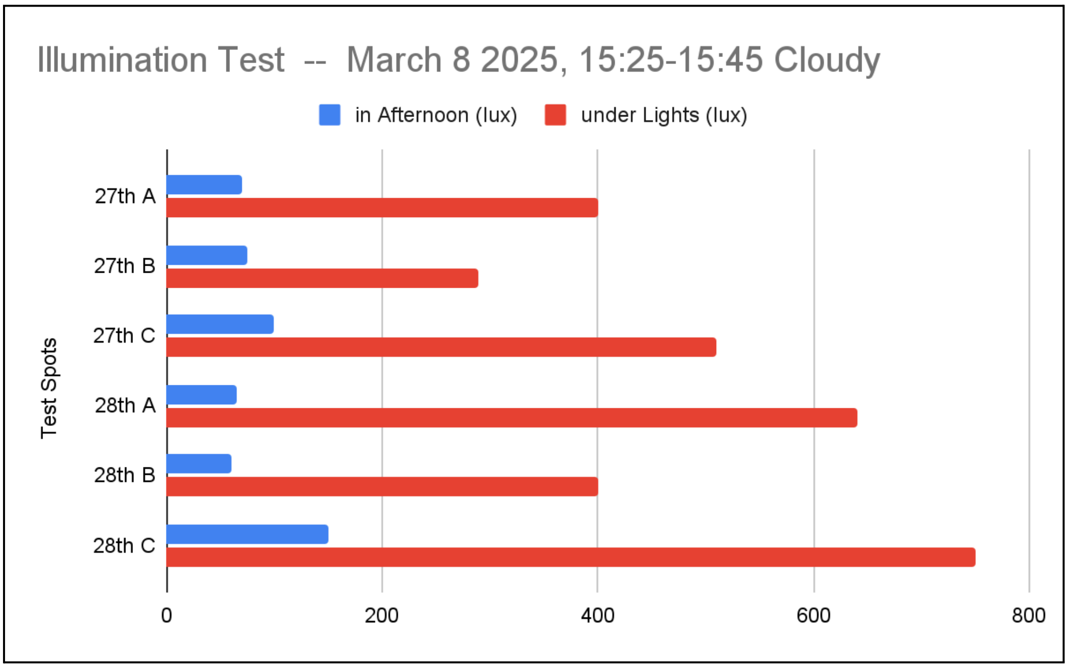

Figure 9. Illumination evaluation.

3.3 Human Environment

The usual occupancy levels of both floors were measured or derived from familiarity. High/Low counts are from 6:00 pm-10:00 pm and 2:00a m-7:00 am, respectively. Important points are summarised in the following table:

Table 1. Occupancy levels

	Max capacity	Weekday high/low	Weekend high/low
27th	100	40/5	60/15
28th	32	10/2	25/5

3.4 Virtual Environment

UofT's wifi network covers both floors. The upload and download speeds are shown below. (Measured by Speedtest app [9]).

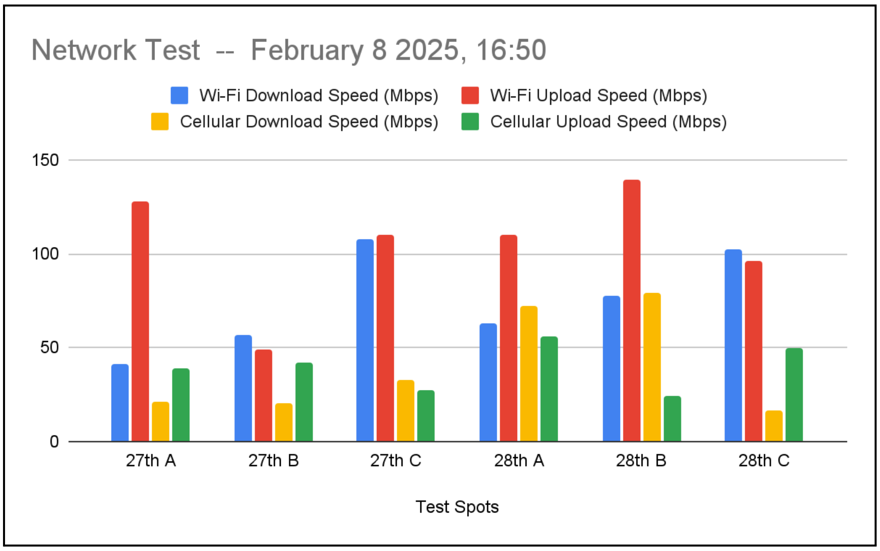

Figure 10. Download and upload speeds.

Other observations less relevant to the design, including noise levels and network latency can be found in Appendix E.

4.0 Stakeholders

The primary users of this design are Chestnut residents who will use the space on the 27th and 28th floors. Additionally, there are stakeholders who influence and/or are impacted by this project. The primary stakeholders are summarized in Table 2, after being brainstormed using an interest-impact graph (Appendix B). Additional stakeholders are in Appendix A.

Table 2. Summary of Stakeholders Ordered by Decreasing Influence.

Stakeholder	Influence	Interest/Impact
UofT Sustainability Office	High: - Property of UofT - Promotes its agenda to improve sustainability [10]	High: - Office aims to maintain UofT's reputation as the #1 most sustainable university in the world [11]
Director of Residence Operations	High: - Oversees planning, budgeting, and drafting proposals [12]	High: - Design adds to their job responsibilities
Residence Manager of Finance	High: - Helps director in overseeing budgeting and planning [13]	High: - Design adds to their job responsibilities
Ministry of College and Universities	High: - Provides funding to UofT, directly influencing budget [14]	Low: - Unaffected by design

Ministry of Municipal Affairs and Housing	High: - Design must obey building codes and regulations [15]	Low: - Unaffected by design
Maintenance crew	Low: - No authority over the project	Medium: - Change in building systems may result in change in maintenance operations

5.0 Detailed Requirements

This section outlines the various functions, objectives, and constraints of this project.

5.1 Functions

By employing the Black Box Method (Appendix C), the functions have been identified below.

Table 3. List of functions

Primary Function	Secondary functions
• The design will maintain an indoor environment	• Provide heating/cooling • Provide lighting • Provide ventilation • Protect from weather elements

5.2 Objectives

Objectives listed in Table 4 provide measurable goals for a sustainable design. They were ranked using a pairwise comparison to summarize crucial objectives (extended list in Appendix F).

Table 4. Objectives

Objectives	Goals	Metrics	Justification
Should reduce HVAC energy consumption.	Reduce energy consumption of building by 1% monthly	Compare monthly energy bill after design implementation to baseline	Client expressed a desire to reduce energy by this specific amount [3]
HVAC should adapt performance depending on the outdoor temperature.	Consume less electricity for cooling cool on cold days, and for heating on hot days	Measuring a high SEER2 rating of 13 to 21 [16]	SEER2 measures the average efficiency over a range of temperatures

HVAC should maintain even cooling and heating throughout the floors	Temperature throughout the floor is uniform within the range of ± 1℃	Measuring a High CFM value under : 5,000 to 9,000 CFM [17]	CFM Measure airflow velocity to determine if air is properly circulating.
Glass should enhance the thermal efficiency of windows	Reduce heat loss/gain by 7%-15% [18]	Measuring an R-value of glass greater than R-5 [19]	R-value is the Insulating value of a material
HVAC should adapt performance to occupancy	Set HVAC's cooling/heating to a minimum of 30% - 50% of the maximum air-flow rate when occupancy is minimal [20]	Measuring HVAC's air flow's ft^3/min	HVAC costs can be reduced with real-time occupancy data, optimizing HVAC systems by responding to conditions in the building.
Lighting should minimize energy consumption	Implementing 1.5 - 2 watts per square foot throughout the floors [21]	Dividing total wattage by square footage	Allows for adequate brightness while minimizing energy consumption
Lighting should adapt to the outdoor environment conditions	Save 40% of lighting energy [22]	Measuring high Gain adjustment on lighting systems	Gain determines how much the lights will dim when daylight is present [23]

5.3 Constraints

The design of the 27th and 28th floors must comply with multiple constraints to fit within the scope of the project.

Table 5. Constraints

Constraint	Metric	Justification
Abide by the Building Code Act from the Government of Ontario [24]	Chapter 34 must be used "to establish standards for public health and safety, fire protection, [and] structural sufficiency." Chapter 28 must be used to decide on building materials [25]	Must pass Toronto Building Inspection [26]
Indoor air quality	ANSI/ASHRAE Standards 62.1 and 62.2 must be used to create a ventilation system that ensures an air quality index of 100 [26]. This is required by law. [27]	Seniors, children, and people with lung or heart disease must not report health effects after prolonged exposure to these rooms.

HVAC temperature range	Must maintain a maximum of 26°C between June 2 to September 14. Must maintain a minimum of 21°C between September 15 to June 1 [28]	Health outcomes such as sleep disorders, blood pressure, respiratory and cardiovascular disease, and general health problems must not be reported after prolonged exposure to these rooms.
Students have no control of the lighting	Lighting must be controlled by the Chestnut Residence building operators	Client specified that students must not have control of the new lighting system
Budget is not exceeded	Budget of $500,000	Client imposed budget

6.0 Generation, Selection and Description of Alternative Designs

This section details the structured approach to ideating, refining, and selecting designs for the 27th and 28th floors of the Chestnut Residence. This includes methods for generating multiple ideas, criteria for selecting the most ideal solutions, and detailed descriptions of the final three designs.

6.1. Idea generation Process

We began by generating ideas to meet each function individually and as a team. Random stimulation was used to expand the design space with unconventional means. ChatGPT was used to generate additional means for each secondary function (Appendix Q). In the end, we combined our generated ideas in a morph chart (Appendix G) and used the SCAMPER model (Appendix H) to generate additional solutions.

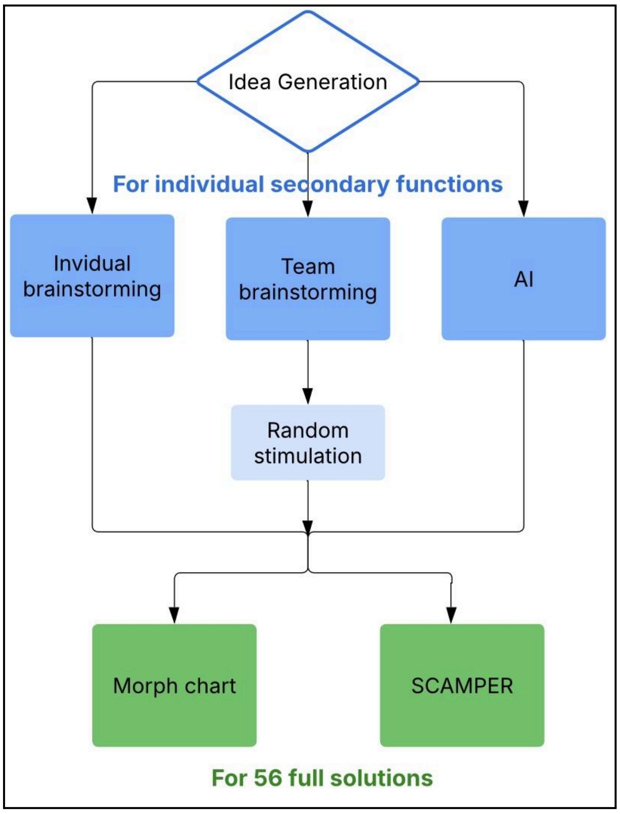

Figure 11. Idea generation process.

These full solutions were organized into three categories based on the extent of change they would make to the current system. This categorization is summarized in Figure 12, and the full list of solutions is in Appendix I.

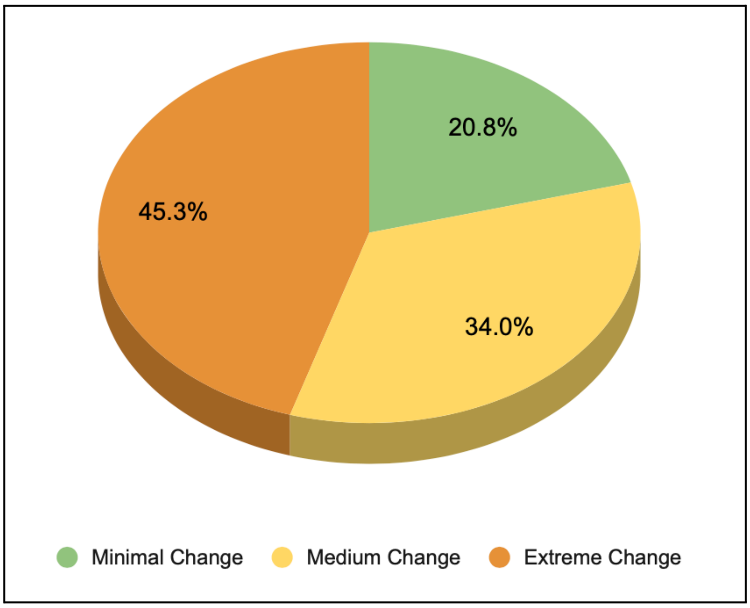

Figure 12. Categorization of full solutions.

6.2 Alternative Designs Selection Process

The design space was narrowed through consolidation (Appendix J), feasibility (Appendix K), multivoting (Appendix L), and a weighted decision matrix (Appendix M) to select three strong alternatives.

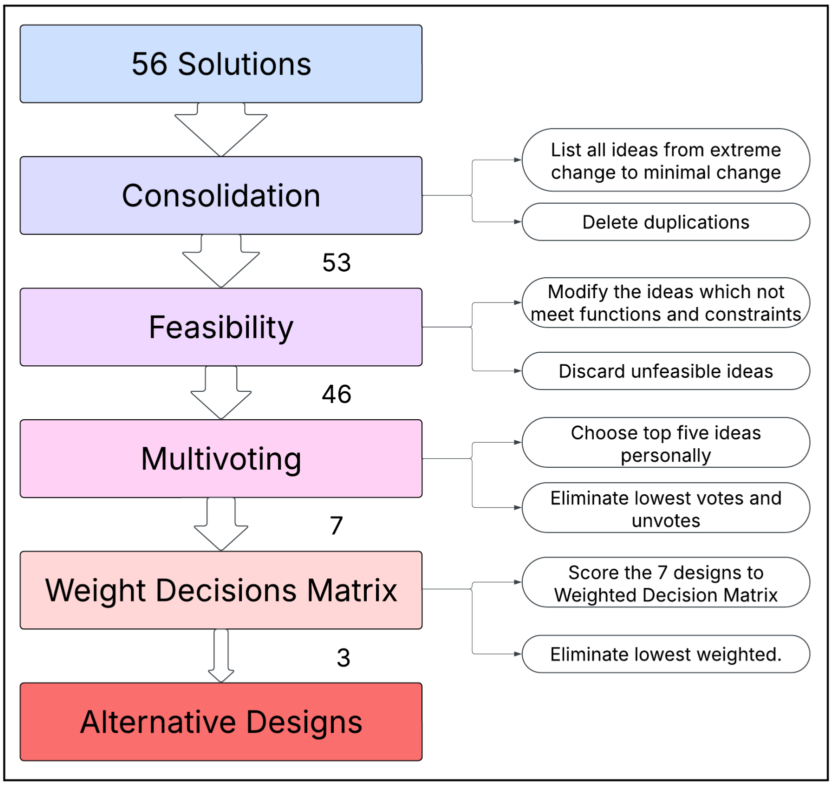

Figure 13. Idea selection process.

During multivoting, team members voted on the solutions that they perceived to meet the objectives the best. Three alternative designs were then selected using a weighted decision matrix that ranked these solutions based on how they fulfilled the objectives, with the highest weighted objectives being reducing operating costs and HVAC energy consumption.

6.3 Alternative Design Descriptions

Our three alternative design solutions are outlined below. Fulfillment of specific detailed requirements by each alternative design is outlined in Appendix N.

6.3.1 Solution 1: AI Based Control System

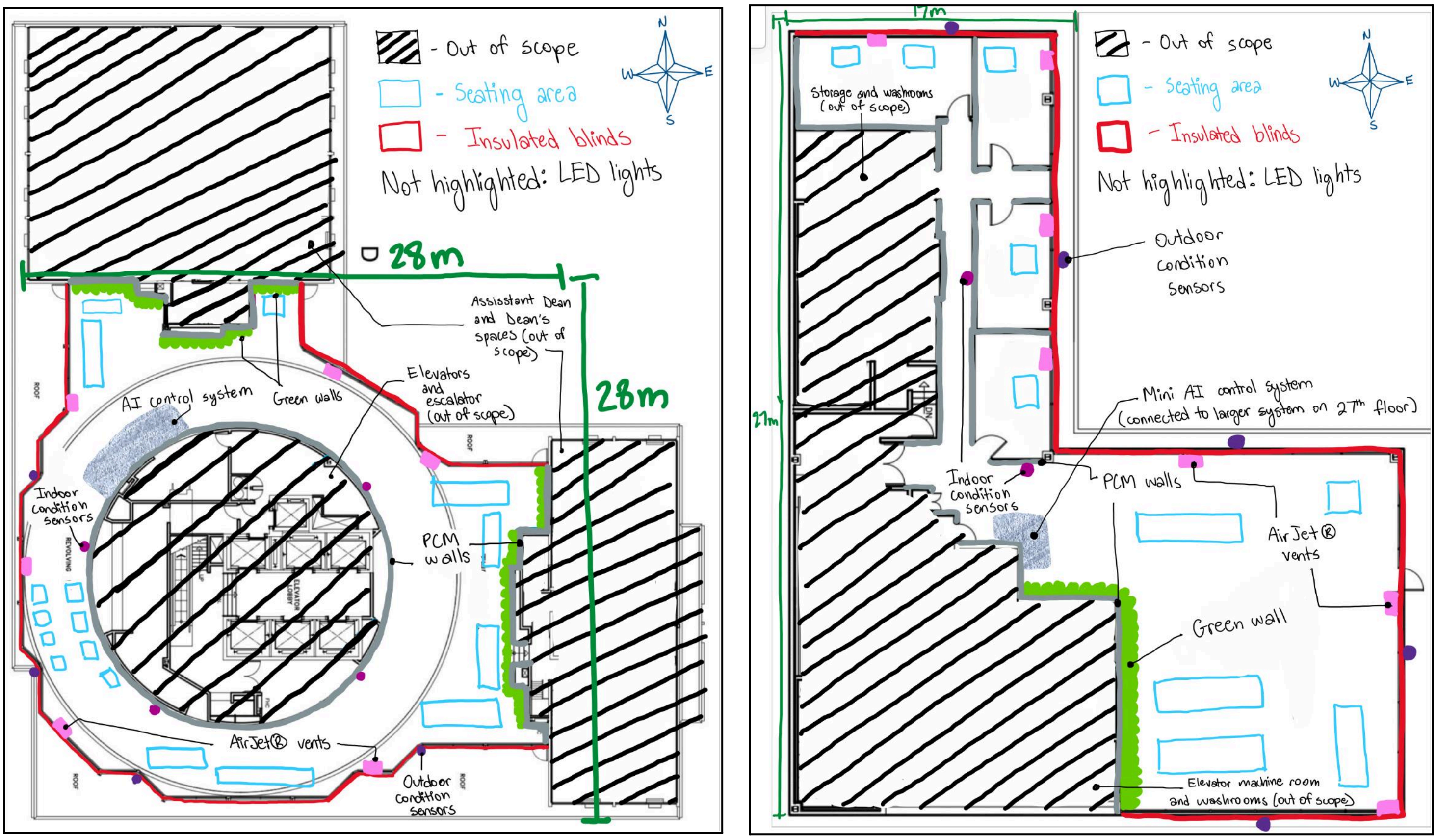

Figure 14. Floor plan of Solution 1 on the 27th (left) and 28th (right) floors.

This solution implements AI based systems in addition to the current HVAC and glass system, and replaces the current lighting system with LED lighting, in order to increase energy efficiency.

Firstly, green walls (Figure 16) add natural air purification [29], and are maintained by an AI controlled spray system. The phase change material (PCM) interlayer (Figure 17) passively regulates temperature by absorbing and releasing thermal energy based on ambient conditions [30]. The AI-controlled AirJet® ventilation system [31] (Figure 18) reduces heat on glass surfaces and enhances indoor air circulation using high-efficiency particulate air filters (HEPA) [32]. Altogether, they decrease the dependency on the current HVAC system.

For supplemental lighting, high-efficiency LED panels [33] provide uniform illumination of high lux levels when natural light is insufficient.

Additionally, the blinds system installed behind the windows, made from insulating aerogel material [34], (Figure 19) is opened partially/fully/closed based on indoor illumination and heating needs.

At the core of this design is an AI control system, which analyzes both outside climate conditions, and inside conditions (temperature, air circulation, oxygen, occupancy, and illumination levels) to control each element of the design.

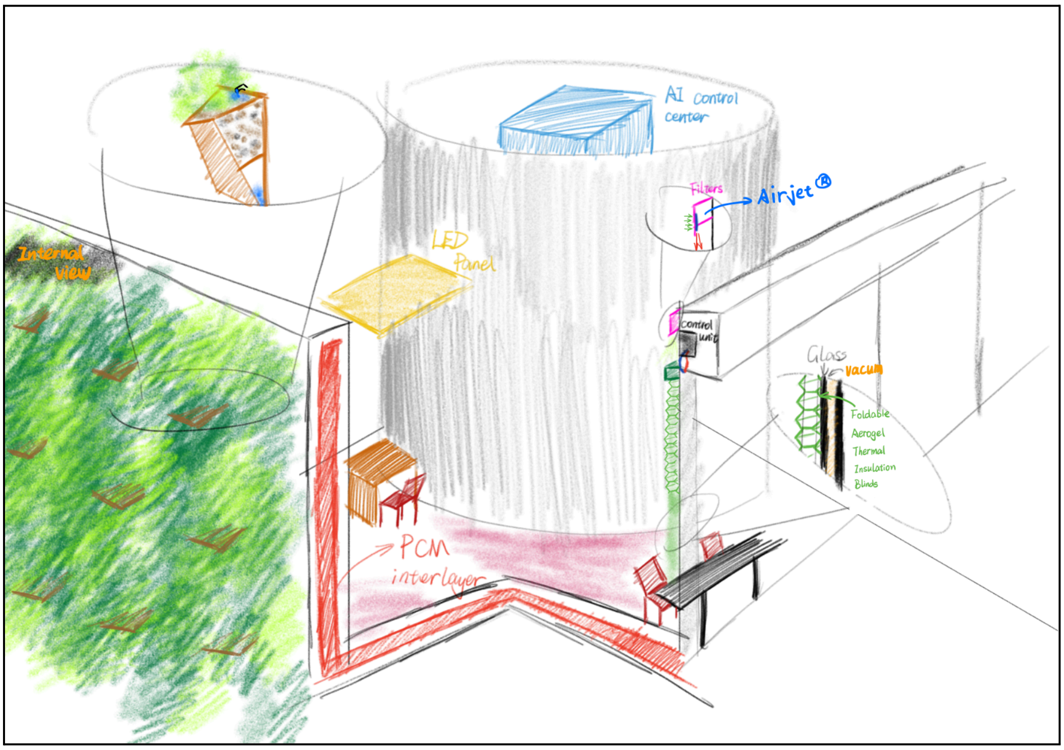

Figure 15. Schematic diagram.

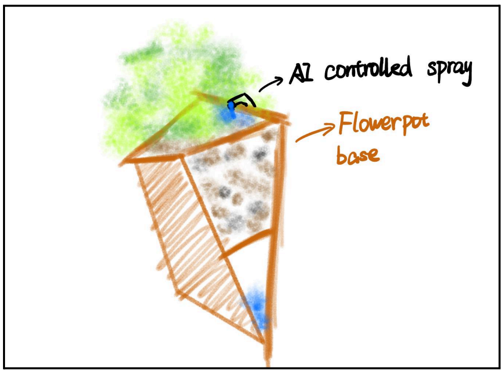

Figure 16. Green wall.

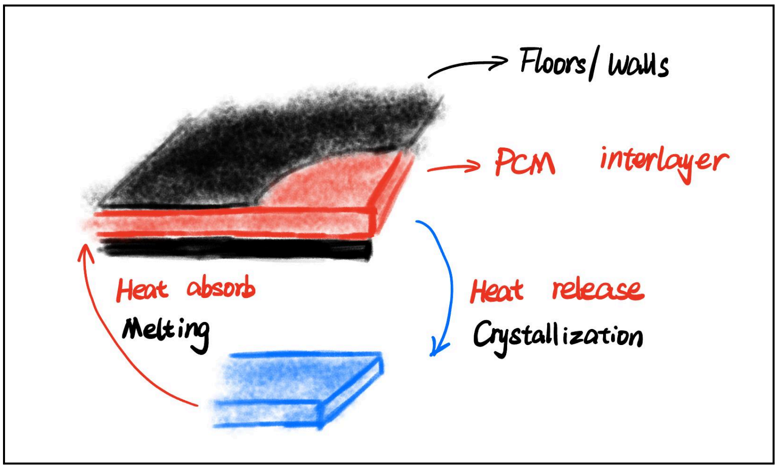

Figure 17. PCM interlayer.

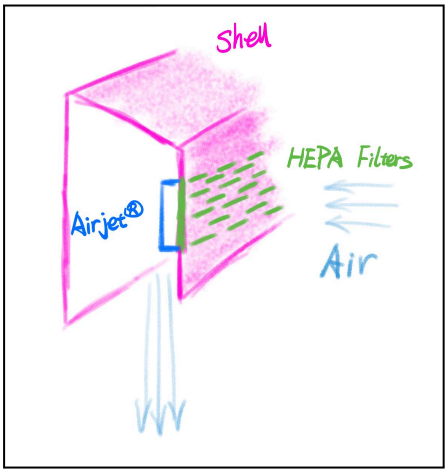

Figure 18. AirJet® vent.

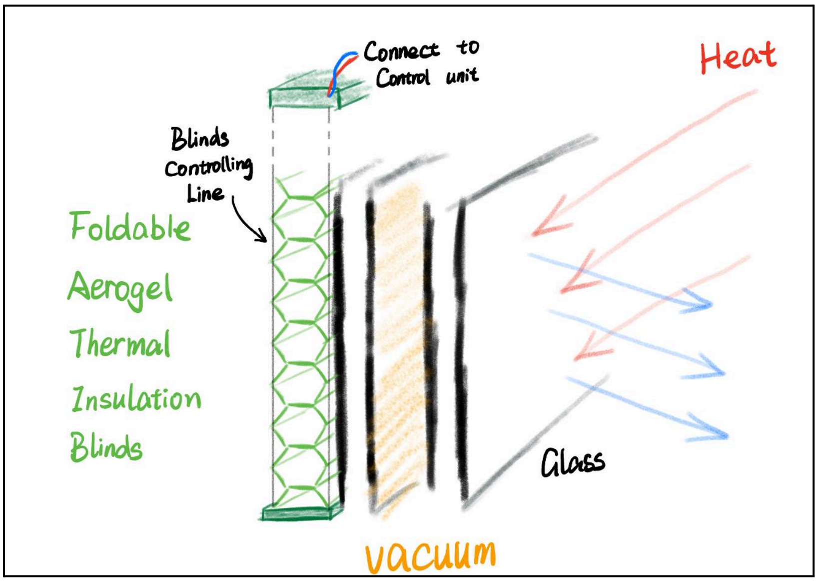

Figure 19. Insulated blinds.

6.3.2 Solution 2: HRV Integrated Smart Glass System

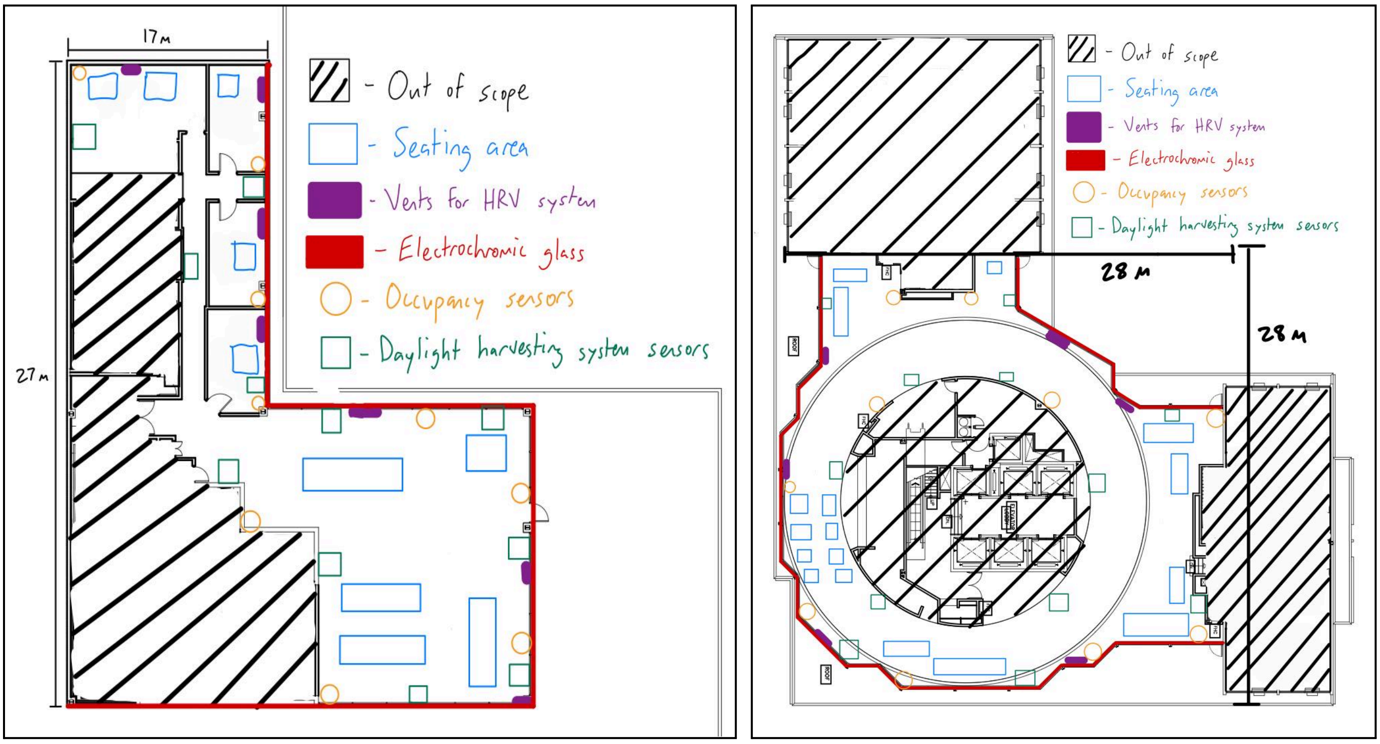

Figure 20. Floor plan of Solution 2 on the 27th (right) and 28th (left) floors.

This energy management solution integrates an advanced HVAC integrated heat recovery ventilation (HRV) system, occupancy sensors, daylight harvesting systems, and electrochromic glass.

Firstly, the HRV system provides heating, cooling, and ventilation. HRV is used in multi-unit residential buildings to improve indoor air quality while enhancing energy efficiency [35]. An Infinity® Variable Ultimate Cold Climate Heat Pump (Infinity® Heat Pump) (Figure 21) provides precise temperature control with its variable-speed technology and exceptional cold-climate performance, maintaining 100% heating capacity [36]. This is combined with a Performance™ Energy Recovery Ventilator (Figure 22: Performance™ ERV), which exchanges indoor and outdoor air while recovering energy from exhaust air to condition incoming fresh air [37] .

Furthermore, Lutron Caseta® occupancy sensors [39] automate the HVAC system and adapt heating and cooling based on real-time occupancy data [38], reducing HVAC load when spaces are unoccupied. These sensors are strategically placed in regions with high activity like corridors and seating areas.

Additionally, an LED daylight harvesting system will be implemented. This system will have sensors by LUTRON® [40] placed throughout the floors to read the light levels of both natural and artificial light.[41]. The system will automatically dim or brighten LED lights accordingly, reducing reliance on artificial lighting.

Finally, electrochromic glass (Figure 23), a type of glass which changes its tint or transparency and transmittance in response to external conditions such as daylight and solar heat, will be installed [42]. This will reduce HVAC energy consumption and optimise natural lighting within the floor [43].

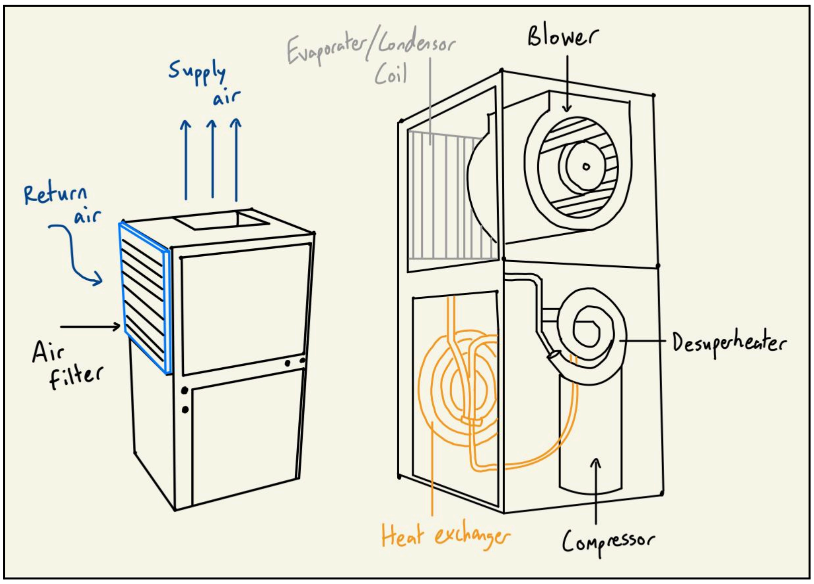

Figure 21. Infinity® Heat Pump.

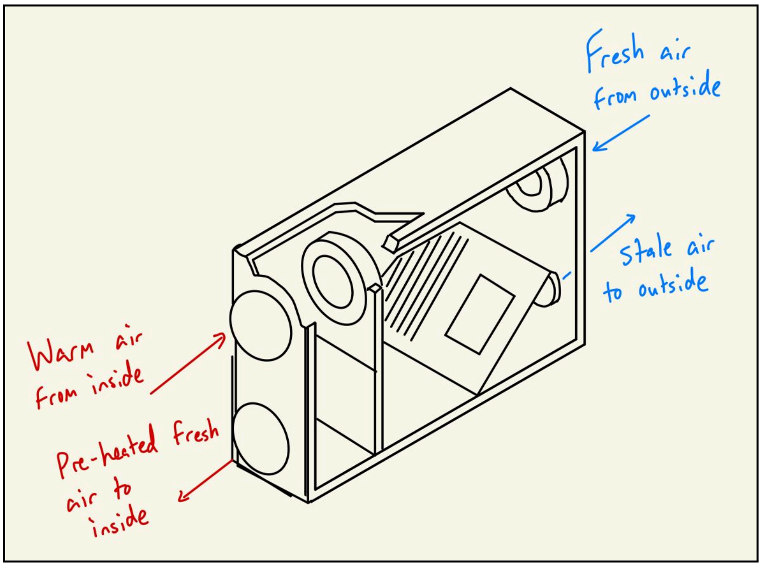

Figure 22. Performance™ Energy Recovery Ventilator.

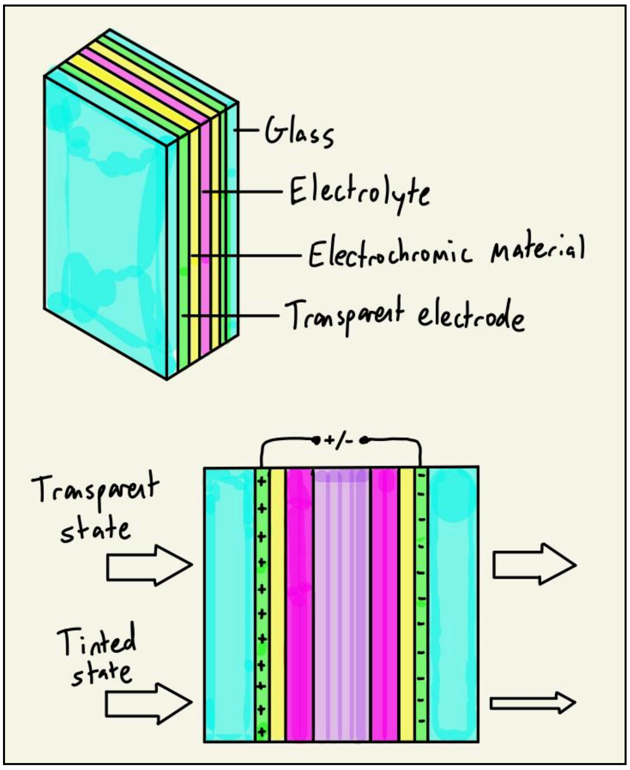

Figure 23. Electrochromic glass.

6.3.3 Solution 3: Automatic Thermostat and Light System

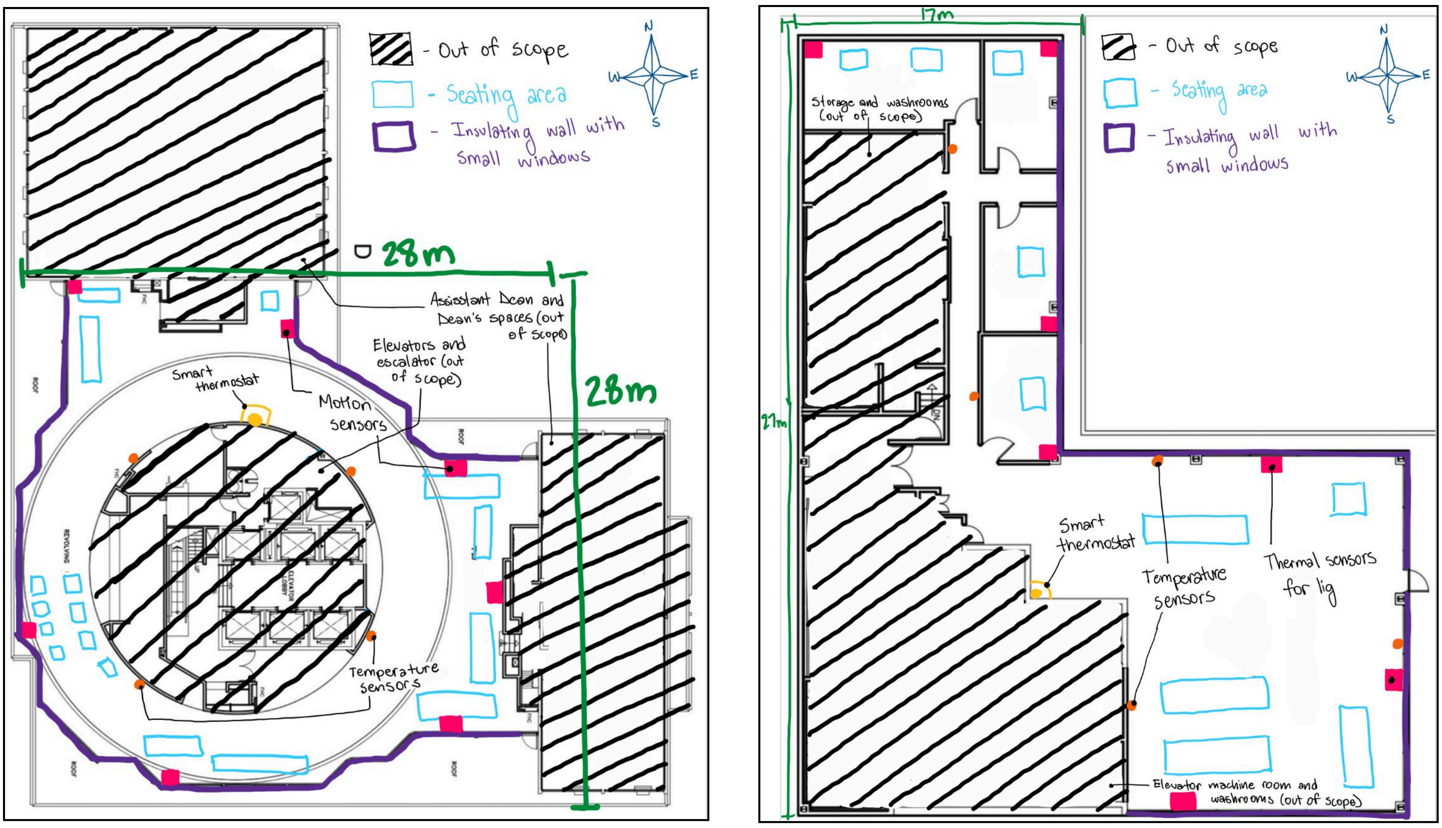

Figure 24. Floor plan of Solution 3 on the 27th (left) and 28th (right) floors.

This solution integrates an entirely automatic system that consists of smart thermostats, motion-sensing lights, insulated concrete walls instead of glass walls, and the original HVAC design.

Firstly, smart thermostats (Figure 25) continuously adjust their setpoint based on ambient temperature and preset building occupancy patterns as a means of reducing energy consumption. [44]. An ecobee® thermostat will be used for this application [45]. They will also be configured with a passcode to prevent student control.

The original HVAC system features no structural changes. However, the smart thermostat will always reconfigure HVAC performance and fresh-air exchange rates to maintain a consistent indoor environment. This effectively reduces the building's carbon footprint [46].

Moreover, motion-sensing lights adjust to occupancy levels to conserve electricity. These sensors are installed in corridors and seating areas to ensure illumination is only provided where necessary. Multiple Lutron Radio Powr Savr® Occupancy Sensors will accomplish this task [47].

Finally, glass walls will be replaced with concrete wall sections with smaller windows for better insulation (Figure 26). Standard walls have R-values between 20 to 30, many times better than quality IGU's [48]. These walls will also be insulated with rigid polyurethane foam boards [49]. Canadian company Prevost will then provide updated IGU's for the windows [50]. Together, these components effectively limit heat transfer and reliance on HVAC [51].

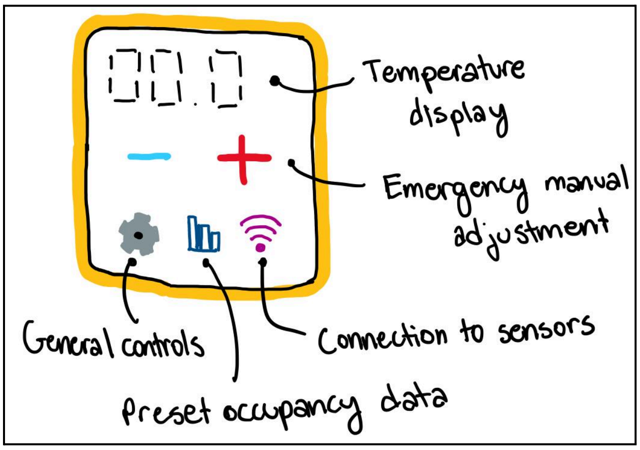

Figure 25. Smart thermostat.

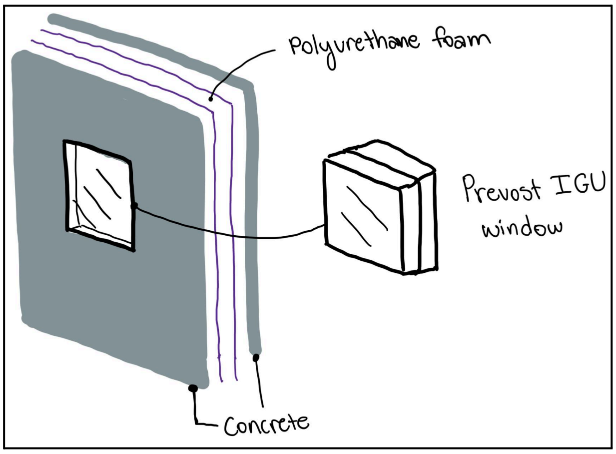

Figure 26. Insulating wall with small window.

7.0 Proposed Conceptual Design Specification

By the Pugh Chart (Appendix O), Solution 2 (S2): HRV Integrated Smart Glass System was chosen as the proposed design. It integrates multiple energy-saving technologies most effectively, as concluded by the Pugh Chart.

Unlike S1, which enhances HVAC efficiency through passive (green walls and phase change materials) technologies, S2 employs an active HRV system that simultaneously improves ventilation and recycles energy from exhaust air. It also uses occupancy sensors to reduce HVAC load when occupancy is low, which is where S3 falls short.

In terms of lighting efficiency, S2 utilizes daylight harvesting, leveraging light sensors to dim lights when sunlight is prevalent to reduce lighting energy consumption. Electrochromic glass helps to take full advantage of sunlight to reduce HVAC load by dynamically adjusting its transparency to control solar heat gain. S3 does not harness sunlight's potential and ignores possible energy savings from daylight harvesting. S1 uses blinds which are not as robust as electrochromic technology.

Finally, both S1 and S3 involve significant infrastructure modifications (ex. green walls, PCM interlayers for S1, addition of concrete walls for S2) while S2 offers a more practical implementation making it the most efficient and convenient design which follows the budget constraint (Appendix P).

8.0 Measures of Success (MOS)

The goal of this test plan is to evaluate the effectiveness of the design solution in fulfilling our top objective: reducing HVAC energy consumption. We will do so through a process called Building Energy Modeling (BEM). BEM is the practice of using simulation software to perform detailed analysis of a building's energy use using a simulated representation of a building. EnergyPlus, a building energy simulation program that engineers use to model energy consumption [52], will be used to do so.

1) Conduct research to gather data on the current system. Contact the client, conduct a site visit, and complete external research to gather manufacturer specifications of the current glass and HVAC system (coefficient of performance, heating/cooling capacity).
2) Conduct research to gather data on climate conditions using OneBuilding [53] to obtain Typical Meteorological Year (TMY) files (hourly climate data on temperature, humidity, solar radiation, and wind speed collected over multiple years) critical for simulating HVAC performance under realistic climate conditions.
3) Create an EnergyPlus model for the current system by inputting current floor plan measurements, manufacturer specifications, and temperature data into the simulator. It is important to note that we are simulating only two floors of the building as it is those floors' energy savings that we are analyzing.
4) Use the baseline model to run simulations with summer and winter conditions.
5) Extract total HVAC consumption (kWh).
6) Create a new EnergyPlus model for design solution with Infinity® Heat Pump and smart glass, modify floor plan, adjusting EnergyPlus input parameters.
7) Run model with identical conditions.
8) Extract total HVAC consumption (kWh).

9) Compare the new model to the current model and analyze percentage reduction in HVAC energy consumption.

9.0 Conclusion

The energy efficiency of the 27th and 28th floors of Chestnut Residence is poor, stemming from the outdated glass walls, unadaptable light fixtures, and old HVAC system. By considering the needs of diverse stakeholders like the UofT Sustainability Office, building managers, and government regulators, the team identified key functions, objectives, and constraints to ensure a relevant redesigned environment. During the idea generation process, we conducted an in depth exploration of the design space resulting in the formation of 56 candidate solutions. The idea selection process that followed carefully narrowed down these 56 ideas, while considering the extent to which each solution fulfilled the objectives of the design, to one final idea. The HRV Integrated Smart Glass System was selected as the most suitable design for implementation, and our plan for our measures of success highlights how we will verify that the design meets our top objective moving forward.

10.0 Reference list

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11.0 Appendices

Appendix A: Extended List of Stakeholders

Here is our full list of stakeholders.

Table 6. Extended Summary of Stakeholders Ordered by Decreasing Influence.

Stakeholder	Influence	Interest/Impact
UofT (Sustainability Office)	High: - Property of UofT - Promotes its agenda to improve sustainability [10]	High: - Solidifying UofT's reputation as highly sustainable [11]
Director of Residence Operations	High: - Oversees planning, budgeting, and drafting proposals [12]	High: - Design adds to their job responsibilities
Residence Manager of Finance	High: - Helps director in overseeing budgeting and planning [13]	High: - Design adds to their job responsibilities
Provincial Government (Ministry of College and Universities)	High: - Provides funding to UofT, directly influencing budget [14]	Low: - Unaffected by design
Provincial Government (Ministry of Municipal Affairs and Housing)	High: - Design must obey building codes and regulations [15]	Low: - Unaffected by design
Glass manufacturers	Medium: - Available glass technology will influence the design	Medium: - Gain profits
HVAC companies	Medium: - Available HVAC systems will influence design	Medium: - Gain profits
Lighting companies	Medium: - Available light technology will influence the design	Medium: - Gain profits
Maintenance crew	Low: - No authority over the project	Medium: - Change in building systems may result in change in maintenance operations

Appendix B: Influence-Impact Graph

We used this graph to brainstorm and rank stakeholders.

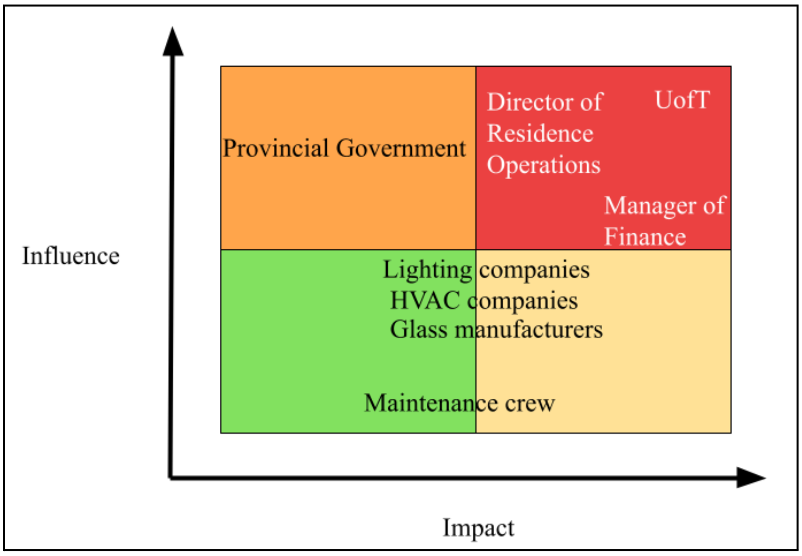

Figure 27. Influence-Impact Graph

Appendix C: Black Box Method

Used to brainstorm and identify primary and secondary functions - refer to engineering notebooks.

Appendix D: Service Environment Extended

A meeting with the client happened on Wednesday Feb. 5th, 9-10am. Notes are written in engineering notebooks.

Appendix E: Service Environment Extended

Firefighting Facilities

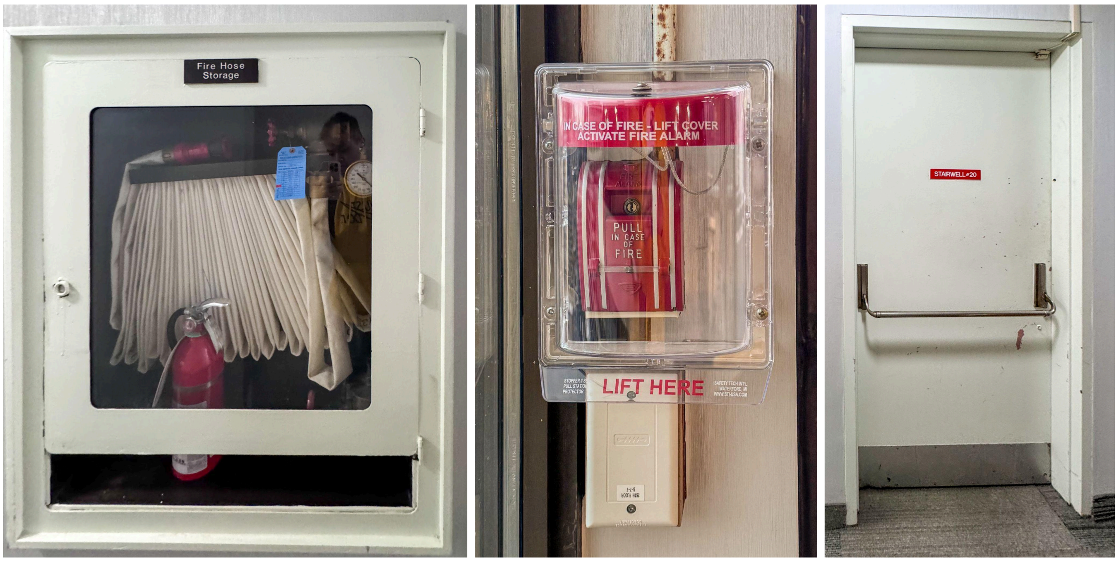

Figure 28. Fire Hose, Fire Alarm, Fire Stairs

Accessibility

Figure 29. Accessible Lift on 27th floor

Noise

The noise levels of the 27th and 28th floors are shown below at six different points across both floors. The data was collected through the “Decibel Meter” app on a mobile device.

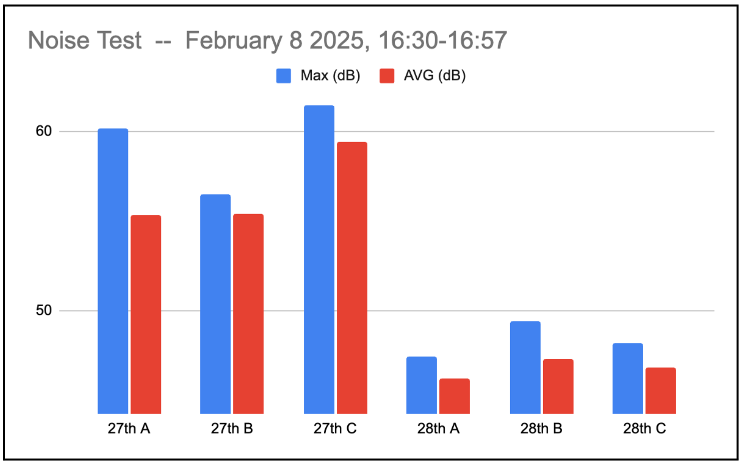

Figure 30. Noise Levels on the 27th and 28th Floors.

Network Latency

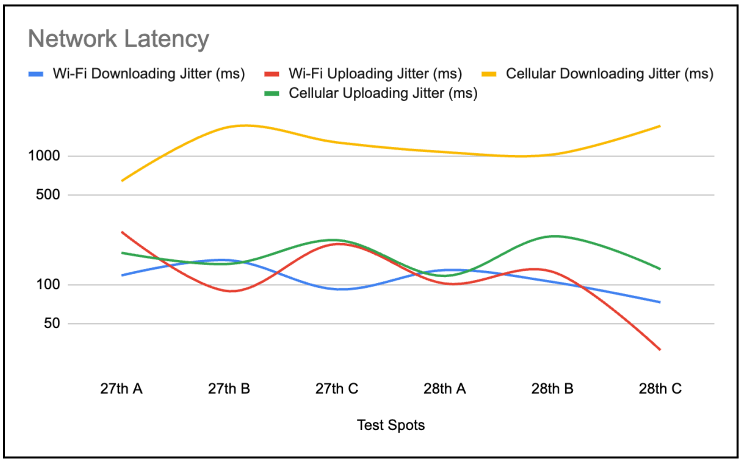

Figure 31. Graph of network latency.

Figure 32. Aruba AP-315 Wireless Access Point APIN0315 Ceiling Router

Other Observations:

Table 7. Extended List of Observations

Sections	Objective Environment	Analysis
Glasses Wall	- 4 types of glass panes used on both floors	- Glass is 20-40 years old, meaning they have sustained significant wear.
Lighting System	Incandescent lights and fluorescent bulbs are still used on the 27th floor.	These lights aren't as efficient as LED lights which means that with the same illumination, they will cost more electricity.
HVAC System	The HVAC system utilizes vents on the ceiling and radiators that line the bottom of the walls.	The system is fully operational on both floors.
Weather Condition	The weather is not always in a comfortable zone outdoors, as people feel comfortable when the temperature is from 20 to 22.	The temperature tends to be cooler inside, despite the radiators inside.
Network	The local Wi-Fi is over 50Mbps and low latency in most test spots, but the Cellular is below 50 Mbps and low latency in most spots.	The local Wi-Fi experience is fast and has low latency, but the Cellular experience is poor, depending on its poor speed and high latency.
Illumination	The illumination under lights is over 400 lux in most spots, but the illumination at the same time which is not directly under lights is below 100 in most spots.	The illumination is distributed unevenly, one of the reasons is the incandescent lights on 27th 27th-floor provide small area lighting and enough lighting is essential for reading and studying
Noise	The noise level on the 27th floor is greater than that on the 28th floor.	The 27th floor is more frequented and the 28th floor is set for Quite Study Commons, therefore there is more noise.
Accessibility	Only the 27th floor is reachable by an elevator. There are stairs and an escalator to reach the 28th floor.	The 27th floor is more accessible because of the elevator.

Appendix F: Objectives

Table 8: Pairwise Comparison of Objectives

Pairwise Matrix	Should reduce HVAC energy consumption	HVAC should adapt performance depending on the outdoor temperature	HVAC should maintain even cooling and heating throughout the floors.	The glass should enhance the thermal efficiency of windows	HVAC should adapt performance to occupancy	Lighting should minimize energy consumption	Lighting should adapt to the outdoor environment conditions	**Score**	**Rank**
Should reduce HVAC energy consumption	-	1	1	1	1	1	1	**6**	**1st**
HVAC should adapt performance depending on the outdoor temperature	0	-	1	1	1	1	1	**5**	**2nd**
HVAC should maintain even cooling and heating throughout the floors.	0	0	-	1	1	1	1	**4**	**3rd**
The glass should enhance the thermal efficiency of windows	0	0	0	-	1	1	1	3	4th
HVAC should adapt performance to occupancy	0	1	0	1	-	0	0	2	5th
Lighting should minimize energy consumption	0	0	0	0	0	-	1	1	6th
Lighting should adapt to the outdoor environment condition	0	0	0	0	0	0	-	0	7th

Table 9. Minor Objectives

Objectives	Goals	Metrics	Justification
Lighting should adapt to occupancy levels	Save 6% - 13% of lighting energy [54]	Monitor total daily energy use (kWh) compared to baseline	The Lighting Research Center at the U.S. Environmental Protection Agency has studied the amount of energy wasted on unnecessary lighting of spaces and has measured how much energy was saved after implementing a new system in Figure 20.

HVAC system should allow some user control	Allow users to customize temperature by ± 2℃	Measure the automation range of temperature	During the meeting, the client wanted to keep students from changing the temperature by this specific amount.
Should not use up entire budget	Maintaining a total cost below $250k	Total cost of solution	Client imposed objective

Energy Use (%)

	Weekdays			Weekends			Total monitoring period		
	Day	Night	Total	Day	Night	Total	Day	Night	Total
Break room	69%	19%	88%	8%	5%	12%	77%	23%	100%
Classroom	55%	26%	82%	11%	7%	18%	66%	34%	100%
Conference	65%	19%	83%	11%	6%	17%	76%	24%	100%
Private office	74%	12%	86%	11%	3%	14%	85%	15%	100%
Restroom	43%	33%	76%	12%	12%	24%	55%	45%	100%

Energy Waste (%)

	Weekdays			Weekends			Total monitoring period		
	Day	Night	Total	Day	Night	Total	Day	Night	Total
Break room	50%	29%	79%	12%	8%	21%	63%	37%	100%
Classroom	40%	36%	76%	13%	11%	24%	53%	47%	100%
Conference	55%	24%	80%	12%	9%	20%	67%	33%	100%
Private office	67%	21%	87%	8%	5%	13%	75%	25%	100%
Restroom	29%	41%	70%	14%	16%	30%	42%	58%	100%

Figure 33. U.S. Environmental Protection Agency's findings on the amount of energy wasted on unnecessary lighting of spaces vs. energy saved after implementing a new system.

Appendix G: Morph Chart

The morph chart includes an organized list of all brainstormed and AI (Appendix Q) generated ideas to fulfill each secondary function.

Legend:
AI
Brainstorm

Provide heating/cooling	Provide lighting	Protect from weather elements	Provide ventilation
Smart thermostat	Motion-sensing lights	electrochromic glass	Original HVAC design
biogas bonfire	LED Panel	Smart glass	Windows that open
hot water reuse	Open Bonfire	Automatic curtains	HRV(Heat recovery ventilators) - Exchange air
Thermal Mass Flooring	Halogen light bulbs	translucent solar panel	ERV(Energy recovery ventilators) - also transfer moisture
Body Heat Capture	Fluorescent light bulbs	Fraunhofer (metal lenses)	Personalized Micro-Vents

Passive Infrared (PIR) sensor	Chinese Lanterns	infrared absorbed polymer gels in glass unit	Inhalers
Solar air heater	CFL light bulbs	Transparent Power-Generating Windows Based Solar-Thermal-Electric Conversion	AI and sensors to redirect air based
Heat-Recovery Ventilation (HRV)	Infrared light bulb	Brick wall	Air jet (MEMS)
Compost Heating	Xenon lamp	Plastic tarp	UV light to break down pollutants and bacteria in the air.
Wind-powered Electrical Heating	Quartz lamp	robots with umbrellas	Smart Ventilation with CO_2 Monitoring
Geothermal Heat Storage	Mercury vapour bulb	Wind gun blows away rain	CO_2 sensors on HVAC
Floor Heating	Metal halide bulb	Automatic windows	Energy recovery ventilators (ERVs)
Infrared Heating Panels	Krypton bulb	colored glass	Heat recovery ventilators (HRVs)
Wall/Ceiling pipes, circulating warm water	UV lamp	DMD (micro mirrors)	Dedicated outdoor air systems (DOAS)
Wall Panels that stores heat during the day and releases it at night	Filament light bulb	CPL (filter)	Variable air volume (VAV)
Using stone or concrete furniture elements to absorb and radiate heat over time.	Sunlight based optical fiber system	variable ND filter	Design separate supply and return duct systems
Steam engine	CC	CPL with liquid crystal	Optimize ductwork design with properly sized, low-resistance ducts for uniform distribution.
Have a kitchen- stove provides heat	Candles	Thermal-Responsive Window Coatings	Utilize carbon dioxide sensors along with occupancy sensors
Severe room waste heat	Torches	Heated Window Frames	Incorporate economizer controls to use favorable outdoor air conditions for cooling and ventilation.
lighting system waste heat	Glowsticks	Bio-Adaptive Facades (materials like algae panels)	Employ zoned ventilation
Geothermal	Sunlight	Retractable Reflective Blinds	Use displacement ventilation systems
Thermal-Responsive Window Coatings	Workout bikes to generate electricity	Green Walls (absorbs extra radiation)	Implement underfloor air distribution, using raised floors to deliver conditioned air evenly.
Water Based Heated floors	Glow in the dark painted walls	Pressure-Activated Door Seals:	Use variable speed drives (VSD) on fans
Electrical Based Heated floors	Daylight harvesting systems	Lead Wall	Install dedicated exhaust systems in areas with high pollutants
Biomass pellet stoves	Smart Windows with Electrochromic Glass	Magnetic wood	Integrate UV germicidal irradiation (UVGI) systems within ducts to disinfect circulating air.
Rocket mass heaters	Lava lamps	Solar Screens	Utilize high-efficiency particulate air filters (HEPA) or MERV-rated filters

Infrared radiant heaters	Fish Tank with bioluminescent algae	Insulated Window Blinds	Dual-fan arrangements
Smart thermal paint	Mirrors direct in sunlight from outside	Double/Triple Pane Windows	Install exhaust fans with automatic controls in moisture- or odor-generating areas.
Micro-wind turbine heating	Harvested fireflies in jars	Air Curtains	Utilize variable refrigerant flow (VRF) systems paired with dedicated outdoor air units
Heat reflector panels	Solar-powered lights	Storm Windows	Systems with motorized dampers that modulate or shut off airflow in response to environmental data.
Heated furniture	Contained fire	Vapor Barriers	Electronically commutated (EC) fans
Phase-change materials (PCM)	Oil lamps	IGU	Implement overhead mixing plenum systems
Heat-capturing flooring materials	Chandeliers	Trees	Integrate displacement cooling coupled with ceiling or high-side air returns
Sunrooms or solariums	Kerosene lamps	Rain Screens	Low pressure drop air filters and duct accessories
Solar water heating systems	Plasma lamp	Permeable Paving	Install inline duct fans to boost airflow
Geothermal cooling systems	Incandescent light bulb	Humidity-regulating Plasters	Employ moisture sensors in areas subject to high humidity
Ice-based air conditioning	Sulfur lamp	HEPA Air Filtration Systems	Integrate desiccant dehumidification systems with HVAC
Underground air tunnels	Carbon button lamp	Airlock Entrances (Vestibules)	Radiant barrier materials in duct construction to maintain the integrity of conditioned air.
Evaporative coolers	Harvested glow worms	Electrostatic Air Filters	Incorporate bypass damper designs to allow maintenance without compromising full ventilation.
Passive ventilation	LED light strips	Dust Barriers	Variable frequency drives (VFDs) on ventilation fans
Reflective roof coatings	Diode	Smart Air Quality Sensors	Pressure-independent control dampers to maintain consistent airflow
Green roofs	Dimmer switch	Double-glazed Acoustic Windows	Thermal energy storage (such as chilled water or ice storage) with ventilation systems
Hydronic radiant cooling	Flame Shape Bulb	Mass-loaded Vinyl (MLV)	Split system
Shade sails or awnings	Twisted Fluorescent Light	Positive Air Pressure System	Hybrid split
Water walls	Adaptor light	Activated Carbon Filters	Packaged heating and cooling
Desiccant cooling	Globar	Waterproof Membranes	Zoned system
Heat pumps in reverse (cooling mode)	Acetylene lamp	Dehumidifiers	Duct-free mini-split
Smart shading systems	Hollow cathode lamp	Desiccant Packs/Absorbers	Hydronic heating

Car exhaust	Constant fireworks	Gutter Guards & Drainage Systems	Portable spot cooler
	Radioactive furniture	Awning Systems	Portable heat pump
	Strobe lights	Wall	
	Ford-F150 with bright LEDs at eye level		
	disco ball w/lasers		

Figure 34. Morph chart.

Appendix H: SCAMPER

These SCAMPER tables were used to generate additional full solutions from already generated solutions.

Original solution: Smart Adaptive Climate Control (means used: Infrared Heating Panels, Daylight harvesting systems, Windows with automatic covers that close based on sunlight + insulation needs, and Smart Air Quality Sensors)

Table 10. New solution: Smart Hybrid Heat-Recovery System

SCAMPER Technique	Modification	New Idea
Substitute	Replace the existing infrared heating panels with an under-floor radiant heating system that uses a water-based heat pump for more efficient heating.	The under-floor radiant system lowers energy consumption and improves occupant comfort.
Combine	Merge daylight harvesting with occupancy sensing to allow HVAC and lighting to adapt automatically.	A dual-sensor control synchronizes lighting and HVAC in response to occupancy and daylight conditions.
Adapt	Adjust mechanical blinds with electrochromic (smart-tint) windows.	The electrochromic window system precisely adjusts window tint to reduce heat gain and glare.
Modify	Shift from simple on/off sensors to continuous monitoring of carbon dioxide and humidity.	Climate monitors deliver real-time data for HVAC adjustments and ventilation rates.
Put to other Use	Recapture waste heat from HVAC to pre-warm other zones.	Heat recovery loop channels are used to reduce consumption and costs.

Eliminate	Remove separate daylight and HVAC sensors by integrating them into one central hub.	This all-in-one sensor simplifies installation, uses fewer devices, and makes control easier.
Rearrange/reverse	Move HVAC near the exterior of the building, and move occupant workspaces to a central zone of the building.	The perimeter HVAC and central workspace allows for a more stable core environment.

Original solution: Smart HRV system (heat-recovery ventilation recycles heat, motion-sensing lights, translucent solar panels, and UV lights that purify the air)

Table 11. New Solution: Smart HRV System

SCAMPER Technique	Modification	New Idea
Substitute	Replace motion-sensing lights with low-power LEDs that also track air quality.	Lights become dual sensors, monitoring both movement and indoor air conditions.
Combine	Integrate translucent solar panels with the HRV system so incoming sunlight assists in pre-warming or pre-cooling air.	The solar-assisted HRV cuts energy loads by using solar heat for ventilation demands.
Adapt	Add UV purifiers to the HRV's ducts for direct disinfection of circulated air.	This expanded UV treatment reduces airborne germs.
Modify	Use a more efficient heat-exchange core in the HRV, designed for a higher heat-transfer rate.	The upgraded core recovers more heat and reduces cost.
Put to other Use	Use leftover heat from the HRV to warm a greenhouse space.	Captured heat helps support on-site plant growth.
Eliminate	Remove manual toggles for UV lights and automate them with air-quality sensors.	Automatic activation saves power and ensures continuous air purification.
Rearrange/reverse	Put solar panels and UV lights in sunny halls, and place the	Grouping solar and UV systems near natural light will maximise

	HRV in a central spot for easier duct work.	energy capture and disinfection. Shorter ducts also allow for better airflow.

Appendix I: List of Full Solutions

Here is an organized list of full solutions after idea generation was completed. They are organized based on the extent of change to the current system.

Legend:
Red - Removed by Consolidation (Appendix J)
Blue - Removed by Feasibility Check (Appendix K)

Minimal Changes

1. Solar-Optimized Living Space (means: Solar Air Heater, Transparent Power-Generating Windows, Smart Glass, Smart Ventilation with CO_2 Monitoring)
2. Sustainable Heat and Light Exchange System(means: Severe Room Waste Heat Reuse, Mercury Vapor Bulbs, Sunlight-Based Optical Fiber System, integrate UV Germicidal Irradiation in Ducts)
3. Balanced Solar Control System (means: Solar Air Heater, incandescent Light Bulbs, Thermal-Responsive Window Coatings, Variable Refrigerant Flow)
4. AI based control System (means: Phase-change materials (PCM), Windows with AI controlled and outdoor sensors, Green Walls (absorb extra radiation), Air jet (MEMS))
5. Solar based control system (means: Solar air heater, Solar-powered lights, Automatic curtains, Energy recovery ventilators (ERVs))
6. Heated pillows/furniture: (means: Students go without shoes (for cleanliness) into rooms blanketed with heated sheets and pillows. They provide heat and insulate. Same lights and HVAC.)
7. Thermal mass flooring system (means: Thermal mass flooring to retain heat, LED panels for light, smart glass for weather protection, and a hybrid split HVAC system)
8. Smart Adaptive Climate Control (means: Infrared Heating Panels, Daylight harvesting systems, Windows with automatic covers that close based on sunlight + insulation needs, and Smart Air Quality Sensors)
9. AI-Driven Climate Control System (means: Heat pumps in reverse (cooling mode), Smart thermal paint, Bio-Adaptive Facades (e.g., algae panels), and AI-based ventilation system)
10. Renewable Energy-Based Climate System (means: Ice-based air conditioning, Solar-powered lights, Permeable Paving, and Low pressure drop air filters and duct accessories)
11. Passive and Renewable energy (means: Thermal Mass Flooring + Phase change materials, Solar powered LED, Retractable Reflective Blinds + green walls, and Smart Ventilation with CO_2 Monitoring)

Medium Changes

12. HRV integrated Smart Glass System (means: Daylight Harvesting Systems, Electrochromic Glass, Smart Ventilation with CO_2 Monitoring)
13. Thermal Harmony System (means: Thermal Mass Flooring, Mirrors directing sunlight from outside, Retractable Reflective Blinds, Heat Recovery Ventilators)
14. Smart Climate Regulation Hub (means: Infrared Heating Panels, LED Light Strips, Windows with Automatic Covers, Energy Recovery Ventilators (ERVs))
15. Dynamic Indoor Climate Balancer(means: Wall Panels That Store Heat and Release It at Night, Daylight Harvesting Systems, Pressure-Activated Door Seals, Variable Air Volume System)
16. Eco-Adaptive Airflow System (means: Hot Water Reuse for Heating, Solar-Powered Lights, Heated Window Frames, Dedicated Outdoor Air System)
17. Electrochromic Glass Lighting Control System (means: Smart thermostat, LED Panel, Electrochromic Glass, AI and Sensors to redirect air based on occupancy)
18. Human Traffic based control system (means: Smart thermostat, Passive Infrared (PIR) sensor, electrochromic glass, AI and sensors to redirect air based on occupancy)
19. Heat Recovery based System (means: Hot Water Reuse, LED Panel, Transparent Power-Generating Windows Based Solar-Thermal-Electric Conversion, Heat recovery ventilators (HRVs))
20. Smart Glass and Phase change recovery system (means: Phase-change materials (PCM), Smart Windows with Electrochromic Glass, Thermal-Responsive Window Coatings, Heat recovery ventilators (HRVs))
21. Biogas and Smart Glass system (means: biogas bonfire, Smart Windows with Electrochromic Glass, Green Walls (absorbs extra radiation), AI and sensors to redirect air based)
22. Automatic Thermostat and Light System (means: Smart thermostat, Motion-sensing lights, replace glass with an insulating wall with small windows, retain original HVAC design)
23. Floor heating with glow sticks for lighting, heated window frames for weather protection, and variable air volume for ventilation.
24. Holiday special: electric fireplace provides light and warmth, brick walls to prevent heat loss, same HVAC system.
25. Solar air heater system (solar air heater for warmth, CFL light bulbs for light, infrared polymer gels in windows, and HRV system for air circulation)
26. Hybrid Thermal Efficiency System (means used: Hydronic radiant cooling, Sunlight-based optical fiber system, Double/Triple Pane Windows, and Energy recovery ventilators (ERVs))
27. High-Efficiency Heat Retention System (means used: Phase-change materials, Infrared light bulbs, Insulated Window Blinds, and Heat recovery ventilators (HRVs)
28. HRV system (heat-recovery ventilation recycles heat, motion-sensing lights, translucent solar panels, and UV lights that purify the air)
29. Solar Assisted HRV (heat-recovery ventilation recycles heat, UV lights, solar-powered air purifier)

Extreme Changes

30. Infinity pool + sauna: laminated glass (commonly used in these types of pools) holds an infinity pool on the 28th floor. A sauna on the 27th heats both floors. LED pool lights provide light.
31. Eco-Thermal Regulation System (means used: Geothermal Heat Storage, LED Panel, Thermal-Responsive Window Coatings, and Demand-controlled ventilation using CO_2 sensors)
32. Smart Energy Conservation System (means used: Electrical Based Heated Floors, Dimmer switch-controlled LED lights, Storm Windows, and Install inline duct fans to boost airflow)
33. Sustainable Airflow and Insulation System (means used: Rocket mass heaters, Plasma lamp, Vapor Barriers. and Smart Ventilation with CO_2 Monitoring)
34. Nature-Inspired Thermal Control System(means : Brick Wall (Thermal Mass), Flame-Shaped Bulbs for Aesthetic Warmth, Bio-Adaptive Facades (e.g., algae panels), Smart Ventilation Integrated with Natural Daylight Control)
35. Car park: Keep windows as is. Bring up automobiles. Exhaust from running engines heat air, pickup trucks with high-beams constantly on light up space. Camper vans provide additional shelter.
36. Open-air camping: windows removed and replaced with a circle of plants. Students shelter in tents, with propane heaters with jars of fireflies providing light.
37. 360 aquarium: giant 2-storey aquarium wrap around floors. Filled with bioluminescent life for lighting. Clear glass lets in light during the day.
38. Steampunk: Steam engines heat air, oil lamps provide ambient light, metal panels mashed together create a wall with ventilation strips. Science-fiction lovers would love this.
39. Compost heating system (compost heating generates warmth, xenon lamps for light, electrochromic glass, and Integrate displacement cooling coupled with ceiling or high-side air returns)
40. Stone system (stone furniture for absorbing/releasing heat, UV lamps, bio-adaptive facades, and green walls as an oxygen source)
41. Radioactive: nuclear waste produces heat. And, when immersed in water, it can produce a blue glow due to a phenomenon called Cherenkov radiation for light.
42. Virtual reality: Outside blocked off with a wall to prevent heat loss. Screens depict beautiful pictures to mimic windows. Same HVAC. cut off some lights because screens will be bright enough.
43. Concert hall: Lasers and disco balls provide light, Windows are blocked off or blacked out. Body heat from roaring dancing crowds provide heat.
44. Bio-Integrated Comfort System (means : Compost Heating, Algae in a Fish Tank, Green Walls (absorb excess radiation), Demand-Controlled Ventilation using CO_2 Sensors)
45. Thermal Mass and Smart Ventilation System (means used: Using stone or concrete furniture elements to absorb and radiate heat over time, Glow in the dark painted walls, Rain Screens, and Pressure-independent control dampers to maintain consistent airflow)
46. Bio based Control System (biogas bonfire, Open Bonfire, Green Walls (absorbs extra radiation), Smart Ventilation with CO_2 Monitoring)

47. Thermal Gradient Airflow Based control system (Smart thermostat, Smart Windows with Electrochromic Glass, Green Walls (absorbs extra radiation), AI and sensors to redirect air based)
48. Geothermal system (geothermal heat storage, sunlight based optical fiber system, thermal-responsive window coatings, and partially zoned ventilation)
49. Steam engine system (steam engine for generating heat, torches for lighting, retractable reflective blinds, and dedicated outdoor air systems for fresh air intake)
50. Wind-powered system (wind-powered electrical heating, mercury vapor bulbs, windows with automated covers, and demand-controlled ventilation using CO2 sensors)
51. Infrared heating system (infrared heating panels provide heat, halogen light bulbs, plastic tarp to protect against weather, and personalized micro-vents)
52. Steam engine system (steam engine for generating heat, torches for lighting, retractable reflective blinds, and dedicated outdoor air systems for fresh air intake)
53. Wind system (wind-powered electrical heating, LED panel lights, windows with automated covers, and demand-controlled ventilation using CO2 sensors)
54. Solar panel system (solar panels provide heat, halogen light bulbs, metal tarp to protect against weather, and personalized micro-vents)
55. Smart Hybrid Heat-Recovery System

SCAMPER Technique	Modification	New Idea
Substitute	Replace the existing infrared heating panels with an under-floor radiant heating system that uses a water-based heat pump for more efficient heating.	The under-floor radiant system lowers energy consumption and improves occupant comfort.
Combine	Merge daylight harvesting with occupancy sensing to allow HVAC and lighting to adapt automatically.	A dual-sensor control synchronizes lighting and HVAC in response to occupancy and daylight conditions.
Adapt	Adjust mechanical blinds with electrochromic (smart-tint) windows.	The electrochromic window system precisely adjusts window tint to reduce heat gain and glare.
Modify	Shift from simple on/off sensors to continuous monitoring of carbon dioxide and humidity.	Climate monitors deliver real-time data for HVAC adjustments and ventilation rates.
Put to other Use	Recapture waste heat from HVAC to pre-warm other zones.	Heat recovery loop channels are used to reduce consumption and costs.
Eliminate	Remove separate daylight and HVAC sensors by integrating them into one central hub.	This all-in-one sensor simplifies installation, uses fewer devices, and makes control easier.

Rearrange/ reverse	Move HVAC near the exterior of the building, and move occupant workspaces to a central zone of the building.	The perimeter HVAC and central workspace allows for a more stable core environment.

56. Smart HRV System

SCAMPER Technique	Modification	New Idea
Substitute	Replace motion-sensing lights with low-power LEDs that also track air quality.	Lights become dual sensors, monitoring both movement and indoor air conditions.
Combine	Integrate translucent solar panels with the HRV system so incoming sunlight assists in pre-warming or pre-cooling air.	The solar-assisted HRV cuts energy loads by using solar heat for ventilation demands.
Adapt	Add UV purifiers to the HRV's ducts for direct disinfection of circulated air.	This expanded UV treatment reduces airborne germs.
Modify	Use a more efficient heat-exchange core in the HRV, designed for a higher heat-transfer rate.	The upgraded core recovers more heat and reduces cost.
Put to other Use	Use leftover heat from the HRV to warm a greenhouse space.	Captured heat helps support on-site plant growth.
Eliminate	Remove manual toggles for UV lights and automate them with air-quality sensors.	Automatic activation saves power and ensures continuous air purification.
Rearrange/ reverse	Put solar panels and UV lights in sunny halls, and place the HRV in a central spot for easier duct work.	Grouping solar and UV systems near natural light will maximise energy capture and disinfection. Shorter ducts also allow for better airflow.

Appendix J: Consolidation of Solutions

The extensive list of individual solutions for this project was refined to 53 final ideas. This step ensured that each solution was unique and that the list remained manageable. In particular, solutions 29, 52, and 53 were removed due to their similarity to solutions 28, 50, and 51 respectively.

Appendix K: Feasibility check

Feasibility checks confirm that a solution will meet the project's functions and constraints. It is critical that a solution is removed if it can not be feasibly justified. First off, solutions 30, 37, and 43 regarding infinity pools, 360 aquariums, and a concert hall were removed since they did not fit within the physical constraint of the service environment. Likewise, solutions 35, 36, 38, and 41 regarding car parks, open-air camping, steampunk themes, and radioactive elements were removed since they did not fit within legal and ethical constraints.

Appendix L: Multivoting

In order to conduct the multi-voting process, each team member was given the opportunity to vote on five of the best solutions.

Each team member's top five solutions:

Table 12. Top Five Solutions for Multi-voting

Anushka	Mayan	Nayan	Noelle	Richard	Tim
AI based control System (4)	Smart Adaptive Climate Control (8)	Automatic Air-conditioning system (22)	Smart Adaptive Climate Control (8)	Hybrid Thermal Efficiency System (26)	Smart Glass and Phase change recovery system (20)
Smart Adaptive Climate Control (8)	AI based control System (4)	Smart Climate Regulation Hub (14)	Electrochromic Glass Lighting Control System (17)	Smart Adaptive Climate Control (8)	Electrochromic Glass Lighting Control System (17)
Human Traffic based control system (18)	Smart Glass and Phase change recovery system (20)	Smart Adaptive Climate Control (8)	Smart Glass and Phase change recovery system (20)	Balanced Solar Control System (3)	HRV integrated Smart Glass System (12)
Automatic Thermostat and Light System (22)	HRV integrated Smart Glass System (12)	Thermal Mass Flooring System (7)	Hybrid Thermal Efficiency System (26)	Nature-Inspired Thermal Control System (34)	Solar based control system (5)
HRV system (28)	Automatic Thermostat and Light System (22)	Electrochromic Glass Lighting Control System (17)	High-Efficiency Heat Retention System (27)	Passive and Renewable energy (11)	Biogas and Smart Glass system (21)

Number of votes for each of the top ideas:

Table 13. Organized Multi-voting

Idea #	3	4	5	7	8	11	12	14	17	18	20	21	22	26	27	28	34
Number of Votes	1	2	1	1	5	1	2	1	3	1	3	1	2	2	1	1	1

The top 7 out of 46 remaining ideas are highlighted. They will be used in the weighted decision matrix.

Appendix M: Weighted Decision Matrix

1) Pairwise Comparison to Rank a List of Objectives

Table 14. Pairwise Comparison of Objectives

Pairwise Matrix	Should reduce HVAC energy consumption	HVAC should adapt performance depending on the outdoor temperature	HVAC should maintain even cooling and heating throughout the floors.	The glass should enhance the thermal efficiency of windows	HVAC should adapt performance to occupancy	Lighting should minimize energy consumption	Lighting should adapt to the outdoor environment conditions	Score	Ranks
Should reduce HVAC energy consumption	-	1	1	1	1	1	1	6	1st
HVAC should adapt performance depending on the outdoor temperature	0	-	1	1	1	1	1	5	2nd
HVAC should maintain even cooling and heating throughout the floors.	0	0	-	1	1	1	1	4	3rd
The glass should enhance the thermal efficiency of windows	0	0	0	-	1	1	1	3	4th
HVAC should adapt performance to occupancy	0	1	0	1	-	0	0	2	5th
Lighting should minimize energy consumption	0	0	0	0	0	-	1	1	6th
Lighting should adapt to the outdoor environment condition	0	0	0	0	0	0	-	0	7th

2) Weight for each of these objectives.

Table 15. Weight of Each Objective

Objectives	Rank from Pairwise	Weights through discussion
Should reduce HVAC energy consumption	1	34%
HVAC should adapt performance depending on the outdoor temperature	2	22%
HVAC should maintain even cooling and heating throughout the floors.	3	16%
The glass should enhance the thermal efficiency of windows	4	12%
HVAC should adapt performance to occupancy	5	8%
Lighting should minimize energy consumption	6	6%
Lighting should adapt to the outdoor environment conditions	7	2%

3) Comparing solutions against the objectives. Through discussion, we decided how well each alternative meets each objective. Using the textbook's suggested scale:

Table 16. Scale for Weighted-Decision Matrix

Suggested Scale	
0%	Does not meet the objective at all
20%	Meets objective very weakly
40%	Meets objective somewhat
60%	Mostly meets objective
80%	Meets objective Strongly
100%	Outstanding concerning the objective

Table 17. Weighted-Decision Matrix Uncalculated

Idea	Should reduce HVAC energy consumption	HVAC should adapt performance depending on the outdoor temperature	HVAC should maintain even cooling and heating throughout the floors.	The glass should enhance the thermal efficiency of windows	HVAC should adapt performance to occupancy	Lighting should minimize energy consumption	Lighting should adapt to the outdoor environment conditions
AI based control System	100%	80%	80%	80%	20%	40%	60%
Smart Adaptive	80%	80%	100%	40%	30%	60%	100%

Climate Control							
HRV integrated Smart Glass System	80%	100%	100%	80%	40%	60%	40%
Electrochromic Glass Lighting Control System	60%	80%	80%	100%	100%	100%	20%
Smart Glass and Phase change recovery system	80%	100%	60%	100%	60%	40%	20%
Automatic Thermostat and Light System	100%	80%	60%	100%	40%	40%	20%
Hybrid Thermal Efficiency System	80%	100%	60%	100%	40%	60%	20%

4) We combined these two tables by multiplying the scores in each column to find the Highest-scoring solutions

Table 18. Weighted-Decision Matrix Calculated

Solutions	Should reduce HVAC energy consumption 34%	HVAC should adapt performance depending on the outdoor temperature 22%	HVAC should maintain even cooling and heating throughout the floors. 16%	The glass should enhance the thermal efficiency of windows 12%	HVAC should adapt performance to occupancy 8%	Lighting should minimize energy consumption 6%	Lighting should adapt to the outdoor environment conditions 2%	Total
AI based control System	0.34 x 1.0 34%	0.22 x 0.8 18%	0.16 x 0.8 13%	0.12 x 0.8 9.6%	0.08 x 0.2 1.6%	0.06 x 0.4 2.4%	0.02 x 0.6 1.2%	79.8 %
Smart Adaptive Climate Control	0.34 x 0.8 27%	0.22 x 0.8 18%	0.16 x 1.0 16%	0.12 x 0.4 5%	0.08 x 0.3 2.4%	0.06 x 0.6 3.6%	0.02 x 1.0 2%	74%
HRV integrated Smart Glass System	0.34 x 0.8 27%	0.22 x 1.0 22%	0.16 x 1.0 16%	0.12 x 0.8 9.6%	0.08 x 0.4 3.2%	0.06 x 0.6 3.6%	0.02 x 0.4 0.8%	82.2 %
Electrochromic Glass Lighting Control System	0.34 x 0.6 20%	0.22 x 0.8 18%	0.16 x 0.8 13%	0.12 x 1.0 12%	0.08 x 0.1 8%	0.06 x 1.0 6%	0.02 x 0.2 0.4%	77.4 %

Smart Glass and Phase change recovery system	0.34 x 0.8 27%	0.22 x 1.0 22%	0.16 x 0.6 9.6%	0.12 x 1.0 12%	0.08 x 0.6 4.8%	0.06 x 0.4 2.4%	0.02 x 0.2 0.4%	78.2 %
Automatic Thermostat and Light System	0.34 x 1.0 34%	0.22 x 0.8 17.6%	0.16 x 0.6 9.6%	0.12 x 1.0 12%	0.08 x 0.4 4.8%	0.06 x 0.4 2.4%	0.02 x 0.2 0.4%	80.8 %
Hybrid Thermal Efficiency System	0.34 x 0.8 27.2%	0.22 x 0.8 18%	0.16 x 0.6 9.6%	0.12 x 1.0 12%	0.08 x 0.4 3.2%	0.06 x 0.6 3.6%	0.02 x 0.2 0.4%	74%

Appendix N: Alternative Design Fulfillment of FOCs

The following tables describe how each of the three alternative designs meet functions, objectives, and constraints.

Table 19. Fulfillment of Functions

Functions	Solution #1	Solution #2	Solution #3
Provide heating/cooling	Current HVAC system with additional elements (PCM walls, AirJets) to increase efficiency of heating and cooling.	Infinity® Variable Ultimate Cold Climate Heat Pump maintains 100% heating capacity.	Original HVAC system with smart thermostats that adjust setpoints based on occupancy and ambient temperature.
Provide lighting	LED lighting.	LED daylight harvesting system will read the light levels of both natural and artificial light.automatically dim or brighten LED lights accordingly.	Motion-sensing lights installed in corridors and seating areas to ensure illumination is only provided where necessary.
Provide ventilation	Current HVAC system with additional elements (green walls, AirJets) to increase efficiency of airflow.	The Performance™ Energy Recovery Ventilator exchanges indoor and outdoor air while recovering energy from exhaust.	Original HVAC system remains unchanged, but smart thermostats will reconfigure HVAC performance and fresh-air exchange rates.

Protect from weather elements	Current window system with added blinds.	Electrochromic glass will change its tint or transparency and transmittance in response to external conditions such as daylight and solar heat.	Glass walls replaced with insulated concrete wall sections and smaller windows.

Table 20. Fulfillment of Objectives

Objectives	Solution #1	Solution #2	Solution #3
Should reduce HVAC energy consumption	Insulating blinds, green wall and PCM interlayer help to reduce dependency of HVAC.	The HVAC and HRV system enhances ventilation efficiency by recovering heat from outgoing air, reducing the need for additional heating or cooling. Electrochromic glass minimizes heat gain in summer and retains warmth in winter, decreasing HVAC load. Occupancy sensors dynamically adjust HVAC output based on real-time occupancy, reducing unnecessary energy consumption.	Smart thermostats continuously adjust setpoints based on ambient temperature and occupancy patterns, reducing energy consumption. Insulated concrete walls and smaller windows limit heat transfer, reducing HVAC reliance.
HVAC should adapt performance depending on the outdoor temperature	Blinds are closed when excess sunlight is available which saves energy based on outdoor conditions. No direct control to HVAC based on outdoor conditions.	The HVAC and HRV system optimizes ventilation by pre-warming incoming air in winter and transferring heat from incoming air to outgoing air in summer.	Smart thermostats automatically adjust HVAC performance based on ambient temperature, ensuring efficient heating and cooling.

HVAC should maintain even cooling and heating throughout the floors.	PCM Interlayer and AirJet® Ventilation System helps to make the indoor temperature uniform throughout.	The HVAC and HRV system, integrated with occupancy sensors and a dual-flow ventilation system, ensures uniform airflow distribution across all floors, preventing temperature fluctuations and improving occupant comfort. The new glass	Smart thermostats regulate HVAC performance to maintain a consistent indoor environment across all floors.
The glass should enhance the thermal efficiency of windows	Blinds increase insulation and reduce heat transfer.	Electrochromic glass dynamically adjusts its transparency to reduce heat gain during hot conditions and maximize heat retention during cold weather, enhancing the building's overall thermal performance.In summer, electrochromic glass darkens under intense sunlight to block excess heat, reducing cooling demands. In winter, it remains clear to allow solar heat to enter, reducing the need for additional heating.	Glass walls are replaced with insulated concrete wall sections and smaller windows. These walls have R-values between 20-30 and are insulated with rigid polyurethane foam boards.
HVAC should adapt performance to occupancy	AI Control System will control the target illumination and temperature in different areas dynamically depending on real-time occupancy.	Occupancy sensors detect real-time space utilization and adjust HVAC airflow accordingly. This reduces heating and cooling in unoccupied areas, optimizing energy use without compromising	Smart thermostats prevent unnecessary HVAC operation by adjusting setpoints based on building occupancy patterns.

		comfort.	
Lighting should minimize energy consumption	High efficiency LED panels provide supplemental lighting and minimise the energy consumption.	Daylight harvesting sensors adjust brightness based on available natural light, reducing reliance on artificial lighting.	Motion-sensing lights ensure illumination is only provided where necessary, reducing electricity consumption.
Lighting should adapt to the outdoor environment conditions	AI Control System will control indoor illumination dynamically depending on time of day.	The daylight harvesting system continuously monitors natural light levels and adjusts indoor artificial lighting accordingly. This maximizes the use of natural daylight while preventing over-illumination, reducing energy consumption.	Smaller windows reduce excessive daylight exposure, maintaining a balanced indoor lighting environment. Motion-sensing lights conduct majority of the lighting

Table 21. Fulfillment of Constraints

Constraints	Solution #1	Solution #2	Solution #3
Abide by the Building Code Act from the Government of Ontario [24]	The design does not violate building code.	The design does not violate building code.	The design does not violate building code.
Indoor air quality	Design modifies the current HVAC system which is already up to code.	The HRV-ERV system continuously exchanges indoor and outdoor air, removing pollutants and maintaining optimal oxygen levels.	Design does not modify the current HVAC system, which is already up to code.
HVAC temperature range	Design modifies current HVAC to be more energy efficient and with less temperature fluctuation, enabling	Design uses the HRV-ERV system to prevent temperature fluctuations and stays within standard.	Smart thermostats automatically adjust HVAC setpoints based on ambient temperature and occupancy, ensuring

	HVAC temperature range to be within standard.		the temperature remains within the standard range.
Students have no control of the lighting	Lighting is controlled by an AI system.	Design's use of daylight harvesting does not enable any student control.	Lighting is controlled by motion sensors.

Appendix O: Pugh Chart

Table 22. Pugh Chart

	Solution 1: **Datum**	Solution 2	Score	Justification	Solution 3	Score	Justification
Should reduce HVAC energy consumption	S		1	Combination of HRV, electrochromic glass, and occupancy sensors makes for overall strongest reduction of HVAC energy consumption.		-1	Combination of smart thermostat, insulating walls, and small windows less effective than datum.
HVAC should adapt performance depending on the outdoor temperature	S		1	HRV enables HVAC to adjust to outdoor conditions more effectively than datum.		1	Smart thermostat enables HVAC to adjust to outdoor conditions more effectively than datum.
HVAC should maintain even cooling and heating throughout the floors.	S		1	HRV and occupancy sensors manage highly effective distribution of heating, cooling, and airflow.		0	Smart thermostats control HVAC for effective distribution of heating, cooling (as effective as datum).
The glass should enhance the thermal efficiency of windows	S		1	Electrochromic glass is highly effective in enhancing thermal efficiency.		-1	Smaller window designs increase efficiency less effectively.

HVAC should adapt performance to occupancy	S		0	HRV and occupancy sensors use real-time occupancy levels to balance heating, cooling, and airflow (as effective as datum).		-1	Smart thermostat is preset with occupancy data to adapt HVAC use based on time of day (less effective than datum).
Lighting should minimize energy consumption	S		1	Daylight harvesting sensors adjust brightness based on available natural light.		1	Motion-sensing lights remain off until occupants are present.
Lighting should adapt to the outdoor environment conditions	S		1	Daylight harvesting sensors adjust brightness based on available natural light.		-2	Light adapts to occupancy only, not the outdoor environment.
Total	0	6			-3		

Appendix P: Budget

To enhance energy efficiency and temperature regulation on the 27th and 28th floors, a comprehensive upgrade is proposed, focusing on HVAC improvements, lighting enhancements, and smart glass installation. For a comprehensive demonstration of the solution, an estimated budget has been calculated. Starting with the HVAC System, pricing information for the Infinity® Variable Ultimate Cold Climate Heat Pump is not readily available, appointments must be made to speak to associates. However, similar high-efficiency heat pumps typically range $14,000 and $18,000 including installation [55] . Similarly, pricing information for the Performance™ Energy Recovery Ventilator (ERV) is also not readily available, however comparable systems generally cost between $1000 to $4,500+ with installation. [56]. Next, Lutron Caseta Occupancy Sensors are priced at $66.99 each [57]. The average floor area being 8439 sq ft and one sensor covering 500 sq ft, approximately 38 sensors would be required.The total price would be 2546$. The LUTRON® Daylight Sensors prices are also not readily available, however similar products are priced at $66 each [58]. One sensor covers 2500 sq ft, 7 sensors would be needed. Total price is 462$. Next the High-quality dimmable LED fixtures average $150 to $200 each.[59]. One 5000 lumen fixture covers 250 sq ft, 68 fixtures are required. The total price would be 10 200$- 13 600$. In addition, the current market cost for lighting control system and Installation, including wiring, controls, and labor, ranges from $3,900 - $4,760 [60] . Finally electrochromic Glass Panels Costs range from glass ranges from $80-$140 USD ($112 - $196 CAD) per square foot [61]**.** Around 3000 sq ft of window area is needed. The total price would be 336 000 - 588 000. The total estimated cost for the project falls between $387,092 and $615,668, depending on the final specifications and material selections.

Appendix Q: Use of GenAI

We used ChatGPT during our idea generation to help generate ideas to fill out our morph chart. The specifically AI generated ideas are labelled in the morph chart in Appendix G.

Prompts used included:

- "List systems that provide heating and cooling to residential buildings"
- "List systems that provide lighting in residential buildings"
- "List systems in residential buildings that protect users from weather elements"
- "List systems that provide ventilation in residential buildings"

Results: https://chatgpt.com/share/67dfa0cc-0ecc-800c-b456-b227ad454db5

We read through, discussed, and verified the ChatGPT generated ideas with external research before adding them to our table in order to ensure that these ideas were valid. Many of these ideas had to be modified based on our discussion and verification or removed if too repetitive or nonsensical.