Mid-century Modern Building Improvement Strategies and Impact on Performance

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ABSTRACT

One of the universal ideals of modern architecture in the Mid-century (MCM) was to streamline the built environment to allow for an improved quality of life. Critics often lament that these attempts to streamline also result in poor building envelope performance (i.e. non-thermally broken details, insufficient insulation, etc.). As a result, while some MCM buildings are celebrated as unique designs, others are branded as dated-looking energy hogs.

According to the U.S. Energy Information Administration, the building sector consumes nearly half (47.6%) of all energy produced in the United States. Furthermore, nearly seventy-five percent (74.9%) of all electricity produced in the U.S. is used to operate buildings. As such, in order to make a meaningful impact on energy usage, the design and construction community has turned to improving the performance of existing buildings.

In this technical paper, property-specific whole-building energy usage, recently made public by the Chicago Building Energy Use Benchmarking Ordinance (herein called "Ordinance"), will be evaluated to determine energy use trends for MCM buildings in Chicago. Buildings of this age and construction are predicted to perform more poorly than generations of earlier buildings, which often relied on mass construction techniques, and more recent buildings, which have been designed and built under updated energy codes.

To further study the potential of MCM buildings, a parametric energy model of a 1960s brutalist commercial building, located in the Chicago Loop, was studied to generate a discussion on the impact of various building improvement strategies.

ORDINANCE BACKGROUND

Initially passed in 2013 with the first reporting period in 2014, the Ordinance requires all commercial, institutional, and multifamily residential properties 50,000 square feet (ft2) or greater to measure and report whole-building energy use once per year, and to verify the accuracy of reported data once every three years. The results have been published in the "City of Chicago Energy Benchmarking Report 2016;" a summary of the results as they relate to MCM construction is included herein. It should be noted that since the Ordinance utilizes the U.S. Environmental Protection Agency's ENERGY STAR Portfolio Manager online software tool to track consumption, reporting is given in terms of ENERGY STAR Score (the ENERGY STAR Score is a 1-100 rating of energy performance, with 100 being a top performer).

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SUMMARY OF RESULTS

For the purposes of this review, MCM buildings will refer to buildings constructed between the years 1933 to 1965. In Chicago in 2016, the average ENERGY STAR Score of office buildings from this era was nearly 72, which is significantly higher than the median for all office buildings in Chicago, which was 59. Additionally, as buildings grow in size, the energy use tends to grow as well; for buildings greater than 500,000 square feet, the median Energy Star Score exceeds the Chicago Median and trends upwards. Refer to Figure 1.

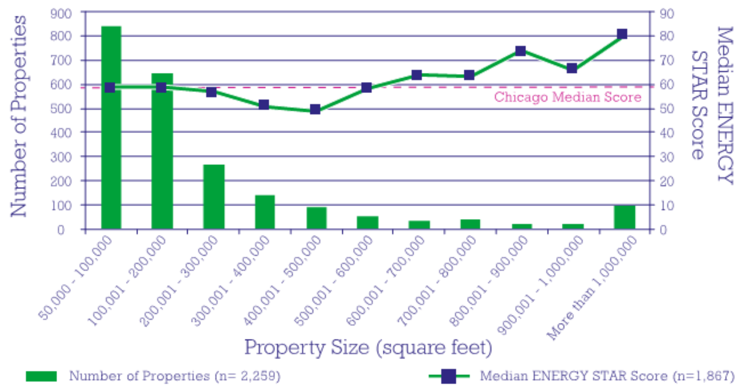

Figure 1 Number of Properties and Median ENERGY STAR Scores by Floor Area.

Many buildings that are of fifty years of age or older require considerable maintenance of various systems (e.g. building windows, roofing, mechanical equipment) to perform adequately. For example, in the case of window systems, gaskets or sealants have often failed due to age, resulting in issues such as water intrusion and costly repairs. When various components reach their anticipated lifespan, building owners may turn to replacement in an effort not only to improve performance, but also to update the building aesthetics and compete with newer building stock.

The results validate the notion that the design community has a unique opportunity to improve the energy performance of MCM buildings, particularly in dense areas such as the Chicago Loop (buildings larger in size use more energy, and they tend to be located in areas such as the Chicago Central Business District).

CASE STUDY

The research in this paper utilized parametric analysis of a 1968 Brutalist cast-in-place concrete building (herein referred to as the "Building"), located in Chicago Loop, to evaluate the potential of various building performance improvement strategies. Typical of buildings of this construction type and age, the Building's windows are constructed of single pane bronze glass at the typical floors (insulated glazing units, or "IGUs," are located at the mechanical floor only, presumably for acoustic reasons). Based on the 2016 Energy Benchmarking data, the Building has a reported Energy Use Intensity (EUI) of 88 kBtu/sf-yr and an ENERGY STAR Score of 76, which exceeds the overall Chicago median but is near the average for MCM commercial buildings.

Thermal and energy analysis was performed and calibrated to the architectural details and Energy Benchmarking EUI value. The objective was to better understand the way in which the Building is performing, as well as the most optimal areas for improvement. The goals for the improvement strategies were aesthetics, energy performance, and occupant comfort. T implementation strategies were identified, Option 1: Retrofit and Option 2: Overclad.

THERMAL ANALYSIS METHODOLOGY & RESULTS

The existing construction of the exterior wall was first investigated for its thermal performance. Two-dimensional computer heat transfer analyses were performed with LBNL software THERM 7.4 and WINDOW 7.4. These programs enable the calculation of stationary (steady-state) distributions of temperature and heat flow using the finite element analysis (FEA) method. The analysis was performed with the goal of understanding the thermal performance in terms of thermal mass and potential for condensation. Boundary conditions were assumed to be typical for winter, with 0° F outside and 70° F inside. This would be the worst-case for condensation, as cold air would be meeting warm interior surfaces.

The results indicated that the concrete performs quite well in terms of acting as a thermal mass, with a gradual gradation from outside to inside, and maintaining the interior surface warm and above the dew point. However, the frame and single pane glass are poor performing, creating extremely cold surfaces and likely resulting in heat loss and thermal discomfort. Refer to Figure 2.

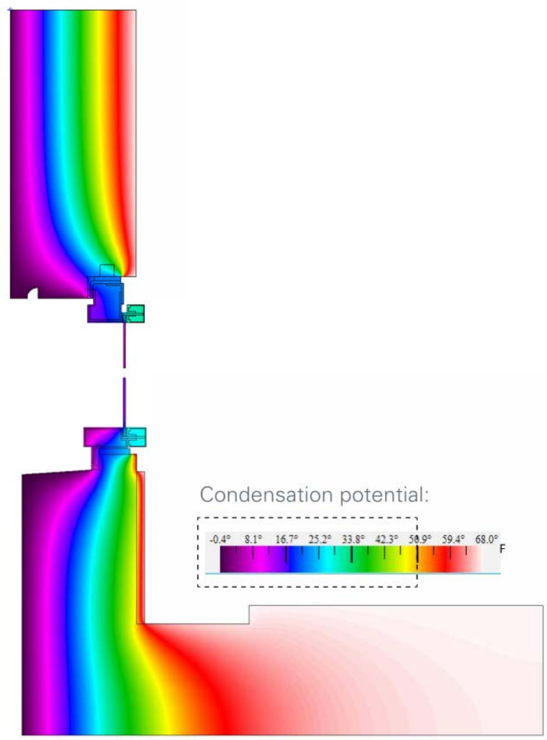

Figure 2 THERM Model of typical section of the Building.

ENERGY ANALYSIS METHODOLOGY & RESULTS

An optimal energy approach is to first reduce loads, and then incorporate highly efficient mechanical systems (Figure 3). This ensures the most efficient building performance, because mechanical systems are sized appropriately. As such, the approach for this case study was to focus on the building envelope in lieu of mechanical improvements, as well as other measures accessible to building occupants (e.g. plug loads) prior to review of the mechanical systems.

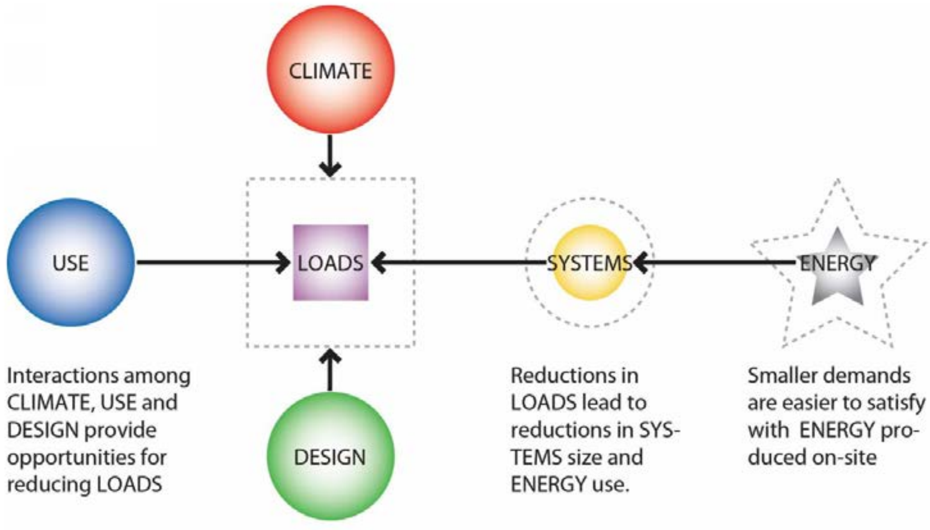

Figure 3 Compounding energy use reduction by right-sizing mechanical equipment for reduced heating and cooling loads.

With this in mind, a schematic energy model was created with DOE-2 eQuest v3.65 (Figure 4). This model was based on architectural drawings, particularly for the envelope: the wall construction, glass composition, and window-to-wall ratio. Typical assumptions were incorporated for lighting, equipment, people, and schedules. A basic Variable Air Volume (VAV) system was modeled, with the intention of refinement with future mechanical information. Calibration was possible only to the Chicago Energy Benchmarking data, which showed the building to have an Energy Use Intensity (EUI) of 88 kBtu/sf-yr.

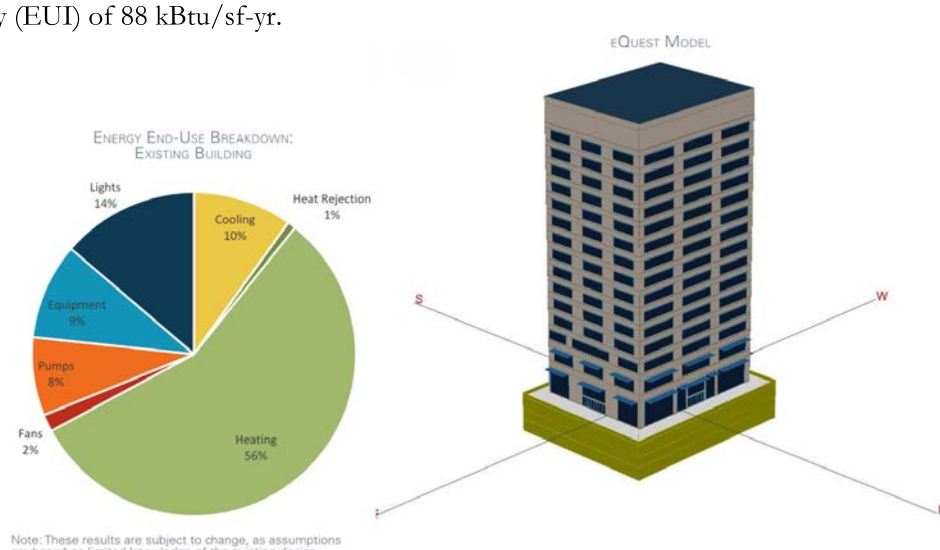

Figure 4 Building energy model and breakdown of resulting end-uses.

While the model was based on limited knowledge of the existing design, particularly of the mechanical systems, the results demonstrate that the largest end-use is heating (56%), followed by lights (14%), cooling (10%), equipment (9%), pumps (8%), fans (2%), and heat rejection (1%). Refer again to Figure 4.

ENERGY CONSERVATION MEASURES (ECMs) SUMMARY

Energy Conservation Measures were developed to target the largest end-uses. Efficient equipment and lighting, daylighting, high performance glass (Bronze VE4-85 and Clear VE1-2M), interior insulation (R-11, R-15, and R-21), an overclad (R-14), and a re-clad (R-21) were all considered and evaluated. The target was considered to be 20% reduction in energy use, based on the Retrofit Chicago initiative, an energy efficiency program with which the building was shown to be participating. Refer to Figure 5.

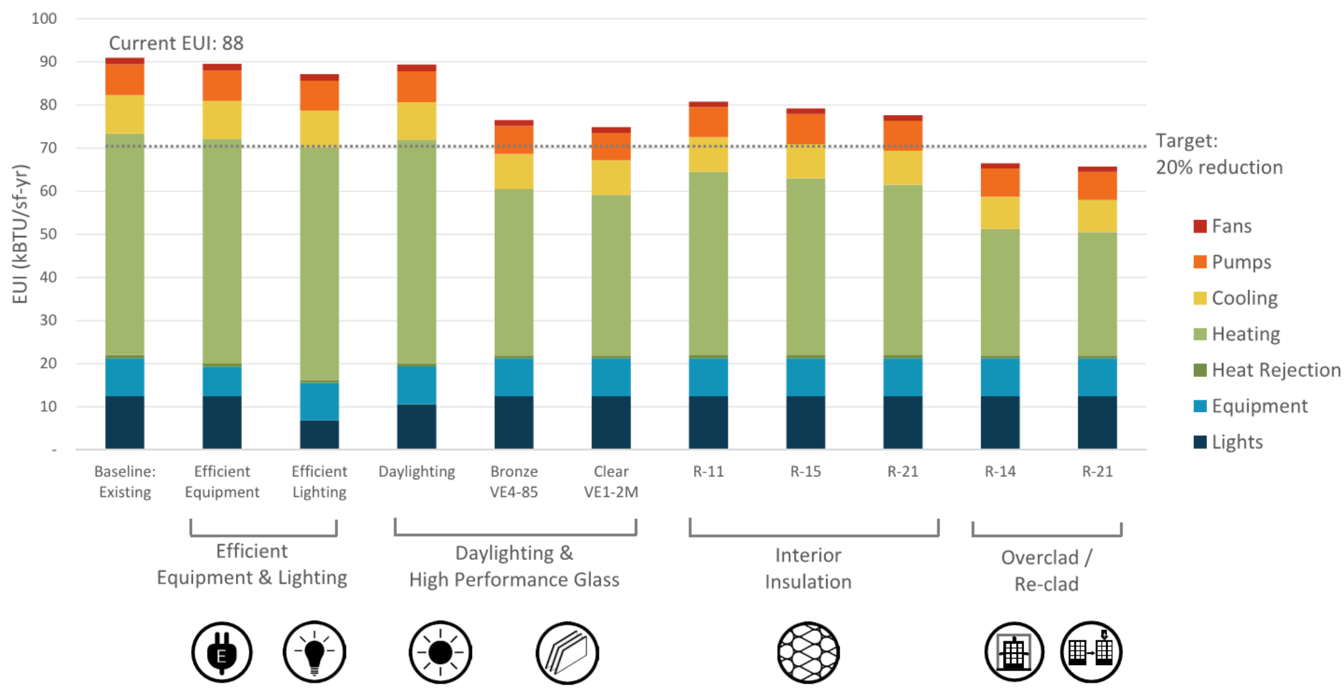

Figure 5 Energy Use Intensity of various ECMs considered for the Building.

Although each individual ECM would be an improvement to the existing design, some were more drastic, and therefore more significant in terms of energy use reduction, than others. A combination would be required to achieve the target, and therefore, cumulative cases for Option 1: Retrofit and Option 2: Overclad were evaluated. The Retrofit case included efficient equipment and lighting, high performance glass, and interior insulation, and resulted in a potential energy use reduction of 33%. The Overclad case included efficient equipment and lighting, as well as a double skin façade, and showed a potential energy use reduction of 34%.

With the implementation strategies – Option 1: Retrofit, and Option 2: Overclad – there is also significantly better thermal performance. The Retrofit, with double pane glass and thermally broken frame, still show surfaces colder than the dew point, but much improved from the current design. The Overclad, with a double skin façade, provides thermal insulation and results in interior surface temperatures greater than the dew point, with minimal condensation risk. Refer to Figure 6. Both options would also likely provide a more thermally comfortable environment for occupants.

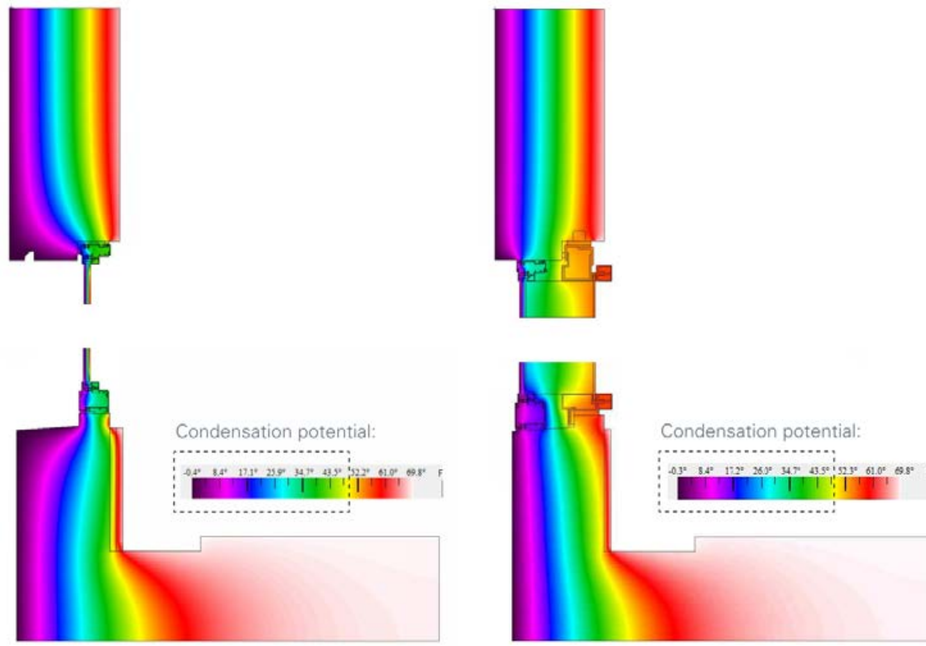

Figure 6 Heat transfer analysis comparison of Option 1: Retrofit versus Option 2: Overclad.

MECHANICAL SYSTEMS CONSIDERATIONS

As discussed, the mechanical systems were not modelled in detail. The intent was to first understand the amount of energy savings that could be realized with significant improvements to the building envelope, so that future mechanical replacement projects could be “right sized,” ultimately resulting in further cost and energy savings. Future work would involve modeling of more detailed mechanical system.

For the purposes of this paper, a discussion of mechanical system design from the MCM time period is included herein, along recent advantages in mechanical system design that can be leveraged to improve overall building performance.

MCM-ERA MECHANICAL DESIGN

MCM mechanical systems were frequently designed as constant volume; that is, the system level air handling unit (AHU) would supply a constant volume of air at a varying temperature. By nature, constant volume systems consume large amounts of fan power, as their supply fans lack the ability to "turn down" in times of reduced airflow requirements (i.e. in heating mode, when a space has little heat loss or has a perimeter heating device). Constant volume systems are available in a variety of configurations, including a dual duct scheme as well as being coupled with induction units.

The dual duct systems use two constant volume air streams, one hot and one cold, which are commonly referred to as the “hot deck” and “cold deck.” These hot and cold decks maintain a constant discharge temperature (e.g. 50°F for the cold deck and 90°F for the hot deck), and make use of a mixing box at the zone level to determine the portion of air that should come from each deck depending on the current load. While this configuration successfully satisfies simultaneous heating and cooling loads, it does so at a huge cost in the form of increased duct work, increased fan power, and increased heating & cooling consumption.

A second (and perhaps more common) variation of a constant volume primary system is coupling the main AHU with zone level induction units. For interior spaces with relatively low loads, the main AHU is used alone to condition the space, whereas for perimeter spaces (with increased and varying loads) induction units are used to complement the main AHU. The induction units make use of chilled and hot water to satisfy diverse heating and cooling needs of the space, but require increased static pressure by the units in conjunction with a high volume of primary air.

LEVERAGING MORE AGGRESSSIVE MECHANICAL SYSTEMS

The most common replacement for an outdated constant volume system is a single duct variable air volume system with a reheat coil located at a zone level. This system discharges a varying amount of air at a constant discharge temperature. Once the varying volume of air reaches the zone level, it is either released into the space at its system level discharge temperature (typically 55°F in cooling mode) or it is reheated as necessary (heating mode). This change alone from constant volume to variable volume provides a great deal of energy savings.

These energy savings can be even further compounded on by the implementation of efficient hydronic zone level systems. As a heat transfer medium, water is substantially more potent than air, which allows passive or active (chilled sail or chilled beams) systems to be so effective. Rather than relying on large quantities of conditioned air, which must be supplied via substantially sized ductwork at equally substantial static pressure and fan power, today's most energy efficient concepts focus on supplying as little primary air as possible (usually code minimum outdoor air) and handling the bulk of the heating and cooling loads themselves at a zone level. This configuration is most commonly known as a dedicated outdoor air system, or DOAS. As the name alludes, the system is dedicated to only conditioning and supplying the required outdoor air volume.

Unfortunately, finding an optimal auxiliary space level system to function in concert with the previously described DOAS is more complex than simply picking the most “aggressive” system available (the term “aggressive” is used in this context to indicate the most efficient or least energy intensive system types). The successful implementation of a given aggressive system type is only made possible through reductions in the space’s load density. Examples of these technologies and their corresponding load thresholds can be seen below in Figure 7. This chart demonstrates that the successful implementation of an active slab would require a cooling load density of under 50 Btuh/sf.

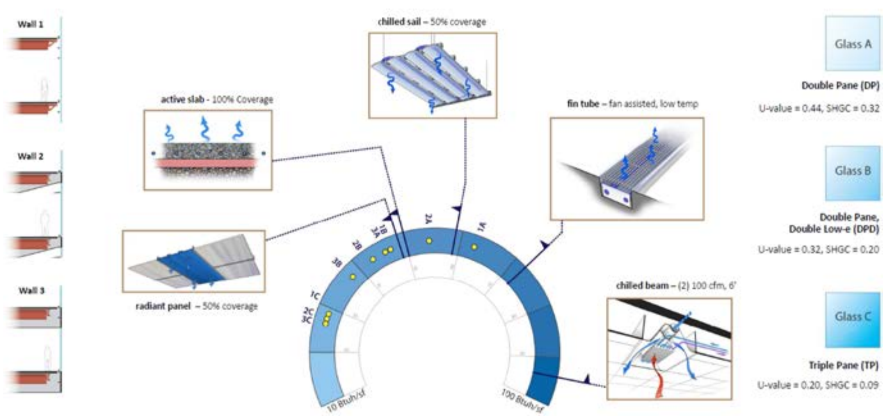

Figure 7 Load density thresholds for various “aggressive” mechanical systems,

CONCLUSION

Major improvements to the MCM building envelope can create synergistic results when coupled with efficient mechanical system design. For example, replacing existing glazing with new glazing possessing a lower solar heat gain coefficient (SHGC) as well as a higher visual light transmittance (VLT) can have a twofold effect on reducing the cooling load density of a space. The new glazing's reduced SHGC means that a lower portion of the radiation falling on the exterior surface of the glazing will manifest itself as heat gain in the space. The increased VLT allows for more visual light to enter the space, which, if used in conjunction with daylight harvesting, will allow for the lighting fixtures in the space to reduce their output or turn off completely. This strategy obviously leads to lower interior lighting power consumption but also means that the heat gains associated with lighting in the space have also been reduced, thus lowering the spaces cooling load density. It is important to note that in terms of energy, a linear addition of the savings from each ECM is not possible, as strategies interact with each other.

In Chicago, MCM-era buildings offer a unique opportunity to make a significant improvement in the energy usage of the existing building stock while keeping with one of the universal ideals of this time period; that is, to use new technology, construction techniques, and materials to result in better living through design.

ACKNOWLEDEGEMENTS

The authors would like to thank Thornton Tomasetti for their ongoing support of this project, particularly Ken Maschke and Vamshi Gooje. We would additionally like to thank the City of Chicago Energy Benchmarking Results, Analysis, and Building Data Reports, and for striving to make Chicago even more energy efficient and sustainable.

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