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Medium office energy consumption optimization using EnergyPlus

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Abstract. This research paper studies the impacts of HVAC system scheduling and building envelope material properties on the building energy efficiency in the downtown New York City, metropolitan area, that is highly associated with Urban Heat Island. By utilizing EnergyPlus for whole energy building simulation, the research compares two HVAC operational cases: a baseline case with constant temperature setpoints, and an occupancy-based temperature setpoint schedule. The study also investigated the influence of thermal conductivity variations in stucco exterior wall materials, with three cases, the default baseline thermal conductivity and a ±15% variance, respectively. Results indicate that occupancy-driven scheduling significantly reduces energy consumption by approximately 16% annually compared to baseline. Conversely, the influence of thermal conductivity on energy consumption is minimal, with only a 0.35% deviation noted in response to a 15% variation in thermal conductivity. This suggests that both optimizing HVAC scheduling and the thermal conductivity of building envelope materials can save building energy consumption while optimizing HVAC scheduling has a relatively stronger impact than optimizing the thermal conductivity with a 15% variance in downtown New York City.

Keywords: Whole Building Energy Simulation, EnergyPlus, Occupancy Based Scheduling

1. Introduction

Building energy consumption contributes largely to global warming. In 2022, data from the U.S. Energy Information Administration (EIA) showed that the building sector revealed substantial energy consumption in the United States, accounting for approximately 40% of the total energy consumption with residential and commercial segments making up approximately 22% and 18%, respectively [1]. Moreover, the number of buildings increased by 22% and total floorspace by 35% from 2003 to 2018 according to a commercial energy building consumption survey generated by U.S. EIA [2]. The global energy demand continues to rise each year driven by such urbanization [2]. Therefore, maximizing energy efficiency is essential to reduce energy demand. Building energy consumption is determined by various factors, such as ambient temperature, building characteristics, appliance efficiency, and occupant activities. Among all the factors, ambient temperature is the most dominant one since heating and cooling contribute to the majority of the energy consumption for a building [2,3]. Due to urban heat islands, densely populated urban areas experience an elevated ambient temperature compared to the surrounding rural areas. This phenomenon results from heat-absorbing surfaces, less vegetation, and energy consumption. Consequently, it leads to an upsurge in cooling demands within buildings, particularly during hot weather as indoor temperatures rise due to the external urban heat, which results in higher greenhouse gas emissions and energy consumption [3,4,5]. Conversely, it forms a positive feedback loop, which causes more frequent and intensified Urban Heat Island (UHI) [6].

This research paper has conducted a thorough quantitative analysis of how to optimize building energy efficiency using the EnergyPlus simulation tool to mitigate urban heat islands with a specific focus on medium office buildings in New York City (NYC). It seeks to address the issue of UHI in urban areas like NYC by enhancing energy efficiency. The study's objective includes quantifying the cyclical loop effect between UHI and energy efficiency, identifying solutions, leveraging EnergyPlus simulations, and providing practical recommendations. By doing so, the paper will provide data-driven recommendations for problems posed by urban heat islands in densely populated urban areas, thereby endeavoring to enhance building resilience to heat and lessen global warming caused by building operations.

2. Literature Review

Urban Green Council has analyzed data from over 4,000 buildings in New York City, which shows the average site energy use intensity (EUI) of medium office buildings (50,000-150,000 sq ft) is approximately 104 kBtu/sq ft for the Education, Health Care and Commercial sectors. It is relatively high compared to the national median EUI around 30.8 kBtu/sq ft based on Benchmark guidelines like ASHRAE 90.1-2019 [7, 8]. Figure 1 illustrates the energy usage distribution in commercial buildings, categorized by various end uses. According to the 2012 Commercial Building Energy Consumption Survey by U.S. EIA, space conditioning including cooling, heating, and ventilation accounts for the majority of energy consumption, approximately 44%, in buildings, while the second largest contributor is lighting and refrigeration, each accounting for 10% respectively [9].

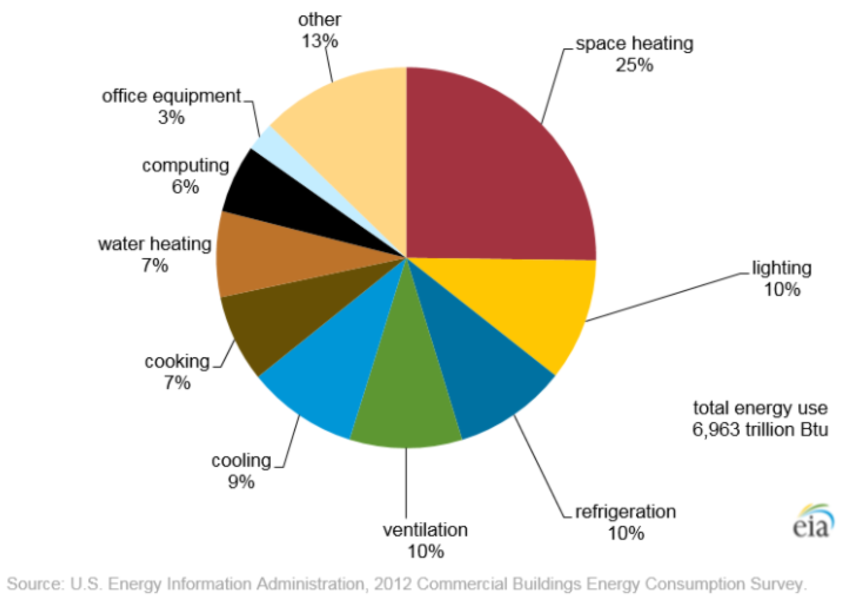

Figure 1. 2012 Commercial Building Energy Consumption Survey [9]

Space conditioning primarily includes two parts, temperature control (sensible heat) and humidification/dehumidification (latent heat). Heating equipment commonly used are heat pumps, packaged heating units, boilers, district heat, individual space heaters, and furnaces. Heat pumps provide both heating and cooling through refrigeration cycle reversal. Packaged terminal heaters are self-contained units with a heat source, fan, and controls. Boilers heat water or generate steam for distribution. District systems distribute steam, hot water, or chilled water from a central plant. Individual space heaters provide local zone heating using various heat sources. Furnaces heat air directly via combustion for distribution by ducts throughout spaces. With space heating accounting for a large portion of building energy consumption, the efficiency and control of these systems are critical for reducing energy usage. Cooling primarily involves lowering the air's dry bulb temperature and removing the moisture (dehumidification) from the air. In practice, typical equipment for cooling is the central system and the distributed cooling system. The central system includes a chiller and direct expansion system, and the latter uses a window air-conditioner and packed terminal air- conditioner. Central systems are more efficient than distributed systems when outdoor air is the coolest and it pre-cools the building in the early morning, removing heat to the air in occupied spaces. But for large building sizes like commercial buildings, distributed systems show less electricity per square foot compared to central systems [10,11].

For lighting, the New York City Energy Conservation Code (NYCECC) has implemented regulations regarding maximum lighting power allowances. These regulations have been progressively reducing lighting power density allowances over time, aiming to phase out inefficient lighting practices. As a result, LEDs would be the primary choice for lighting in most spaces [12].

Whole building energy simulation has been widely utilized at various stages, including design, operation, diagnostics, and commissioning of buildings. Its purpose is to analyze building energy performance, ensure occupant thermal comfort, and ensure compliance with codes and regulations. This tool plays a vital role for engineers, architects, and all stakeholders in the construction industry when making decisions about energy usage and material selection in the built environment. Numerous simulation tools are available such as eQuest, BLAST, DOE-2, DesignBuilder, Energyplus, and TRNSYS. EnergyPlus is widely used due to its prevalence, usability, functionality, and reliability, and it shows better performance while other tools may falter in more complex scenarios like varying conditionings or occupancy-based conditioning [13]. Energyplus is a free software, widely adopted by many users in academia and industry. With a large active user community, it benefits from real-world case studies and support for building energy simulations. EnergyPlus is also highly customizable, adapting different designs and equipment configurations and its co-simulation capabilities with other tools, which allows more comprehensive analyses. It performs sub-hourly time steps so it generates granular results over short intervals of time. Integrating heat and mass balance-based zone simulation gives an accurate analysis of the thermal load of each zone. Overall, all this makes Energyplus a powerful and versatile tool for performing whole-building energy simulation [14].

3. Case study - Building Energy Simulation using EnergyPlus

3.1. Building Introduction

The prototype building is located in Downtown New York City, an urban area heavily affected by UHI and weather data from Central Park, New York, has been selected as the representative dataset for the analysis. The building is a three-story structure, with each floor covering approximately 1666 square meters. The dimensions of each floor are 34 meters in width, 49 meters in length, and with a height of 2.7 meters. The building is oriented along an east-west axis. The facade features a total of 18 windows and 6 swing-wing doors distributed across all four sides. The entire building is divided into 15 occupied zones and includes 3 plenum zones with a height of 1.2 meters has been essential in enhancing airflow and environmental control within the building. Inside the building, it accommodates 15 occupants. The lighting systems are designed with a power rating of 8.2 W per zone. Additionally, the building contains 15 internal masses in the form of interior furnishings.

In terms of construction materials, the interior walls are constructed using a 13mm Gypsum Board, while the exterior walls are a composite of 25mm stucco, and 16mm Gypsum Board on both sides, with exterior wall insulation in between. The roof is constructed using asphalt shingles and plywood, and an AC02 acoustic drop ceiling enhances acoustic comfort within the building. The flooring comprises Res_Floor_Insulation with a thickness of 0.1 meters (4 inches) of heavy concrete, topped with CP02 Carpet PAD for added comfort. The building utilizes a simple glazing system with a U-factor of 2.83W/m^2K for its windows.

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In this case study, the summer design day is set for 07/21, while the winter design day is selected for 01/21. For the winter design day, a heating setpoint of approximately 21°C (69.8°F) has been chosen to ensure a comfortably warm indoor environment during the coldest days. Conversely, the cooling setpoint for the summer design day is set at around 24C (77°F). This specific measure is essential in preventing indoor temperatures from soaring to uncomfortable levels during the peak of the summer season while also considering energy conservation.

3.2. EnergyPlus Simulation Result

This case study investigates the impact of two crucial parameters on energy consumption: temperature setpoint schedules and thermal conductivity of construction materials, specifically stucco. The primary focus of this paper is on the Core_Mid zone with a significant area of 983.5 square meters.

Two sets of schedules are analyzed: the baseline case and the scheduled case. The baseline schedule maintains a constant temperature setpoint for cooling and heating demands, specifically 21 degrees Celsius for summer and 24 degrees Celsius for winter. Conversely, the scheduled-based schedule is occupancy-activities-based. Table 1 & 2 shows the occupancy-activities based on temperature setpoint. The setpoint varies from winter to summer, weekday to weekend, and also when the room is occupant to empty.

Table 1. Occupancy-activities based temperature setpoint schedule - Winter Design Days

Schedule-Based	Time	Temperature (°C)
Winter Design Days	Until 05:00	15.6
	Until 06:00	17.6
	Until 07:00	19.6
	Until 22:00	21
	Until 24:00	15.6
Weekdays (non-Design)	Until 05:00	15.6
	Until 06:00	17.8
	Until 07:00	20
	Until 22:00	21
	Until 24:00	15.6
Saturdays	Until 05:00	15.6
	Until 06:00	17.8
	Until 06:00	17.6
	Until 17:00	24
	Until 24:00	21
Sundays, Holidays	Until 24:00	15.6

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Table 2. Occupancy-activities based temperature setpoint schedule - Summer Design Days

Schedule-Based	Time	Temperature (°C)
Summer Design Days	Until 05:00	26.7
	Until 06:00	25.7
	Until 07:00	25.0
	Until 22:00	24.0
	Until 24:00	26.7
Weekdays (non-Design)	Until 05:00	26.7
	Until 06:00	25.6
	Until 07:00	25.0
	Until 22:00	24.0
	Until 24:00	26.7
Saturdays	Until 05:00	26.7
	Until 06:00	25.7
	Until 07:00	25.0
	Until 17:00	24.0
	Until 24:00	26.7
Sundays, Holidays	Until 24:00	26.7

Stucco, being the thickest layer in the building's walls, plays a significant role in determining the overall thermal performance. Its thermal conductivity is a critical factor due to the extensive use of this material in construction. This research paper focuses on analyzing the influence of varying stucco thermal conductivity levels on energy consumption, specifically Case 1 - default value (0.72 W/mK), Case 2 - 15% increase, and Case 3 - 15% decrease. The research aims to shed light on how subtle changes in stucco's thermal properties can impact the building's overall energy efficiency and comfort levels.

3.2.1. Comparison Analysis When Changing the Temperature Schedule. Figure 2 illustrates the comparative monthly whole building electricity consumption between the baseline and the optimized schedule cases. Both cases show similar consumption patterns, with peaks during the winter (1st highest) and summer seasons (2nd highest) aligned with New York's climatic extremes. Notably, the scheduled case demonstrates a consistent reduction in electricity demand across all months. Quantitatively, this represents a 16% annual reduction in electricity usage compared to the baseline, resulting in operational cost savings of $19,249, given the local rate of $0.21/kWh. The disparity is most pronounced in December, where the scheduled case achieves a 22.3% reduction. These findings confirm the efficacy of optimized scheduling as a key factor for enhancing energy efficiency and minimizing electricity costs. Such strategic scheduling is pivotal for bolstering sustainability and achieving cost-effective building management.

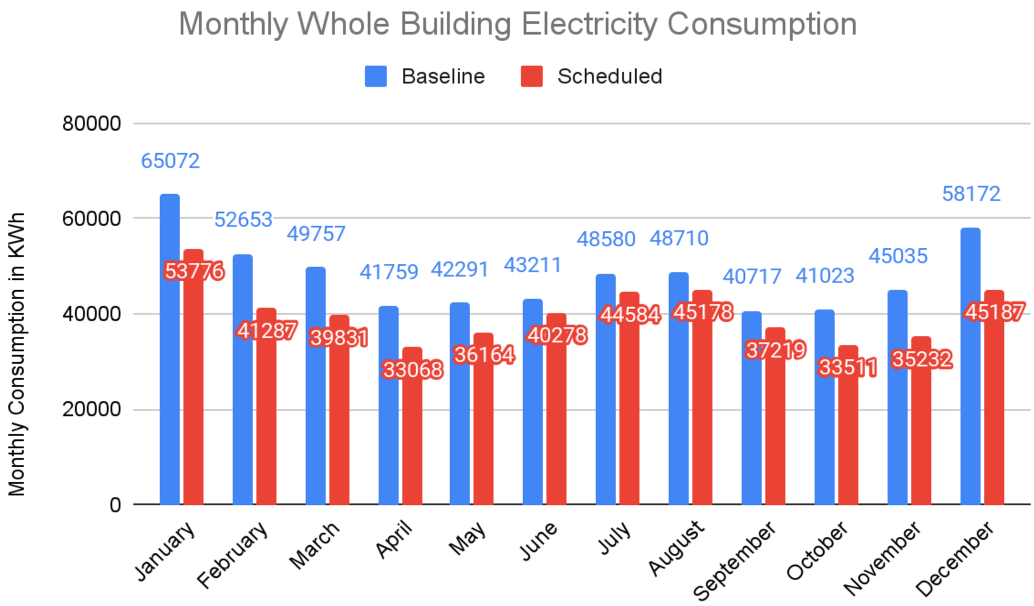

Figure 2. Monthly Whole Building Electricity Consumption of Baseline case VS Scheduled case

Figure 3 presents a monthly comparative analysis of cooling electricity consumption for the baseline and scheduled cases. The peak consumption for both cases occurs in July, the year's hottest month, while negligible demand for cooling is recorded in January. The scheduled case exhibits a 20% reduction in electricity consumption compared to the baseline in the peak month. Notably, the ascent to the peak consumption in the scheduled case (4,826 kWh/month) is less steep than in the baseline (6,262 kWh/month), underscoring the effectiveness of the optimized scheduling in moderating cooling energy usage in the long run. This analysis highlights that scheduling strategies yield substantial energy savings, reflecting a more balanced cooling energy profile throughout the year.

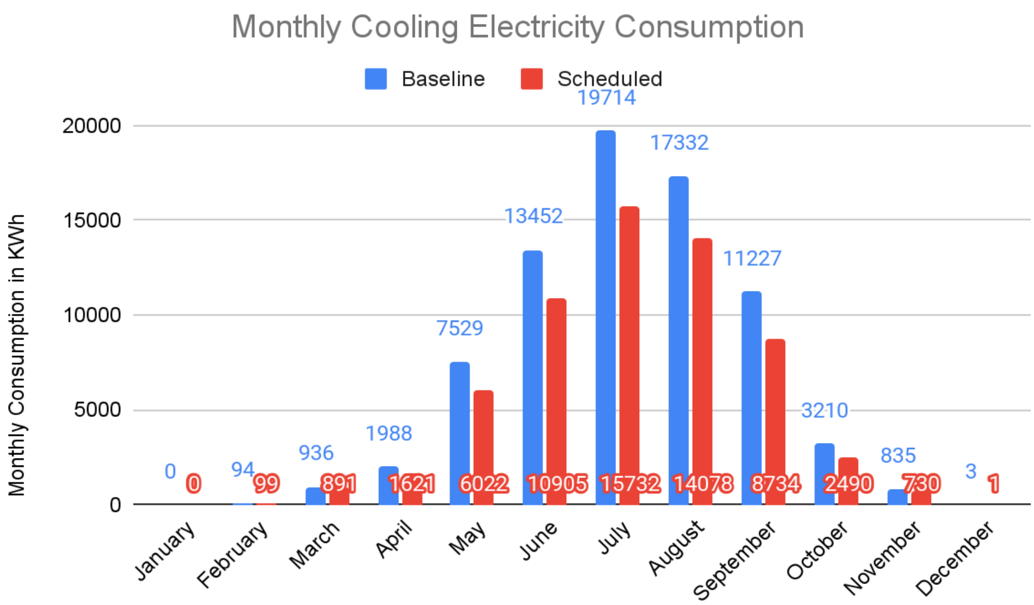

Figure 3. Monthly Cooling Electricity Consumption of Baseline case and Scheduled case

Figure 4 shows monthly comparisons of heating energy consumption, including both electricity and gas, for the Baseline case and Scheduled case. In January, the Baseline case's peak heating energy consumption reached approximately 61,877 kWh, markedly surpassing the Scheduled-Based case, which is around 39,467 kWh. This pattern persists throughout the year. Baseline cas, on average, shows a 61% higher heating energy consumption than its Scheduled case. The greatest discrepancy occurs in January, where the Baseline case's consumption exceeds that of the Scheduled-Based by 48%, emphasizing the impact of strategic scheduling on energy efficiency.

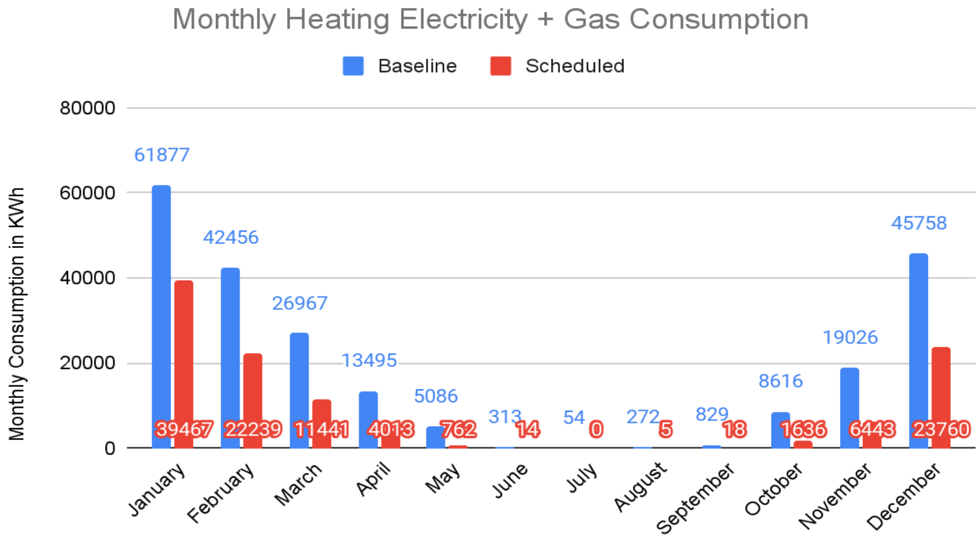

Figure 4. Monthly Heating Energy Consumption of Baseline case and Scheduled case.

Figure 5 shows an analysis of hourly energy consumption on a design day, specifically July 21st, for the Baseline and Scheduled cases. The data reveals that both cases have a similar hourly energy consumption pattern characterized by minimal energy usage before 6 AM, attributable to the absence of occupants. At 7 am, with occupant arrival, there is a significant increase in electricity consumption peaking at 3 PM. Subsequently, from 4 PM onwards, it shows a decline in consumption due to fewer occupants. It is noteworthy that during the 8 AM to 9 PM interval, the Baseline case indicates less electricity use due to a consistent temperature setpoint compared to the Scheduled case. Outside of these hours, the Scheduled case demonstrates less energy use. Overall, the Scheduled case's total daily electricity consumption, amounting to 2,016 kWh, is lower than the Baseline (2,146 kWh), which is about 17% daily electricity saving.

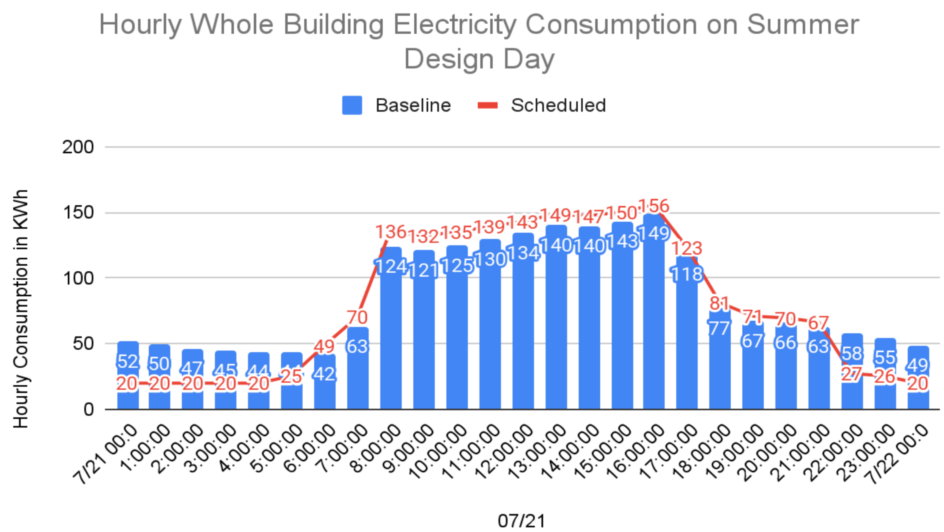

Figure 5. Hourly Whole Building Electricity Consumption for Baseline case and Scheduled case

Figure 6 presented below indicates the hourly cooling electricity consumption, which mirrors the consumption pattern observed for the building's overall electricity use. Before 5 AM and after 10 PM, the electricity use remains minimal due to low occupancy levels and reaches a peak at 3 PM. A distinct point worth mentioning is that the scheduled case has zero cooling electricity consumption due to absent of occupancy, thus postponing activating the cooling system till 5 am and switching off cooling after 10 pm. However, during occupied hours from 6 AM to 9 PM, the scheduled case shows a higher cooling electricity usage than the baseline case. In total, the scheduled case still obtains a daily electricity saving of approximately 14%, with consumption figures of 794 kWh compared to the baseline's 928 kWh, highlighting the benefits of strategic scheduling in energy conservation efforts.

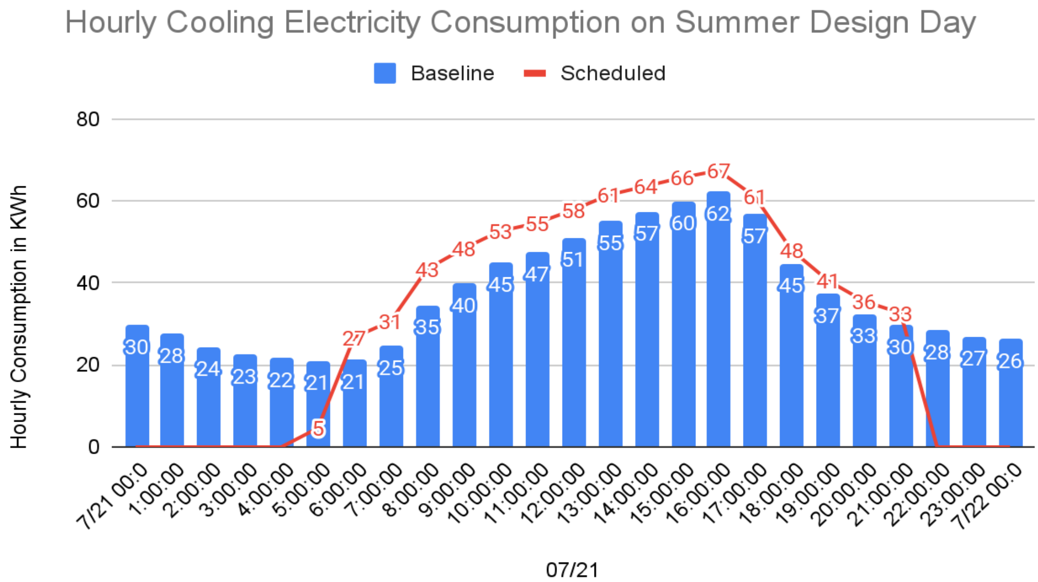

Figure 6. Hourly Cooling Electricity Consumption of Baseline case and Scheduled case

3.2.2. Comparison Analysis When Changing Thermal Conductivity. In Figure 7, Case 1 is the baseline with default thermal conductivity while Cases 2 and 3 have decreased or increased by 15% for stucco's thermal conductivity. Both cases reveal a similar pattern with the reference to Case 1. Moreover, it is positively correlated between thermal conductivity and electricity usage for both cases. This is expected since thermal conductivity measures the ability of a given material to conduct heat, the higher the value it is, the easier it is for the construction materials to lose heat and thus require more energy to maintain the temperature setpoint. In case 2, a 15% increase in thermal conductivity results in an increase in electricity consumption. In Case 3, where a 15% decrease in thermal conductivity, leads to reduced electricity consumption. Both cases demonstrate a similar seasonal pattern, with the differences being minimal from May through October and more substantial during the winter months. The largest discrepancy occurs in December, aligning with the extreme weather conditions typical of New York winters. The anomaly happened in August, and it shows an increase in electricity consumption with a 15% decrease in thermal conductivity. In total, the annual change in whole building electricity consumption is not significant with a 0.19% difference for both cases.

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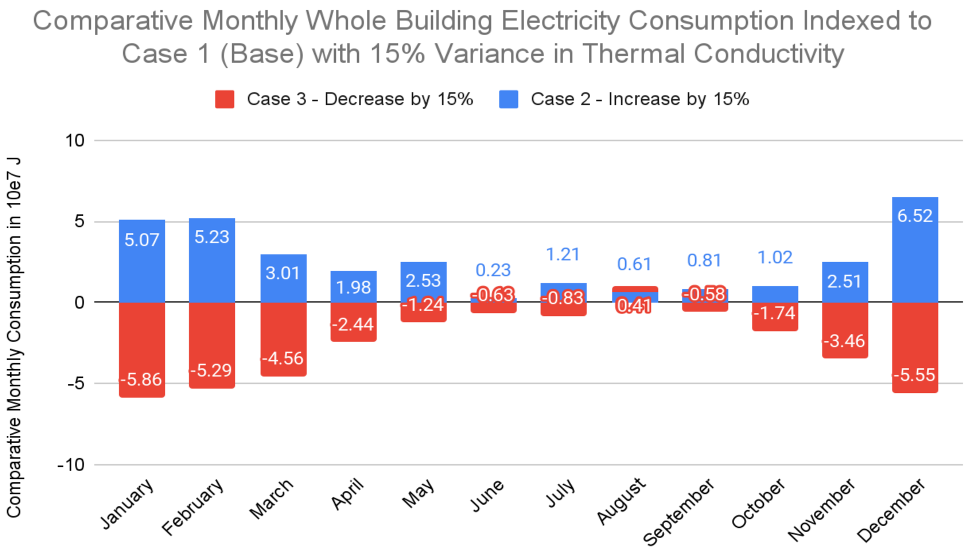

Figure 7. Comparative Monthly Whole Building Electricity Consumption Indexed to Baseline Case 1

Figure 8 depicts the variance in cooling electricity consumption for Cases 2 and 3, benchmarked against Case 1. It appears that alterations in thermal conductivity do not exert a direct impact on the cooling loads when considered in totality, in contrast to heating loads. Data shows a 0.022% consumption increase for Case 2, and a 0.008% change in consumption decrease for Case 3. Notable deviations are recorded in August and April, where a reduction in the thermal conductivity of the building's envelope material, stucco, correlates with a rise in cooling electricity consumption. This may suggest that the influence of thermal conductivity on enhancing energy efficiency is very constrained.

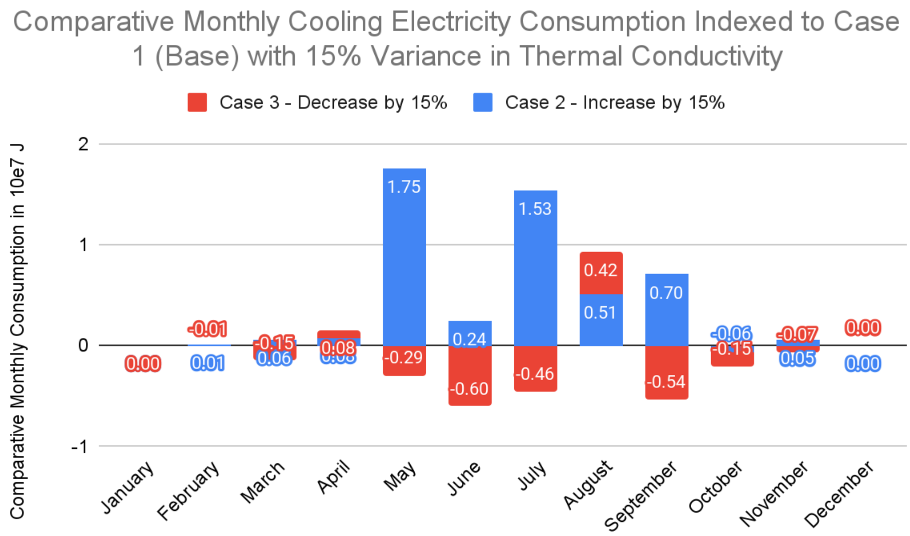

Figure 8. Comparative Monthly Cooling Electricity Consumption Indexed to Baseline Case 1

Figure 9 presents the monthly results of heating electricity consumption of Case 2 and Case 3, taking Case 1 as the baseline for comparison. Both Case 2 and Case 3 follow a similar seasonal consumption trend regarding variations in thermal conductivity. The data indicates a higher energy usage during the winter months, peaking in December, while mid-year months show a reduced demand for heating. This pattern consistently shows a positive correlation between thermal conductivity and electricity consumption. Furthermore, these variations in consumption align with the overall monthly energy usage trends as in Figure 9. However, the data suggests that the potential for energy savings through modifications in the thermal conductivity of stucco is somewhat constrained because the annual change in heating electricity is only about 0.35% in both cases in comparison to baseline Case 1.

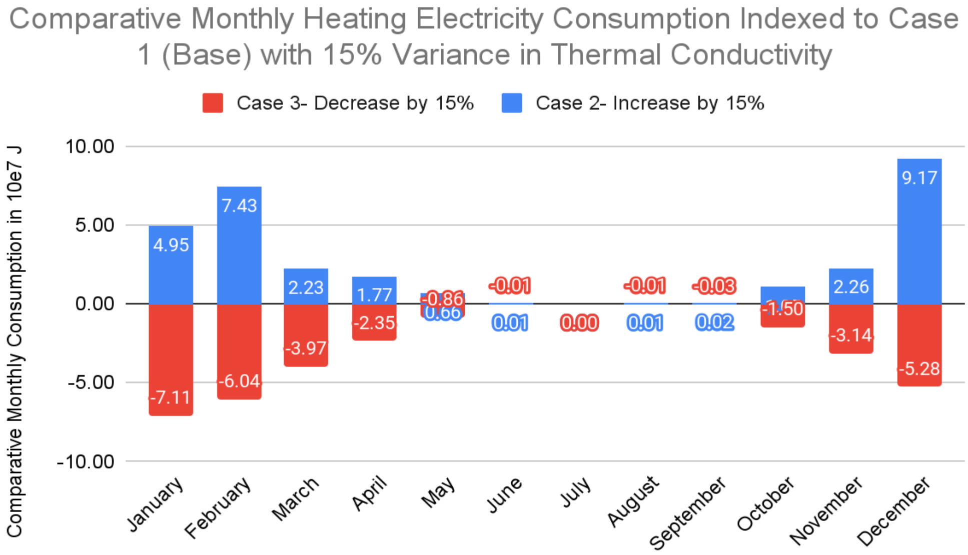

Figure 9. Comparative Monthly Heating Electricity Consumption Indexed to Baseline Case 1

4. Conclusion

In conclusion, the observations from this case study indicate that optimizing HVAC schedules based on occupancy can lead to significant reductions in electricity consumption, improve HVAC performance, and generate operational cost savings. The impact of thermal conductivity (changing by 15% on stucco materials, particularly) on energy efficiency, while present, appears to be marginal, particularly during seasons with extreme weather such as the hot summer months. It is recommended that the implementation of smart thermostats, which can dynamically adjust to occupancy patterns, could serve as an effective measure to enhance energy efficiency further. This approach aligns with the broader objectives of sustainable building management and energy conservation.

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