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Sustaining Modernity: An Analysis of a Modern Masterpiece -The Gropius House

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SUSTAINING MODERNITY: AN ANALYSIS OF A MODERN MASTERPIECE, THE GROPIUS HOUSE

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ABSTRACT

This paper presents a method and initial studies to evaluate the energy performance of the Gropius House, a Modernist icon. The objective is to quantify energy intensity of the house by creating and optimizing a parametric computer energy model. The procedure described in this paper provides a detailed outline of the energy modeling process with accompanying results. The goal is to advance the understanding of the performance of Modernist icons, offering insight into sustainable building strategies in use before the advent of contemporary technologies.

The present study is part of a larger project to create a knowledge base of the environmental performance of iconic homes. In addition to adding knowledge to the two disciplines, Building Science and Architecture, analytical studies using the digital model are intended to aid property administrators in evaluating the economic realities of retrofitting and upgrading opportunities as well as provide information about energy saving characteristics and shading technique designs. Furthermore, by outlining a protocol and methodology, improvements in the building industry's energy performance analysis methods may be developed.

INTRODUCTION

Residential buildings in the United States account for more than 20% the energy use and 17% of national emissions of greenhouse gases [1]. Americans spend over $160 billion a year to heat, cool, light, and operate 125 million residential homes. Newly constructed homes are more efficient than the existing housing stock, due to improved equipment and construction methods. However, climate and site sensitive building design philosophies and strategies as well as innovative technologies, and construction and management methods urgently need to address the emerging energy and environmental crisis. This research focuses on Iconic Modernist residential buildings designed and constructed before the advent of super insulation, advanced construction techniques, and high efficiency HVAC equipment. The goal is to quantify how much energy these historical structures consume, and to identify non-technological and site sensitive strategies to conserve resources and energy.

There are not, at present, any contemporary energy performance studies that quantify the energy use of Modernist homes. Most of the literature on the energy demand of historical buildings focuses on vernacular traditions [2]-[5]. A notable exception is the 1977 paper "Analyzing the Gropius House as Energy-Conscious Design" by Neil Summers published in the AIA Journal [6] and the follow up article, "Climactic Adaptation and Solar Performance of the Gropius House" published in "Energy, AIA Energy Notebook" [7]. Summers work was done in conjunction with interviews with Ise Gropius, Walter Gropius's widow, and provided first hand information concerning behaviors within the house relevant to energy usage. It is a detailed analysis of the building based on prevailing

techniques and data available, some of which this study will recapitulate with contemporary technologies and information.

This study centers on the environmental performance of the residence Walter Gropius designed and built for himself and family in Lincoln, Massachusetts in 1938. Known eponymously as the Gropius House, it is now a museum property owned by Historic New England, listed on the National Register of Historic Properties, and richly deserving of the subtitle, Modernist icon. The process to develop a quantitative data set in order to evaluate the structure's energy performance is a critical component of this study, as it establishes a method for retrieving and quantifying a variety of data from complex existing buildings.

The Gropius House, built prior to the advent of sustainable building standards, is, of course, in possession of many (by today's expectations) substandard design features and exhibits many energy saving deficiencies when subjected to even a cursory examination. This study will provide an information-rich, decision-making baseline for the administrators and custodians of Historic New England, the caretakers of the property, along with the conservationists and preservationists who work to maintain the house. With this information, they will be better prepared to evaluate the long-term performance of the existing construction materials and details of the house and to evaluate the utility of energy saving improvements.

A concurrent aim is to investigate the actual efficiencies of some of the property's early energy saving and shading technique design attributes. These techniques are derived from earlier architectural design traditions that were beginning to absent themselves from design syntax as cheap oil and petroleum-driven active mechanical systems replaced more subtle passive techniques.

Analysis of direct and indirect solar gains, overshadowing, internal gains, inter-zonal heat flows, reflectivity, geometry, geo-position, insolation, thermal properties, and heat and light transmission are all possible through parametric studies of the Gropius House. For this paper, the following design characteristics are examined in detail:

1. The effect of the brise-soleil on the western end of the south façade to determine the degree of protection it offers the south facing living and dining room windows and the bedroom windows above. This feature, brought to the attention of designers in 1933 by Le Corbusier in Plan Marcia of Barcelona [8], is one of the first mentioned when the architecture of the house is discussed.
2. Gropius's original landscape plan directed the planting of two very large trees in the southwest corner (one a deciduous Red Oak and one a coniferous White Pine). These large trees are unusually close to the house, 4 m. (13ft.) in the case of the Red Oak, and play a significant role in the energy analysis.

The project begins with a review of historical records, scholarly documents, and archival data. Second, the analysis is quantified using Autodesk's Ecotect, an energy analysis software in which a three-dimensional digital model is created. Third, a comprehensive building audit is conducted and utility records are consulted to assess the building's energy use. Fourth, Ecotect's building performance analysis tools are used to examine the present energy consumption characteristics of the building. Fifth, the existing (computer model) structure is modified to explore and optimize the

building's efficiency and performance. Finally, insight into how our modernist forebearers dealt with issues of efficiency and conservation is provided.

HISTORICAL CONTEXT

FIGURE 1: GROPIUS HOUSE, PHOTO BY L.C. FIOCCHI

The 1937 arrival of Gropius to the United States, precipitated by the European political and economic crisis and related right wing events of the 1930s, was not solely an action in pursuit of safe harbor. Within one year of his arrival, in 1938, Walter Gropius, in collaboration with Marcel Breuer, designed and constructed, a residence, in Lincoln, Massachusetts, for himself and his family that was to become an icon of Modern Architecture, Figure 1.

It was of paramount importance for Gropius to bring his full powers of design into the building. This would be a true marquis for him in both the narrower intellectual community of Harvard and greater Boston as well as a branding image to be projected onto the greater American architectural screen. Moreover, Gropius had at his disposal, not only Marcel Breuer, but also the Harvard Graduate School of Design faculty and students. Material research, manufacturer sourcing and cooperation, model making, lighting studies, solar studies, were all available at a scale that is realistically unmatched for any other comparable residential design and construction project.

CONSTRUCTION

> *As to my practice, when I built my first house in the U.S.A. - which was my own - I made it a point to absorb into my own conception those features of the New England architectural tradition that I found still alive and adequate. This fusion of the regional spirit with a contemporary approach to design produced a house that I would never have built in Europe with its entirely different climatic, technical and psychological background* [9].

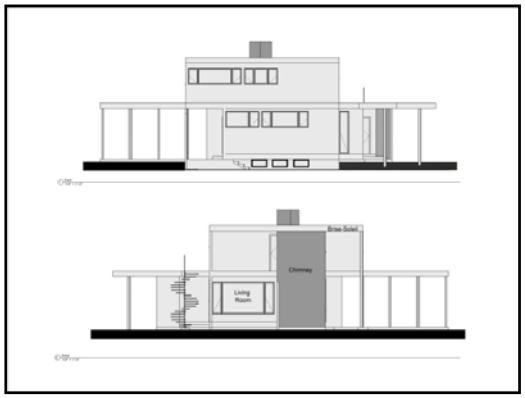

FIGURE 2: EAST- WEST ELEVATIONS

NORTH- SOUTH ELEVATIONS

The Gropius House is a two story, flat roofed, wood frame structure 213.6 m^2 (2300 ft^2) in floor area, with white painted vertical redwood siding, a tar and gravel roof, and a stone foundation. A gray-painted exterior chimney on the west side is of brick laid in Flemish bond, Figure 2 (left). Fenestration, arranged in horizontal bands is composed of fixed panes of glass alternating with casement sash, both with gray painted steel frames. Windows are narrower on the principal elevation on the north for privacy and weather protection and wider on the other elevations where they provide access to views, passive solar heat, and sunlight. Windows are largest in the living and dining areas, where two windows 1.8 m (6 ft.) high by 3.2 m and 4 m.(10 ft. 6 in. and 13 ft. 3") wide, Figure 2 (right) act to minimize the barriers to the outdoors and create ever-changing patterns of shadows on the interior walls. These large windows on the south elevation are sheltered from the sun by an extension of the roof that functions as a brise-soleil in the summer, Figure 2 (left). Open joists next to the house support the brise-soleil keeping moisture from being trapped next to the house under the roofline. The tongue-in-groove redwood siding gives the house's exterior a subtle texture, while the central roof drain that extends down through the house eliminates the need for exterior gutters and downspouts. A partial cellar extends under the kitchen and hallway. Elsewhere there is crawl space.

The structural system combines modern balloon frame construction with larger structural components such as 10.2 cm (4 in.) x 15.2 cm (6 in.) corner posts and 10.2 cm (4 in.) and 20.3 cm (8 in.) sills that are suggestive of the timber frame construction that prevailed in New England until the mid-nineteenth century. The house is constructed with diagonally braced wood frame floors, walls, ceilings, and roof. Wall studs are 5.1 cm (2 in.) x 10.2 cm (4 in.); roof and floor joists are 5.1 cm (2 in.) x 25.4 cm (10 in.). Two steel I-beams span the plate glass windows in the living area, and steel lally columns support the marquee, the porch roof, and the roof overhang in the southwest corner.

All components used to construct the house and the fittings (excepting the main staircase railing and exterior light fixture) were stock building materials or standard items available from catalogs: glass bricks, steel sash, doors and door hardware, lighting and plumbing fixtures. Stock items were selected for reasons of economy, but also because Gropius wished to demonstrate that readily available American industrial products could be used to create elegant solutions to modern building design.

There are conflicting reports as to the envelope insulation. The book, *Classic Modern Homes of the Thirties*, mentions Cabot's Quilt Insulation [10]. This is an insulating material consisting of dried eelgrass held between layers of cloth or paper and used as thermal insulation. The effective R-Value of this antique product is R_{si} value-.5 per 2.5 cm (R_{imp} value - 2.8 per in.) [11]. It is verifiable that this is indeed the insulation used between the first floor and one room of the full height basement spaces as the basement is without ceiling finish so the material is plainly visible. Gropius's original specifications of which there is a copy in the archives of Historic New England are in accord [12]. The high iodine content of this product made it especially resistant to degradation by vermin and probably the reason Gropius selected it for what he designated as the "Storage and Wine Room".

The reports of ceiling and wall insulation vary, however. In *Gropius House: A History by Ise Gropius*, the author states that 4" (10.2 cm) fiberglass bats were used in the roof and 3" (7.6 cm) fiberglass bats used in the walls [13]. The thicknesses are consistent with the assembly voids, but the material is in question. Fiberglass was not yet a building material having only recently been invented (1932) [14]. However, according to Gropius:

The entire house is to be insulated with Sprayo-Flake Insulation. Material to be applied to walls a minimum thickness of 1½" including roof of living room and soffit of overhang on south side. [15]

This is consistent with available building materials and practices at the time as mineral wool and cellulose fiber insulation building products of various types were available with (now tested) relatively effective R_{si} value- .37 to .65 per 2.5 cm (R_{imp} value - 2.1 to 3.7 per in.) [16].

Sprayo-Flake Insulation is reviewed in Popular Mechanics of May 1928 and described as ground-up, confetti-sized magazine and newsprint that is mixed with water and sprayed on, to a desired thickness, resulting in a fluffy coating with billions of air cells, which make an exceptional insulator [17]. This spray technique also is in keeping with the physical realities of a construction sequence involving the prescribed materials and assemblies used in the house's construction. Gropius's choice of cellulose was an excellent one as the product delivers a respectable R-value per unit of thickness and has superior air sealing properties to fiberglass [18].

Concerning the fenestration, in *Classic Modern Homes of the Thirties*, there is a reference to "heavy sash" and Hopes Windows [19]. The Window Schedule from the North and South Elevation Sheet of Gropius's original drawing set lists Plate Glass, Window Glass, Ribbed, and Magnalite A (unknown material) along with instructions that multiple windows (designated "S" on drawings) are to have roll shades. The thermal calculations reveal a U_{si} value- .17 (U_{imp} -1.02) for the existing (original) windows in the house. The still active Hopes Window company is studying replacement sash with U_{si} value -.06 (U_{imp} value- .35) [20]. This information is valuable when energy performance modification options are studied for the property.

METHODOLOGY

ORIGINAL DRAWINGS TO DIGITAL DRAWINGS

The Busch-Reisinger Museum at Harvard is the custodian of the Gropius Drawing Archive and has preserved over 100 drawing sheets (many are duplicates) from the project in Lincoln. The library has produced a four-volume set of books chronicling the entire career of Gropius. The third volume [21] (1936–1944) contains all of the existing Lincoln House drawings, which were photocopied/scanned directly from the originals.

The printed pages containing the desired drawings were first scanned at 600 dpi resolution to create a JPeg File. The images were then imported into Adobe Photoshop where brightness, contrast, and sharpness were optimized for readability. Notably, the original drawings were executed in pen and pencil on paper and had lives in drafting studio and on construction site prior to their existing protected environment. The wear of their earlier life along with the age and quality of the original material rendered them considerably less readable than a contemporary digitally plotted drawing.

This enhanced JPeg file was then inserted, as an image, into Autodesk's Revit, a digital drawing program, and scaled and sized using the scale, 1/4" = 1' (approximately 1:50), that Gropius had used in drafting the original set (noted on each sheet). To ensure accuracy, measurements are repeatedly taken of the lines in the drawing with the program's measuring tools and compared with the annotated dimensions written on the drawing sheets.

After scaling was completed, the JPEG files were exported and plotted resulting in a complete, Arch D, 61 cm (24 in.) x 91.4 cm (36 in.) hard copy drawing set, duplicating Gropius's originals. This drawing set consisted of plans (basement, first floor, second floor, and roof), elevations (north & south, east & west), perspective, and schematics (first floor, second floor). It was then possible by referencing these sheets to directly verify and crosscheck with scale rule, sizes and dimensions necessary in the creation of a digital model of the building.

DIGITAL DRAWINGS TO DIGITAL 3D MODEL

The visually optimized, scaled JPEG image files of the four plans were next reinserted into Revit. The drawings served as template underlayments for each level in order to create the digital model of the building. Creation of the digital model was a matter of balancing the dimensions visible on the underlayment with the measuring tools of Revit. Throughout the process, there was a constant crosschecking with the printed drawing set to ascertain that correct insertions and positions of components were being made. The result was a digital model that is a robust geometric representation of Gropius's design, Figure 3.

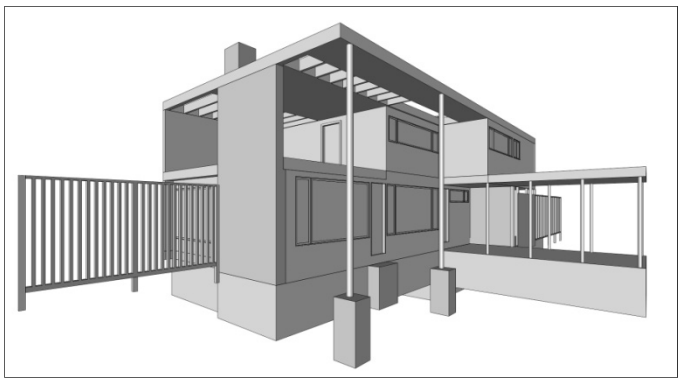

FIGURE 3: REVIT MODEL - VIEW FROM THE SOUTHWEST

FIGURE 4: RENDER OF REVIT MODEL AND SITE - PERSPECTIVE VIEW FROM SOUTHEAST

To complete the digital model, the site topography was created in a separate Revit File. The digital topography was used to size and precisely position landscape objects, i.e. trees, as there were not and are not any buildings nearby to impact on the buildings energy performance. This topography was geopositioned in Revit and the Gropius House model was then inserted and oriented on the site, Figure 4. With the Site plus Model File, accurate shading studies in Revit were performed. These studies were less sophisticated than those simulated with Ecotect's shading analysis tool, but the rendering capabilities of Revit are superior to Ecotect and are helpful for presentation and useful for demonstrations.

DIGITAL 3D MODEL TO ENERGY ANALYSIS

Once the Revit model of the building was completed, it was inserted into Autodesk's Ecotect. Whether one creates a model entirely within Ecotect or inserts a model from a separate program into Ecotect is based on what type of analysis is desired as well as the source files that are available. Ecotect is able to perform analyses in five areas: acoustics, material costing, lighting (artificial and natural), thermal performance, and solar/shading. This study is not concerned with acoustic, material costing, or artificial lighting analyses. If Ecotect's analysis capabilities in a particular category are exhausted, then the model can be exported into additional analysis packages e.g. Radiance, POV-Ray, DOE-2/eQuest, or EnergyPlus.

The types of models that are best suited for a thermal performance analysis or a solar shading analysis are not identical. If only one of the analysis categories is of interest then the model must only possess the requirements of that category and is free to disregard the requirements of the other. In the case of the Gropius House, the intent was to do solar/shading, daylighting, and a thermal performance analysis, so all requirements had to be met.

An Ecotect model for shading/solar and daylighting studies require precise geometries of envelope, overhangs, window openings, shading devices, impacting landscape features, any adjacent building geometries, and anything that affects the sun's light/shadow projection on the building. Model precision is rewarded by the ability to examine in commensurate detail the actual light and shadow projection that falls on any surface interior or exterior, at any time (minute by minute) of the year based on the imported weather file and geopositioning. The examination can be on any surface, e.g. a shadow pattern projected from an overhang on an exterior wall or window, light penetrating through a transparent façade, or light on a roof plane. Ecotect also displays the sun's path (daily or annually) across the site, Figure 5. The model itself does not accurately reflect building materials because it is essentially a geometric model impregnated with invisible material and assembly data.

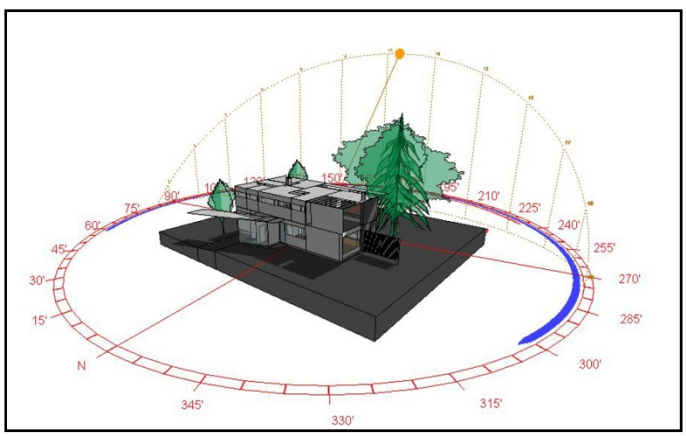

FIGURE 5: ECOTECT SOLAR STUDY, APRIL 1, 1:15 PM, PERSPECTIVE VIEW FROM NORTHWEST

Using this model, it is now possible to examine specific solar energy data, e.g. the exact amount of insolation KWh/m^2 (btu/sf) on a roof plane for a specified time period or the amount of insolation an interior thermal mass receives through a specific window on a façade. Changes to the model's planes or materials of the assemblies can be carried out for various kinds of analyses. For example, the roof pitch can be altered to determine a photovoltaic array's output based on amount of insolation. In addition, the Solar Heat Gain coefficient of the glass of a window assembly can be altered to examine the corresponding increase or decrease in heat transmission to the interior thermal mass.

The Ecotect model for shading/solar and daylighting studies, Figure 5, is a recapitulation of the original Revit model except all elements are reduce to single planes imbued with a substantial data set of materials, material properties, and dimensions. The modeling process for thermal analysis requires additional exactness. Ecotect runs thermal analysis functions through defined zones. Each model may have multiple zones. Large open rooms may have several zones; buildings can be divided into several zones; each room can be an individual zone; zones can be grouped and measured as one zone. Each zone is composed of objects and each object has a relationship to the zone and, in the case of some objects, a relationship to other objects, e.g. a window in a wall is in a child/parent relationship. Each object, i.e. roof/ceiling, wall/partition, window, door, floor, etc. must be *perfectly* aligned or adjacent to its fellow zone member and *perfectly* connected with that object to create a *perfectly* enclosed zonal volume. This zone must in turn be *perfectly* aligned with all adjacent zones. Thus, the thermal performance model, unlike the solar shading model, has zero tolerance for adjacency or alignment mismatches. It requires a model of complete exactness.

With this model, thermal losses or gains, KW/m^2 (btu/sf/hr) of each zone or of the entire building (all the zones) can be examined. These are based on a myriad of data inputs, including internal gains based on occupancy in each zone with adjustments for clo factors, mechanical equipment types and efficiencies, solar heat gains, thermal mass effects, additions of shading devices, desired comfort range, or R or U-values of assemblies and components. All of these variables are parametric, so that various optimization strategies can be examined.

Importing the model into Ecotect, even one as relatively simple as the Gropius House, produced over 500 objects that must be *perfectly* in place. The recommended export from Autodesk Revit to Autodesk Ecotect is by gbXML, but as of yet the technology has not arrived at that magic button stage (nor has any other) where with a few mouse clicks everything is perfectly integrated. The solution for resolving errors is to conduct a zone-by-zone, object-by-object policing of the model. This is necessary to ascertain that all objects are assigned the correct material, all zones are defined, and all geometries are aligned. Ecotect has tools that facilitate the process, but there is a significant time commitment.

The import into Ecotect is done through the import feature. After the import, the model was checked for scale and then imbued with specific data. First, its geoposition was established using GoogleEarth. The site in Lincoln was located. Longitude, latitude, and altitude recorded, and then entered into Ecotect. At the same time while on GoogleEarth, with the aid of their measuring tools, the house's main axis deviation from true north (GoogleEarth's north arrow is true not magnetic north) was measured and recorded. In Ecotect, the model is automatically positioned orthographically on a grid and the north arrow is input with the recorded angle deviation from the house's main axis. Additionally, Ecotect categorizes terrain type and Gropius House was defined as suburban.

The next step was to enter the local time zone, i.e. 5:00 New York. The last item to input was the weather file, which was the nearest available location with the most complete weather data. Ecotect is loaded with a limited number of files, but a complete worldwide set is available through the United States Department of Energy. The Boston/Logan Airport WEA file was inserted after converting from the Department of Energy's EPW file format to Ecotect's WEA file format with Ecotect's Weather Tool (provided by Ecotect at time of installation).

The penultimate step in the process prior to analysis was the resolution of the model geometry. The Revit model was imported in a relatively intact form. Some triangulation had occurred, some elements were missing, and some zones were incomplete. These were corrected. For the thermal analysis, the Gropius House had four non-thermal external zones, i.e. outside, trees deciduous, trees conifer, and external shading. It had 20 (internal) thermal zones involving the three levels including all rooms (closets are included with adjacent rooms). The external shading zone was created after the import by moving the appropriate elements to that zone and the tree zones were created separately after executing the necessary drawing and positioning of the trees. The result is a complete digital model that precisely recapitulates the Lincoln House's geometry, site location, and meteorological dictates.

ANALYSIS

With the above model, a detailed analysis of specific designs can be presented. The present examination will focus on the Brise-Soleil of the Gropius House. This shading analysis first illustrates and then quantifies the performance of the Brise-Soleil on the second level of the South facade. The images focus on the mitigation of the solar impact on the surfaces below the Brise-Soleil; most significantly the Living Room's and Dining Room's large window expanses [two windows assemblies of 1.8 m (6 ft.) high by 3.2 m and 4 m.(10 ft. 6 in. and 13 ft. 3")] totaling 13.2 m^2 (142.5 ft^2). This represents a glazed area of over 50% for the south facing wall of these two rooms. 25.6 m^2 (275.5 ft^2)

By selecting a typical summer day (July 21) when temperatures in New England are at their hottest and solar gains are of maximum concern we are able to study, minute by minute, the shading provided only by the Brise Soleil.

At 9:30, Figure 6, the sun has not yet impacted the facade. Fifteen minutes later, at 9:45, Figure 7, the sun is fully impacting this facade, yet shading at this point is immediately approximately 50%. One hour later at 10:45, Figure 8, as exterior dry bulb temperatures begin to rise to the level where comfort levels begin to be compromised, the Brise-Soleil's lowest shadow line has begun to impact the two windows. Over the next two hours until 12:45, Figure 9, the shadow will travel across the window matching the time period where the exterior temperatures rise toward their maximums and solar gain is most problematic. Not until the latter part of the afternoon, 16:00, Figure 10, when the heat of the afternoon begins to wane does the shadow begin to retreat.

It is of note that the windows visible on the second floor in this study were not nearly as well defended. With respect to the shading geometry provided by the Brise Soleil this is true, but Gropius was concerned with comfort in this room as well. The intermittent voids (aesthetically supplying interesting patterns of light and dark) of the Brise-Soleil that comprise its western end transform into a single large void at the eastern end where it is positioned over the operable windows of that second story bedroom, Figure 3. This encourages passive ventilation in this room by providing a chimney effect outside the room rather than a solid barrier that would have limited air movement in this location. As an alternative to the shading of the Brise Soleil for that second story bedroom we return to Gropius's original landscape plan mentioned in the Introduction. Gropius had directed the planting of two very large trees in the southwest corner (one a deciduous Red Oak and one a coniferous White Pine) very close to the house. Similarly to the shading prowess of the Brise-Soleil, these trees impact

on the windows of this facade have been studied, showing similar shading advantages along with solar gain mitigation.

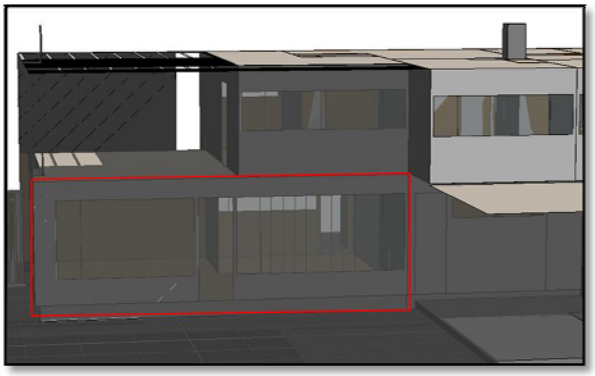

FIGURE 6: 9:30

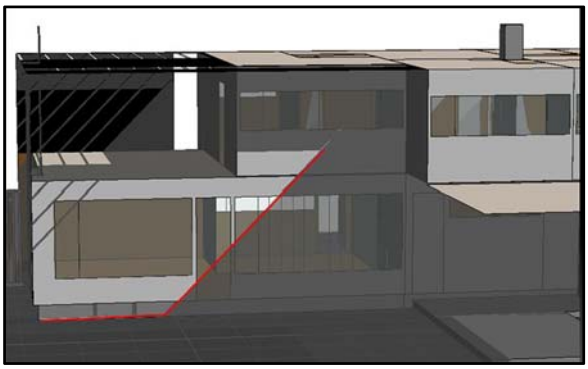

FIGURE 7: 9:45

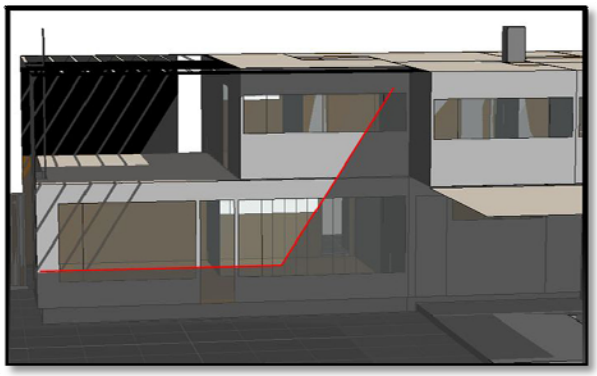

FIGURE 8: 10:45

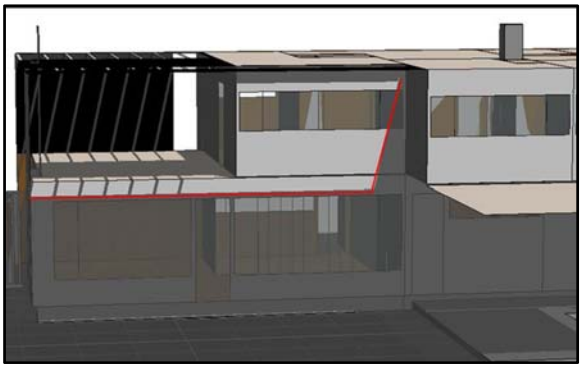

FIGURE 9: 12:45

FIGURE 10: 16:00

Although only images of the shading studies of the Brise-Soleil during summer (July 21) are shown, similar studies have been done at the opposite time of the year (Jan 21) when Solar Gain is a desirable effect. What was found is that the lower sun angle in the southern sky and the positioning of the Brise-Soleil a full 3 m. (10 ft.) above the Living Room and Dining Room windows eliminates most of the shading effect. Duplicate analysis of the presence or absence of leaves on the deciduous trees replicate Gropius's control.

Finally, Ecotect is able to quantify these effects through its visualization prowess. This data can be outputted in the form of spreadsheets or tables, but is best demonstrated with images. Figure 11 illustrates the average daily percentage of sunlight on the facade on July 21 and Figure 12 illustrates the average daily percentage of sunlight on that facade six months later on Jan 21.

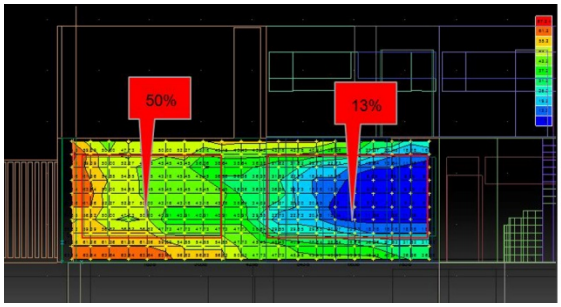

FIGURE 11: JULY 21

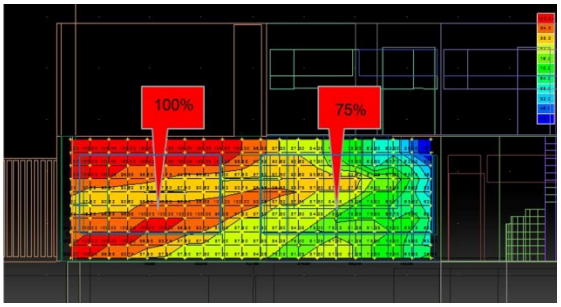

FIGURE 12: JANUARY 21

THE FINAL STEPS

Energy Bills for the Gropius house for the years 2008, 2009, and 2010 were supplied by Historic New England. The invoices will provide data about total electricity used (in kWh) and natural gas purchased (in therms). These numbers will be converted into equivalent energy units per year, per month, and per hour.

Natural gas use is related to space heating and domestic hot water (minimal usage). Electricity use is further divided into two categories: lighting and air conditioning. A lighting audit will enable the assignment of percentages to each of the two categories. After the electric percentages are allocated, the energy consumption totals will be applied to conditioned space areas and volumes followed by straightforward arithmetic computations resulting in baseline figures of joules per area or volume per time period.

More information about the house's systems and specifications was gathered through interviews with the administrators and custodians of the property, conservationists and preservationists, window and equipment manufacturers, and first hand observation. Property administrators also provided insight about building usage, e.g. thermostat set points, hours of occupancy, estimates of numbers of occupants, etc.

This information will be input into Ecotect. The model will then possess not only the geometry of the structure, but also the actual occupancy and usage parameters as well as precise materiality. Each additional input increases the accuracy of solar/shading, daylighting, and thermal analyses.

The thermal analysis will be used to calculate the heating and cooling loads, analyze effects of occupancy, internal gains, and equipment. The solar analysis will display visualizations, e.g. Figures 11 & 13, as well as the metrics of incident solar radiation on roofs, windows, and surfaces, over any time period (as was demonstrated in the previous section). The shadows and reflections will be displayed along with the sun's position and path relative to the model at any date or time. Additionally, the unit costs from the energy invoices will be input to compare the model's energy costs with the real world Gropius House costs. This will provide a definitive crosscheck in both dollars and energy metrics.

The researchers will then be in a position to achieve the project's desired goals. Based on the Ecotect results (coupled with some revealing thermo graphic images taken in March 2010), an accurate portrait of the energy consumption characteristics of the house will be presented.

Optimization strategies, such as modifying building materialities or adding additional ones, will be developed. For example, the existing exterior walls of the envelope are presently framed with 5.1 cm (2 in.) x 10.2 cm (4 in.) studs, 40.6 cm (16 in.) O.C. with the cavity partially filled with cellulose insulation, which has a relatively low cumulative *R*-value. If the cavity voids were filled with a slow rise, low-pressure cavity fill closed cell polyurethane foam insulation, which requires minimal invasion to a structure and is recommended for this type of installation, the cavity R_{si}-value would escalate to 4.31 (R_{imp}=24.5; R_{imp}= 7/in.). This will provide a new greatly reduced energy consumption profile.

The reduction in energy consumption, translated into dollars, at either the current unit cost or an anticipated increase, will allow the caretakers of the property to make a financial evaluation balancing energy cost savings versus installations costs. Similar studies could be done for other non-aesthetic (a paramount concern in a museum property) systems, e.g. low profile interior storm window for fixed windows (altering its U-value) or an insulating system between basement and first floor.

Beyond the pragmatic goals of this study to take advantage of energy saving opportunities for the Gropius House, this work also allows an examination of the energy saving and shading technique building strategies that Gropius used in his design. The goal is to evaluate the techniques employed by Gropius to reduce the energy profile of the house. This will be done by digitally removing the large trees dictated by Gropius's landscape plan, eliminating or altering the brise-soleil on the south façade, replacing the massive stone foundation with 8" thick concrete walls, or reinstalling the absent exterior venetian blind on the west window of the living room.

CONCLUSIONS

A question that arises in any project such as this involving a substantial investment in effort and time is its value. The original goals can seem quite adequate at the beginning of an investigation, but as the journey is made, they might come into question. In the case of this research, that is happily not the case. The rewards are significant on all fronts.

For the caretakers of the Gropius House this research provides an illustrative tool to allow them to make critical financial decisions that will help them combat the ever-rising costs of maintenance of antique properties. In the light of global warming and the looming appearance of peak oil, these decisions are even more crucial.

For architects and designers who studied and learned about Modern masters like Walter Gropius and whose practices are steeped in sustainable and energy saving design this research examines and shines a type of digital searchlight back some seventy years to examine the environmental and energy performance of a modernist icon.

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