ABSTRACT
Historic building preservation should not be considered an obstacle to sustainability, they inherently share the fundamental goal of preserving the environment. The renovation and rehabilitation of a building envelope provides a preservation benefit of the embodied value/energy of the historic building. The scope of this paper examines how the architectural preservation of Ludwig Mies van Der Rohe's S.R. Crown Hall, (home to the Illinois Institute of Technology's College of Architecture) has impacted the energy use intensity (EUI) of the building as well as the indoor environmental quality (thermal comfort) of its occupants. S.R. Crown Hall has adapted to many new technologies and ventilation strategies in a recent envelope rehabilitation but at the most fundamental level of the project the original philosophy of Mies' 1954 design of the building had to be maintained (the fabric of the building was regarded as sacrosanct). Advanced building simulation was used to provide an in-depth building performance analysis to derive the EUI of the building and to model the occupant thermal comfort with the use of Computational Fluid Dynamics (CFD) to simulate internal airflows.

INTRODUCTION
S.R. Crown Hall (a donation by the Crown Family in the name of Sol R. Crown provided the iconic name for the building) was completed in 1956 (see Figure 2) and since then had deteriorated for nearly fifty years of continuous use to the point where the integrity of the building envelope had been seriously compromised. 2006 marked an important year for the historic landmark when the entire building envelope underwent a complete rehabilitation. The scope of work included replacing corroded steel components of the envelope, sandblast removal of all lead-based paint from the interior and exterior steel, application of a three-coat epoxy paint, and the replacement of all the glass lites including the stops. Such a rigorous rehabilitation of an envelope could positively or negatively affect the energy utilization of the building as well as the thermal comfort of its occupants. This paper appraises the original design of S.R. Crown Hall at its completion in 1956 (according to the 1954 permit set) where a retrospective on how the original building operated was examined and compared to the energy profiles and indoor environmental quality of an ASHRAE 90.1-2004 Baseline (code compliant) Model and the 2006 renovation. Three building simulations of S.R. Crown Hall are presented: (1) the 1956 Historic building design (2) the code compliant Baseline and (3) the 2006 Proposed building design. There were several interim renovations leading up to the 2006 rehabilitation of the envelope that will be included in the Proposed simulation to examine the compounding effects of the new building components, electrical loads, and system changes to the heating, ventilation, and air-conditioning of the building. The Baseline building is provided in this study as a benchmarking reference to faithfully compare the design alternatives implemented in the Proposed building design. The Historic building model is merely an academic examination of the influence that modern architecture once had on the energy utilization of a building. The Proposed building will be compared to the Historic building model solely to analyze how the indoor environmental quality has improved. The following building metrics will be discussed:

1. Building Load
2. Daylight Factor
3. Whole Building Performance
4. Thermal Comfort

A general description of the featured elements of the Historic, Baseline, and Proposed building designs are provided in the preceding section.
Historic, Baseline, and Proposed Building Designs


**Figure 2 - S.R. Crown Hall 1956**

S.R. Crown Hall consists of a 120 foot wide by 220 feet long, 18-foot high column-free hall (known now as the Upper Core), in which the space is subdivided by low freestanding wall and two non-structural service shafts into student work areas, a central exhibition space and administration corral. The hall is raised 6 ft above the ground in order to provide natural light and ventilation for the workshops and lecture rooms located on the floor below. From the south the building is approached by a broad flight of steps, interrupted at mid point by a floating platform; this structure is separately articulated from both the building and the ground, and upon mounting it one is imperceptibly lifted from the one to the other.

Four externally exposed steel bents - located at 60 ft intervals - carry a steel framed roof, which in turn cantilevers in the longitudinal direction 20 ft beyond the end supporting members. The building's substructure is of re-enforced concrete construction and is independent of the superstructure. The skin is composed of welded steel components and is glazed with clear and translucent glass. All exposed steel is painted black. The exterior stairs are steel framed and paved with travertine. In the interior, the floors are either dark gray terrazzo with black and white flecks or black Formica tiles, the ceiling is a white acoustic gypsum tile, the walls of the two service shafts are plastered and painted white, and the freestanding walls are panelled in oak.

**Historic Building Design**

S.R. Crown Hall was completed when the influence of Mies van Der Rohe's Modernist style was at its highest. The result of the stunning simplicity and elegance of Mies' transparent design came with its share of environmental challenges.

The Historic building facade consisted of two types of glazing: non-tempered ¼" thick upper panels which spanned 9'-8" by 12'-9" (Center-of-Glass: U=1.025, SHGC=0.818, VLT=0.884) and non-tempered ¼"-thick lower panels with a sandblasted interior surface to provide privacy to the building occupants (Center-of-Glass: U=1.025, SHGC=0.844, VLT=0.891). A 5/8" thick steel bar stock was used for the Historic window stop (see Figure 3). With no energy codes to dictate the size, thickness, or performance of the glazing (at that time), Mies was unrestricted with his architectural concepts.

The 1954 design relied heavily on louvered natural air inlets at the perimeter of the building (located at a low level) that worked in tandem with the cross ventilation system to cool the building. The local mechanical extraction air path was located at a high level (through a perimeter reveal at an 18' floor-to-ceiling height) to encourage the venting of heat gains from the envelope while supplying fresh air directly to the occupied zone.

**Figure 3 – Baseline vs Proposed Stop Detail**

Heating was provided by means of a hydronic radiant floor system (concrete slab embedded with pipework) and through the introduction of forced warm air through the overhead ceiling diffusers. The interstitial radiant concrete floor provided heating to zones on the main floor as well as lower floor zones (in the basement). The perimeter zones were designed on a 1' grid spacing where it operated continuously to counteract cold downdrafts from the glazing and compensated for the heat loss at the envelope. Interior zones were designed on a 2' grid spacing that was thermostatically controlled which allowed the system to respond to variations in internal loads. The main floor ventilating system comprised of three constant volume air-handling units (AHUs) located in the mechanical penthouse. AHU-1 supplied air to the north perimeter of the building; AHU-2 supplied perimeter and interior diffusers in the southeast quadrant; and AHU-3 supplied perimeter and interior diffusers in the southwest quadrant of the main floor. Penthouse exhaust fans (four in total) provided extract for the entire building.

The lower floor rooms were in the most part naturally ventilated by bottom-hung windows that opened approximately 20° from the vertical plane of the
window into the interior of the rooms. Mechanical ventilation was provided only for select interior spaces such as Restrooms and Offices. Perimeter heat was provided by hot water steel finned-tubed radiators that operated on a continual basis.

The Historic internal loads of S.R. Crown Hall were very different from the Proposed building design. The main floor overhead lighting (T-12 fixtures with magnetic ballasts) operated continuously at 2.7 Watts/ft² with no programmable control. This undoubtedly conflicted with the transparent facade design (the lighting was extensive). The occupancy of building was maximized at 230 occupants and simulated at an approximate sensible and latent heat load of 225 Btu/person and 105 Btu/person respectively. The main floor was primarily used as a studio space (see Figure 4) where there was little to no plug load simulated in the Historic building design.

**Proposed Building Design**

As previously mentioned, the envelope rehabilitation included replacing all of the original glazing. The original lites of the upper panels were replaced with PPG Starphire (low iron) glass (Center-of-Glass: U=0.944, SHGC=0.830, VLT=0.899) and the lower lites were replaced with a Clear tempered glass from Viracon (Center-of-Glass: U=0.572, SHGC=0.431, VLT=0.799). To recreate the exact same effect as the original lites, the inner face of the lower glazing panes were sandblasted in addition to an application of three layers of ultra-clear epoxy (which has no reflectivity) to improve the durability of the interior surface.

The Proposed window stop (as shown in Figure 3) has the lower stop matching the original while the upper stop was improved with a 5/8” sloped face which facilitated the removal of moisture accumulation at the glazing channel. The design of the Historic building stop was prone to corrosion and oxidation from the presence of water and air moisture that pooled at the steel stop. This made the steel stops buckle thereby fracturing the large panes of glass (see Figure 5). This type of deterioration was common throughout the building enclosure.

The natural ventilation louvers at the perimeter of the building had all but deteriorated away with the envelope. Operationally, the day-to-day management of opening the 120 or so louvers became unrealistic and quite tedious for the occupants of the building. During the renovation, the louvers were repaired and restored however; the function of introducing air at floor level to feed the cross ventilation system was abandoned.

S.R. Crown Hall relies on district energy to provide steam and chilled water to the building (cooling was added to the building during an interim renovation in 1979). The chilled water runs on the primary side of an exchanger and the secondary side is plain water in the building’s closed loop system. The district chilled water energy is transferred to the building loop through a plate-and-frame heat exchanger located in a lower level mechanical room. Hot water is generated from the campus steam system at a converter. The three main constant volume air-handling units that serve the main floor have been equipped with 6-row chilled water coils and one-row steam coils. The steam coils are located in the pre-heat position upstream of the cooling coils. The basement of the building is served by two new ventilation systems. The west unit supplies air to all classrooms, offices, and similar spaces on the lower level while the east unit supplies air to the shop area to make up for local exhaust from woodworking tools, paint and welding booths.

During occupied periods when the AHUs are running, the system can modulate the relief air dampers and the outside and return air streams to maintain 1,000-ppm CO₂ levels in occupied areas. The result of using demand control ventilation is that ventilation rates can be measured and controlled to a specific cfm/person based on actual occupancy whereas the more traditional method of ventilating a space is fixed, regardless of occupancy. The reduction of energy of such a system is the avoidance of heating, cooling, and dehumidification of more ventilation air than is needed.

The radiant floor heating system remained as part of the renovation of the building because it is a very effective means of heating a space. However, the control and operation of the system was dramatically improved with several features. During unoccupied periods, the temperature of the slab sets backs as a

---

**Figure 4 - View of Main Floor 1956**

**Figure 5 – Pre-Renovation Window Stop Corrosion**
function of the temperature of the space. The convertor steam valve resets the perimeter radiation supply water temperature as an inverse function of outside air temperature. The supply water temperature is provided at 125°F at an outside design temperature of -10°F and resets to 70°F at an outside temperature of 65°F. The interior slab system is operated so that the ventilation system responds more quickly to changes in the load of the space (the thermal inertia of the floor slab results in a lagging response time to varying room temperature changes).

A run-around coil heat recovery system has been retrofitted on three of the AHUs in the penthouse. The heat recovery system involved installing a piping loop containing a circulator pump that is connected a series of finned-tube coils (one in the exhaust plenum and one in the make-up air plenum). In the case of S.R. Crown Hall, the run-around coil preheats fresh air and pre-cools fresh air when the exhaust air stream is cooler than the fresh air (a reduction in peak heating and cooling loads can be expected with this type of configuration).

The main floor was upgraded with modern day lighting controls to maximize daylight harvesting. There were 34 daylight photo sensors installed to control the dimming of the overhead fluorescent lighting system. The daylight control system can reduce the energy demand of the lighting by dimming the lights proportionally to the amount of daylight that penetrates into the space while maintaining the proper illumination level at a specified working plane. The original main floor fixtures were replaced with energy efficient T-8 fluorescent lights and electronic dimming ballasts reducing the full load of the lighting to 1.8 Watts/ft².

The Proposed building occupancy is now more than 1.5 times the Historical building occupancy (total of 330 occupants) increasing the sensible and latent heat significantly. Not only has the number of occupants and their associated heat gain to the space increased but also the type of technology the students now utilize within S.R. Crown Hall. Computer workstations, task lighting, and other electronic devices have significantly increased the casual gains on the main floor, which requires more heat removal and ventilation.

During a roof repair in the 1980's, a coring of the roof revealed that the original specification of 2"-thick cellular polyisocyanurate insulation was actually reduced to a minimum thickness of 1" due to a change in the way the drainage falls were achieved on the roof plane. As a result of this discovery, the roof insulation in the Historic, Baseline, and Proposed building models incorporated the actual cored insulation roof value of 1-inch.

Baseline Building Design

At the time of the envelope rehabilitation, the governing energy code for the City of Chicago was ASHRAE 90.1-2004. To evaluate the energy impact of the various renovations made to S.R. Crown Hall, a Baseline code compliant energy model was created according to the methodology outlined in Appendix G. S.R. Crown Hall has been evaluated as an “Existing Building,” (as described by Appendix G), where the baseline building envelope reflects the existing conditions prior to any renovations. The baseline HVAC system in the Baseline building design was based on usage, number of floors, conditioned floor area, and heating source as specified in ASHRAE Standard 90.1-2004, Table G3.1.1A. The baseline system type was determined to be System 5 - Packaged VAV with Reheat (DX Cooling and Electric Resistance Heating). However, as explained later in this paper the Baseline System was revised from the ASHRAE Appendix G instructions to account for District Energy Systems used in the Proposed design. As a result, the Baseline system was revised to System 7 to include both District Heating and Cooling.

The Proposed and Baseline models utilized the same space setpoint temperatures. In summer mode the air-handling systems provide minimum ventilation air and supplies conditioned air at a design temperature of 75°F and 50% RH (with a setback temperature of 80°F) to maintain comfort levels. In winter mode the air-handling systems provides minimum ventilation air and supplies conditioned air at a design temperature of 70°F and 50% RH (with a setback temperature of 60°F) to maintain comfort levels. The systems schedules overlap the occupancy schedules with 1 hour of morning-warm-up time and 30 minutes of after hours operation. In an effort to normalize the operating schedule of S.R. Crown Hall, the following annual schedule was used: 8:00am-9:00pm Monday-Friday, and 8:00am-3:00pm Saturday-Sunday.

SIMULATION

Simulations were compiled through Integrated Environmental Solutions (IES) VE-Pro Building Performance Assessment Tools (version 6.4.0.7).

All reasonable efforts have been taken to ensure the accuracy of the energy model inputs, including verifying that actual details correspond to the original Historic building design, the Baseline model, and its' Proposed renovation (see Figure 1).

While no utility bills were available to properly calibrate the models in accordance to ASHRAE Guideline 14-2002 the simulated HVAC systems were configured and operated to maintain the comfort settings established within each respective design. Identical weather simulation data was used across the three building design models to facilitate a performance comparison between the envelope and system configurations. The annualized typical meteorological year weather data used for the simulations was type TMY version 3 (USAILChicagoO hareIntlAP725300TMY3.epw).
This annualized data set typifies the weather conditions across all energy simulations.

RESULTS ANALYSIS
Several building performance metrics are illustrated in the preceding section that directly influences the energy use intensity of the building and the thermal comfort of its occupants.

Building Load
Heating and cooling load calculations significantly affect the energy consumption of a building and the comfort of its occupants. Understanding how the rates of heating and cooling (addition or removal) required to maintain a satisfactory indoor environment at a desired temperature and humidity condition is the basis of design for most heating and air-conditioning systems and components. The variables that affect the cooling load results from many convective, conductive, and radiative heat transfer processes throughout the building envelope as well as from internal sources and system components. These variables include the environmental influences on the walls, roofs, floors, and fenestrations; internal loads of lights, people, and equipment; infiltration; and system effects of outside air, fan and pump energy, heat gains, and energy recovery. The heating load calculation determines the heat loss due to envelope losses and infiltration. The outdoor and indoor design conditions are integral to the derivation of the both the heating and cooling building loads. Analyzing established climate zone maps, as found in ASHRAE Standard 90.1, during the pre-design or renovation of a building provides an effective means of exploring optimization strategies.

Figure 6 - Climate Summary Metrics IES<VE>

S.R. Crown Hall resides in Climate Zone 5A where the weather is defined as humid snow (cold winters), fully humid with no dry season, and hot summers (sub-tropical). Winter is the most dominant season in which the design of the building must minimize heating energy. The latitude is mid-solar where the radiation on south/east/west walls and roof are significant. The summer season has a large diurnal range which indicates potential for passive night time cooling and the use of thermal mass (see Figure 6).

THERM, a computer program developed at Lawrence Berkeley National Laboratory (LBNL) for modelling heat transfer was used to simulate the two-dimensional heat-transfer effects in the improved glazing stops. As shown in Figure 7, the thermal performance of the stops remained in the most part unchanged (thermal flux through the stops are illustrated). The U-value of the stops as simulated in THERM accounted for a 3.5% change in the performance (Baseline U-2.637 and Proposed U-2.543).

Figure 7 - Baseline vs Proposed Stop Thermal Performance

As shown in Table 1, clearly the peak heating load of the Baseline and Proposed models dominate. The peak reduction in the heating load of the Proposed model is attributed to the slightly better insulating class of glazing from the envelope rehabilitation and the run-around coil heat recovery system retrofitted on the existing air-handling units.

Table 1 – Peak Heating/Cooling Load Comparison

<table>
<thead>
<tr>
<th>Historic Load (kBtu/h)</th>
<th>Proposed Load (kBtu/h)</th>
<th>Baseline Load (kBtu/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTG</td>
<td>CLG</td>
<td>HTG</td>
</tr>
<tr>
<td>8,553</td>
<td>N/A</td>
<td>5,016</td>
</tr>
</tbody>
</table>

The Historic building model peak heating load is provided to illustrate how the programming of S.R. Crown Hall has changed as compared to the Proposed design model as well as understand the HVAC system selection in the original 1954 design. To counteract the envelope losses and downdrafts from the cold surface of the windows the perimeter radiant floor heating zones required greater heat flux than the core zones and were thus designed on a tighter grid (1-foot pipe spacing compared to the core zones 2-foot pipe spacing). Operating continuously, the radiant floor system promoted uniform temperature conditions from the floor to the ceiling.
while avoiding any radiant asymmetry from the cold windows. The inclusion of radiant heat in system designs was popularized in the 1950’s and 1960’s when modern architecture in the United States was becoming more and more prevalent (the two were undeniably intertwined).

Similarly, a reduction in the peak cooling load is achieved by the Proposed design model. One of the attributing factors to the load reduction is the photo-responsive controls in the Proposed design where the heat gains due to artificial lighting in the “upper core” studio spaces are significantly reduced when the specified illuminance level is achieved (see the discussion provided in Daylight Analysis). While the vast majority of envelope is wrapped with the 9’-8” by 12’-9” upper glass lites a dramatic difference in the SHGC of the lower glass lites is achieved with the Proposed design (a design difference of approximately 49%). The SHGC indicates what solar fraction of energy is transmitted through the window as heat. As the SHGC increases, the solar gain potential through a glazing assembly increases. Therefore, as result of the envelope rehabilitation the lower lites contributed to lowering the peak cooling load of the Proposed design model.

**Daylight Analysis**

The daylight analysis of S.R. Crown Hall was simulated through FlucsDL a daylighting analysis module of Integrated Environmental Solutions (IES) VE-Pro Building Performance Assessment Tools. The FlucsDL module assesses the light levels of a room and generates a daylight factor plot. This provides a means of determining the feasibility of using photometric room sensors in the analyzed room. Daylighting can be a viable energy-efficient energy conservation measure in any building especially with the transparent facade design of S.R. Crown Hall.

![Figure 8 - Historic Building Daylight Factor Plot](image)

The daylight simulation models for S.R. Crown Hall were simulated for regularly occupied spaces, specifically at the perimeter of the building. The simulations included the glazing property effects as well as the surface reflectance properties for interior finishes. For the applicable areas at the perimeter, a horizontal calculation grid was used at the typical work height level for the intended use of the space (approximately 34” for architectural drafting). The metric used to analyze the potential of daylight harvesting within S.R. Crown Hall is the daylight factor. The daylight factor simply expresses the daylight availability in a room. It describes the ratio of outside illuminance over inside illuminance expressed as a percentage (the higher the daylight factor percentage the more natural daylight is available across the analyzed working plane).

A daylight analysis was done for both the Historic and Proposed models to examine the effect of the new glazing. Secondly, a comparison of the Proposed and Baseline models are made to examine the percent energy savings from the photo-responsive controls in the Proposed design. As shown in Figure 8 the Historic model shows great daylight penetration on the north and south facades as well as the east and west exposures of the building at a depth of 30 feet and 20 feet respectively. One of the fundamental goals of the rehabilitation project was to preserve the original philosophy of Mies’ design including the interior environment. This is evident in the two very similar daylight factor plots (see Figure 9 for comparison). Both maintain daylight factors in the range of 30-40% where students of the Illinois Institute of Technology’s College of Architecture could work in a vibrant daylit environment (rooms above 5% are perceived as well daylit).

![Figure 9 - Proposed Building Daylight Factor Plot](image)

The original 1954 design of S.R. Crown Hall could not capitalize on reducing the connected lighting load of the overhead artificial lighting because the technology was just not available. The Proposed model capitalizes where the Historic model could not. The photo-responsive controls in the Proposed design are used to maintain a consistent light level to minimize the occupants perception of the transition from natural light to artificial light. The light fixtures connected to photometric controls have the ability to gradually reduce the connected power to 10% of the fixture wattage total when the illuminance level of 500 LUX is achieved in the space(s). The photometric sensors were simulated using RadianceES, another module of IES<VE>.

The photometric light savings are summarized in Table 2. Three consumption values are illustrated: (1) the Baseline lighting consumption using the code compliant maximum lighting power allowance calculated by the Space-by-Space method (2) the Proposed lighting consumption simulated with
retrofitted T-8 lights only and (3) the Proposed lighting consumption simulated with photometric controlled T-8 lights. While the Proposed renovation lighting consumption (without photometric controls) was greater than the code compliant Baseline model, the natural lighting dynamics of the upper core provided the necessary reduction in lighting power through the use of photometric controls to satisfy the requirements of an energy code compliant building (see Whole-Building Performance section). The Proposed savings shown (39%) is exclusively the energy consumption difference between the Proposed and Baseline designs. However, the actual dynamics of the lighting system is globally included within whole-building simulation of the Proposed building design where an increase in the heating load of the “upper core” occurs from the internal gains reduction.

**Table 2 - Simulated Photometric Lighting Savings**

<table>
<thead>
<tr>
<th>Baseline¹ Model</th>
<th>Proposed² Model</th>
<th>Proposed³ Model</th>
<th>Proposed Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,421 MBtu</td>
<td>2,292 MBtu</td>
<td>861 MBtu</td>
<td>39%</td>
</tr>
</tbody>
</table>

Notes:
(1) Baseline model lighting consumption with the code compliant maximum lighting power allowance.
(2) Proposed model lighting consumption simulated with retrofitted lights only.
(3) Proposed model lighting consumption with Photometric controlled retrofitted lights.

**Whole-Building Performance**

The envelope thermo-physical properties, zone thermal data, and HVAC systems; plants and components were simulated in both the Baseline and Proposed building to derive the whole-building performance. This paper makes use of the energy use intensity (EUI) of a building as a metric comparison between the whole-building performance of the Historic, Baseline, and Proposed models. The building model’s EUI was calculated by taking the total energy consumed in one year (measured in kBtu to normalize units between fuels) and dividing it by the total floor space of the building. Table 3 shows the simulated whole-building performance resultant of the three models.

**Table 3 - Energy Use Intensity Comparison**

<table>
<thead>
<tr>
<th>Historic EUI</th>
<th>Proposed EUI</th>
<th>Baseline EUI</th>
</tr>
</thead>
<tbody>
<tr>
<td>355</td>
<td>285</td>
<td>293</td>
</tr>
</tbody>
</table>

The Illinois Institute of Technology uses a District Energy System (DES) where chilled water and steam are provided to selected buildings on the college campus. The Historic, and Proposed models utilized an energy neutral DES modelled in accordance to the U.S. Green Building Council (USGBC) design document titled the Treatment of District or Campus Thermal Energy in LEED F2 and LEED 2009 - Design & Construction. This USGBC document provides guidance for modeling district or campus thermal energy in building energy simulations when the minimum energy performance of a building is submitted for LEED certification. While this paper does not assess the viability or potential of S.R. Crown Hall pursuing LEED certification, it was the author's intent to use a standardized and documented method for modeling a complex district energy heating and cooling system. The DES cooling and heating system was implemented as described in Option 1 of the document which the energy model’s scope accounts for only downstream equipment.

Using the energy neutral DES in the Baseline and Proposed building simulations appropriately evaluates the performance of the Proposed rehabilitation of S.R. Crown Hall per ASHRAE Standard 90.1. The iconic building required a performance-based code compliance where tradeoffs between building components and systems could occur to offset inefficiencies in Mies’ sacrosanct design. The success of the envelope rehabilitation and renovation of S.R. Crown Hall is evident in the lower energy use intensity of the Proposed building model.

The Historic building model also utilized the same energy neutral DES as in the Baseline and Proposed models. This type of configuration was selected because the actual efficiency of the Steam only plant in the 1950’s was not documented nor could it be fathomed how it operated. While the DES remained neutral in all three building models the Historic model deviated from the others in regards to the Appendix G methodology. This included the outside air ventilation rate, schedules, internal gains, and HVAC systems. The Historic building model was an attempt to historically document the plausible energy use of a building for academic purposes; to understand how a building once operated, the design intent both architecturally and mechanically, and the energy profile that it maintained over a couple of decades.

**Comfort Analysis**

The comfort analysis for the Historic and Proposed building models was performed using the MacroFlo and MicroFlo modules within IES<VE>. MicroFlo is a Computational Fluid Dynamics (CFD) system concerned with the numerical simulation of air flow and heat transfer. The CFD analysis includes the generated boundary conditions from the whole-building simulation such that the effects of climate, internal energy sources and the different HVAC systems and configurations are included in the
The Historic building model was selected rather than the Baseline model to observe the effects of three components of the original design: (1) the natural ventilation louvers (2) the local extract and (3) the performance of the original glazing specifications. Even though the building is heating dominated, it is more interesting to observe the system/envelope interaction during a cooling design day.

MacroFlo simulates the interaction between air flows, pressures (including exterior wind and internal buoyancy forces), and the thermal conditions of the space. The bulk airflow analysis in MacroFlo simulates airflow between building elements such as the facade and the perimeter natural ventilation louvers and provides the infiltration boundary conditions for use in the CFD calculation. The opening properties for the ventilation louvers are defined by several factors in the bulk flow analysis: the crack dimensions and flow characteristics, free opening area, timing and degree of opening, and opening controls. The MacroFlo analysis does not consider the operation variability of louvers to simulate the actual manual operation of the louvers (they are either fully open or fully closed). The ventilation louvers were simulated to open when the room temperature exceeds 75°F where the unconditioned space would become slightly uncomfortable (no mechanical cooling provided).

The bulk flow analysis in MacroFlo is static where the variability of the various boundary conditions is not included. As a result, the design day for peak cooling (from the building load calculation ~ July 19th) was selected to analyze the worst-case condition for thermal comfort in the Historic and Proposed building models. The CFD analysis uses comfort metrics developed by ASHRAE Standard 55–2007, *Thermal Environmental Conditions for Human Occupancy* (in particular the predicted mean vote and the predicted percentage of dissatisfied).

The Historic PPD index illustrated in Figure 10 ranges from 14-28. Juxtaposed with Figure 11 the space is clearly being overheated. This is a result of two factors: (1) exterior warm air passing through the perimeter ventilation louvers and (2) the solar heat gain at the facade of the building. Outside air enters through the ventilation louvers to the occupied thermal zone at a temperature of approximately 83°F. With the typical hot weather of Chicago, it was presumed that S.R. Crown Hall would overheat for many months in the summer. Therefore, the absence of students during the summer term would have made the natural ventilated perimeter Historic design of S.R. Crown Hall acceptable.

In comparison, Figure 12 illustrates the thermal comfort of the Proposed building design at the identical position simulated in the Historic. A significant improvement in comfort is clearly illustrated where a PPD index of less than 8 is achieved. This affirms the improved performance of the proposed glazing where it was specified with a better SHGC than the Historic. ASHRAE Standard 55-2007 defines a PPD index of less than 8 as an acceptable thermal environment for general comfort. The two major contributing factors in the
improvement of thermal comfort was the introduction of forced cooled air from the overhead diffusers and the improved SHGC of the lower glass lites of the envelope.

As shown in Figure 13, the tempered cool air is forced downward and is mixed at the occupied air level. This mixing effect is especially useful to counteract the heat gains at the glass facade. However, the thermal comfort directly beneath the supply air diffusers illustrates a common issue with forced air systems where cool air, being heavier than warm air, naturally tends to drop and increases its velocity when forced downward.  

This is evident in Figure 14 where the plumes of the supply air are clearly defined. The PPD index within this area is in the range of 40-50 (unsatisfactory for thermal comfort). Of the six primary factors that must be addressed when defining satisfactory thermal conditions for comfort, clearly the air speed is excessive directly beneath the supply diffusers.

CONCLUSION

The energy estimating and modelling methods used in this paper to simulate the energy use of an existing building after a major renovation and rehabilitation of the building envelope is in no way absolute. There are numerous refinements to the energy simulation that can be made to reconcile any differences from the simulation to the actual operation of the building. Among these are differences in building design relative to the building modeled, abnormal weather conditions, variations in schedules for equipment, systems, and occupancy, inconsistencies in the application of controls and operations strategies compared to those used in the model, the level of direct loads, and changes in connected loads. Nevertheless, refinements of the energy simulation to reconcile all these differences, when these adjustments are made by a capable building Energy Analyst, can yield simulation results that are more consistent with actual energy use.

In conclusion, historic building preservation is inherently tied to sustainability and should not be overlooked during the feasibility and planning of a project. Clearly, S.R. Crown Hall is a paradigm success a renovation and rehabilitation of a building envelope can provide; the preservation benefit of the embodied value/energy of an iconic and historic building.

REFERENCES


