Frank Lloyd Wright's Oak Park Architecture: A Computerized Energy Simulation Study*

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INTRODUCTION

Frank Lloyd Wright acknowledged the impact of climate on architecture in several of his publications. In his early preface to Ausgefuhrte Bauten und Entwurfe (1910) Wright wrote: "In our vast country alternate violent extremes of heat and cold, of sun and storm have to be considered... Umbrageous architecture is therefore desirable - almost a necessity both to shade the building from the sun and protect the walls from alternate freezing and thawing." He then elaborated on the architectural elements that protect the building from harsh weather conditions. In *Modern Architecture* (1931, p.70). Wright repeats his ideas of "design with climate" by regarding architecture as a shelter: "At this time, a house to me was obviously primarily an interior space under fine shelter." In conjunction with his organic architecture theory, that focused on the synthesis of features of habitation and the harmony with environment, Wright described architecture as a sheltering tree growing from the earth and providing a refuge from sun and rain. Frank Lloyd Wright's notion of architecture as shelter was further elaborated by Hildebrand (1991). Hildebrand demonstrated that Wright's architecture complies with Jay Appleton's theory of refuge (an effective shelter) and prospect (a hiding place). Thus, Frank Lloyd Wright's architecture provides a comfortable shelter—a single environment device to control heat, light, view, ventilation, shade, and privacy.

This paper tests the proposition that Wright's architecture is an expression of environmental forces and provides a comfortable shelter. Furthermore, in analyzing the climatic implications of Wright's early architecture, this paper targets two additional important questions. First, how did Frank Lloyd Wright shape the design of different building types (i.e., religious and residential architecture) to accommodate climatic constraints in an era when no contemporary mechanical systems existed? Second, did Wright design these buildings to accommodate the same climatic comfort in the cold and hot seasons?

Several scholars evaluated part of Frank Lloyd Wright's early architecture according to conventional climatic design guidelines (Banham 1966, 1969; Estoque 1987; and Lechner 1991). These studies show that Wright's systems of environmental management (such as natural cross ventilation, shading devices, and natural light) influenced the design of his exterior and interior architectural forms. In addition to the passive cooling/heating methods Wright developed and designed heating systems. This development allowed him to free his architecture from conventions such as the traditional box:

> "Another modern opportunity is afforded by our effective system of hot water heating... It is also possible to spread the buildings, which once in our climate of extremes were a compact box cut into compartments, into a more organic expression, making a house in a garden or in the country the delightful thing in relation to either or both that imagination would have it" [from the English version (1986, p.15) of *Ausgefuhrte Bauten und Entwurfw* (1910)].

The conclusion of these scholars is that the strength of Wright's design is the combination of the building's architectural elements and the mechanical services: "It was the use he [Frank Lloyd Wright] made of mechanics and structural form in combination that marks out the Prairie Houses as triumphs of environmental art." (Banham 1969, p.92)

The shortcoming of these studies is that they have had a limited empirical basis, focusing mainly on the study of the Robie House (Chicago, 1909), and influenced by subjective interpretations. As Fitch claims in his opening statement to the section on Building Design and Micro-Climate (1948, p. 290): "So many have observed it, so few have measured it..."[1]

This project attempts to fill the empirical gap in the study of climatic considerations in Frank Lloyd Wright's early architecture by utilizing a rigorous empirical methodology in the form of a computerized energy simulation program. Specifically, the three objectives of this research are: (a) to empirically evaluate the notion that Wright's architecture is an expression of environmental forces; (b) to assess and compare the climatic comfort and energy performance of Frank Lloyd Wright's design of different building types: a church and two single family houses located in the same climatic region; and (c) to examine if these buildings were designed to accommodate the same climatic comfort in the hot and cold seasons.

In pursuing these objectives this study examines Frank Lloyd Wright's three buildings in Oak Park, Illinois: Unity Temple (1905), Mrs. Thomas Gale House (1909), and his own first Home (1889). The selection of these buildings was influenced by three main factors. First, all of the buildings are located in Oak Park Illinois, a distinctive cold windy climate in the winter and a hot-humid summer, i.e., climatic conditions that require specific architectural consideration. Second, the Oak Park community consists of a variety of building types, built in the beginning of the 20th century, by the same architect, in a time period when architects had to address climatic constraints by design solutions rather than incorporating HVAC systems. Third, the availability of data pertaining to Frank Lloyd Wright's original design of the buildings (such as drawings, documentation, and pictures).

THE BUILDINGS

Unity Temple (1905)

The design of Unity Temple manifests three architectural concepts: faith and form, building integrity, and solutions for environmental constraints. These concepts underlie the departure of Wright's design from the traditional form of a church (see Figure 1). The new form was accepted by the Unitarian congregation: "By the simplicity and beauty of the design and by its departure from traditional lines, the simplicity and freedom of the faith held by the members of Unity Church is outwardly expressed; the architecture thus typifies the faith of the church." (Pastor Johonnot, 1906)

The Unity Temple is a complex of three buildings. They vary in height/volume and are spread along a 142 feet main axis. The main building is the Temple, which is located in the north side of the complex. The dominant cube of the Temple measures as a square of 64'-0" in plan, with a height of 47'-0". It includes an auditorium with three open galleries, a space for the organ on the fourth side, and a lower floor for storage and restrooms. The plan and volume of the Temple were also influenced by the combination of religious connotation of a cruciform and the simplicity of pure geometry and proportions: "This in simplest terms, meant a building square in plan. That would make their temple a cube, a noble form...The first idea was to keep a noble room for worship in mind, and let that sense of the great room shape the whole edifice." (Wright 1932, p. 154-155) The second building is the Unity House, located in the south, at a right angle to the Temple. It measures as a rectangular of 91'-6" by 50'-0 in plan, with a height of 30'-0". The House includes a main gathering/reception hall, open classrooms on both sides of the upper level of the hall, and a kitchen separated from the hall by a huge chimney. The third building of the complex is a two story, 30'-0" long, 24'-0" wide, foyer/entrance that connects the Unity Temple with the Unity House. Its lower floor opens to the entrance plaza on the west side and to a courtyard on the east. Its upper floor consists of the pastor office. On the wall above the entrance is a large inscription that points out the two main functions of this building: "For the worship of God and the service of man" (for a detailed description and illustrations, see Siry 1996 and McCarter 1997b).

The Unity Temple construction of 'thoroughbred' reinforced concrete at the turn of the century was unique and experimental. The heavy thick concrete walls answered not only the monumental/religious and integrity aspects of the design, but also catered to environmental concerns. The passive cooling effect of thermal mass of these concrete walls was reinforced with long cantilevered overhangs that provided shading, with natural ventilation, and with windows and skylights that granted natural light. To achieve a comfort level in the winter Wright designed a heating system as an integral part of the structure. It seems that this development was more extensive than his design of passive heating systems.

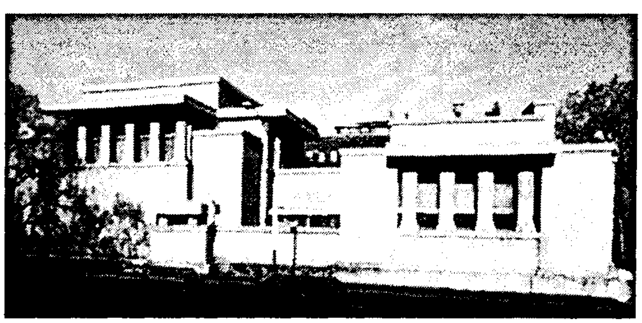

Fig. 1. Unity Temple, Oak Park, Illinois (1905)

Mrs. Thomas Gale House (1904/1909)

The date of Mrs. Gale House's design is assumed to be 1904 (it is not confirmed), therefore, the construction year of 1909 is the commonly accepted year for this house. Wright designed several projects for the Gale family before this one. In 1892 he designed their house on Chicago Avenue and in 1897 he designed their summer cottage in Whitehall, Michigan. After the death of Mr. Thomas Gale, his wife commissioned Wright to design the house on Elizabeth Court in Oak Park for herself and her children (Siry 1996). This building is considered the "progenitor of Falling Water" in its envision of concrete as a construction material (although it was built from wood and finished with plaster), and in its use of a multiple horizontal cantilevers design (Hitchcock 1942; Siry 1996).

Mrs. Gale House is a two-story house and consists of a small basement; a first floor with a reception area by the entrance, a large living room, a dining room and a kitchen; a second floor with four bedrooms, a maid's room, and one bathroom. The roof is flat and is part of the horizontal cantilever design (see Figure 2). The house is considered as the "most abstract in design of the early Prairie houses" (Hitchcock 1942, p.45). It follows most of the fundamental compositional characteristics of Wright's housing pattern (Hildebrand 1991). For example, the house is designed with an open plan: "Let the walls, ceilings, floors become seen as component parts of each other, their surfaces flowing into each other to get continuity in the whole..." (Wright 1932, p.146). This open plan and the walls of windows in all directions provide better cross ventilation and natural lighting for the whole floor. The central location of the fireplace provides a focal point for the open space and serves visually as a vertical anchor for the horizontal cantilevers. The enlarged centralized chimney is also part of the heating/cooling systems of the house. The house is characterized by large terraces that serve as an extension of outdoor living and are part of the horizontal cantilever design. Furthermore, the terraces shade the walls/windows beneath them.

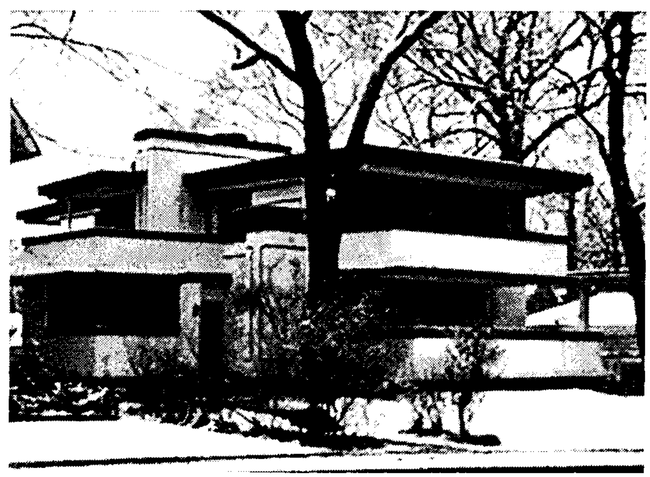

Fig. 2. Mrs. Gale House, Oak Park, Illinois (1904/1909)

Frank Lloyd Wright Original House (1889)

Frank Lloyd Wright built his house for his new bride (Catherine) on a corner lot (Forest Avenue and Chicago Avenue) in Oak Park, Illinois, in 1889. To accommodate his growing family of six children and the expansion of his architectural practice Wright altered this building twice, in 1895 and in 1898. The latest addition to the house was a studio wing of 2,596 square feet (for a detailed description and illustrations of the evolution of this house, refer to Harrington 1996).

The first phase of the house (1889) was an original work of architecture that was not influenced necessarily by family size constraints or expansion of Wright's office (see Figure 3). Therefore, it can be considered as Wright's abstract architectural expression. This study analyzes Wright's original climatic considerations in designing the 1889 version of the house.

The house layout and its relations to the site were typical of Wright's design. The two-story house has an open plan in the first floor that includes an entry, living room, dining room, kitchen, and the stairs going up (the stairs to a small basement are located outside, at the rear of the house). The second floor consists of a master bedroom, a nursery, a studio, and one bathroom. The front terrace screened from the street with solid brick parapets and the fine views of the yard from the house, express the linkage between indoor and outdoor living. Although the entrance is located off-center to the geometry of the house, the house's general expression is of a symmetrical and stable triangular that is set like "a classical pediment above a supporting base of bay windows" (Levine 1996, p.10). The gabled roof sheathed in wood shingles imitates the Mid-West vernacular expression of a shelter. Yet, the interior resembles elements of traditional Japanese domestic architecture (Harrington 1996; McCarter 1997a).[2]

Fig. 3. Frank Lloyd Wright's original house, Oak Park, Illinois (1889)

RESEARCH INSTRUMENT

This study applies ENER-WIN—a computerized energy simulation program that was developed at Texas A&M University.[3] The program's hour-by-hour energy simulations are based on given climatic, building, and economic data. The software includes a weather database of more than 280 US and foreign cities, a catalogue of envelope-materials and their thermal values, and numerous daily user profiles.[4] ENER-WIN's output includes zonal and building's calculations for HVAC loads (Heating, Ventilation, and Air-Condition), energy use, and life-cycle cost predictions.

ENER-WIN (version 97.01) operates under Windows Operation System, and is used by architects, engineers, code officials, and educators who wish to obtain detailed estimates of energy performance of buildings. The program won a citation in the Progressive Architecture Annual Research Award Program (1993). It is described and used in variety of studies, such as, Degelman et al. 1990, 1991, 1994; Lechner 1991; Al-Homoud 1994; Scientific Computing 1995; Geva 1995; Solomon 1996; Soebarto 1996a, 1996b; Geva et al. 1997; Geva 1998.[5]

PROCEDURE

The basic operation of ENER-WIN entails two major steps: generating input files and running the simulations.

Creating an Input File

Figure 4 describes the structure of an input file. The input coding requires general information about the building (such as building type, year of construction, floor area); weather data; economic data on the life cycle of the building;[6] a sketch of the geometry of the building's plans; and the description of the functional zones of the building that include their user profiles and envelope materials.

The required data on the three buildings of this project were obtained from a visit to the site; copies of the original drawings of Frank Lloyd Wright (obtained from the Frank Lloyd Wright Foundation Archives in Taliesin West); Historic American Buildings Survey drawings; books (such as Wright 1910; Hoffmann 1955, 1986; Storrer 1993; Siry 1996; Harrington and Blessing 1996;

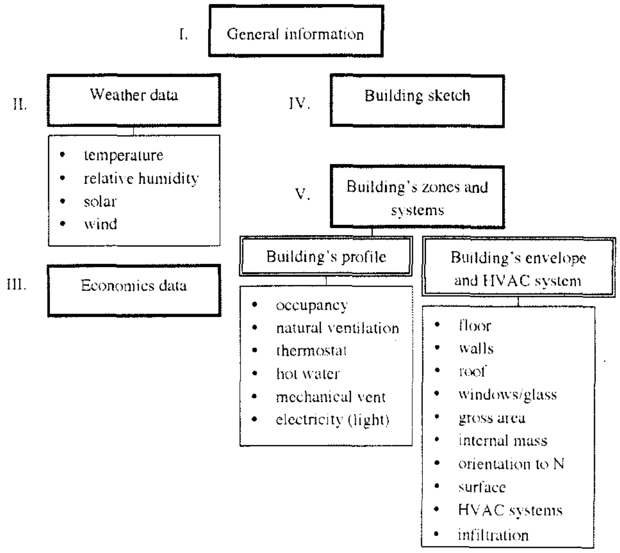

Fig. 4. A schematic structure of an input file

Levine 1996; McCarter 1997a, 1997b); and archival documents.[7] In addition, the ENER-WIN's weather database, user profiles and thermal properties catalogues were used. Furthermore, most of the thermal values (U-Factor, time lag, and decrement factor)[8] of the floor, walls, roof, and openings were calculated using MATERL4 program.[9] The thermal properties of walls, roofs, and glazing were based on tables in the ASHRAE Fundamental Book. The second step in the operation of ENER-WIN entails the simulation runs.

Running the Simulation

The input files of Unity Temple, Mrs. Thomas H. Gale House, and the original Home of Frank Lloyd Wright were run in two modes of the ENER-WIN program: with natural ventilation (passive system) and with air conditioning systems (active system). These simulations assess the internal comfort level and the energy required to achieve designated environmental conditions in the building.

The passive system simulations apply mainly to structures without HVAC. In this mode, the simulations evaluate the comfort level of the passively heated and cooled buildings. The output of this simulation mode represents the deviation of the internal conditions of the building from the designated comfort conditions. In other words, it measures the thermal stress that exceeds the comfort zone.[10] To assess the comfort or discomfort of these internal conditions, the simulation provides a summary of total operative temperatures expressed by the total Discomfort Degree Hours (DDH) which sum the total hot (DDH-H) and cold Discomfort Degree Hours (DDH-C).[11] In addition, the results of the simulation show a percentage of total comfort and discomfort (too hot and too cold) occupancy hours. It should be noted that the output in DDH implies an inverse relation between the total discomfort degree-hours and the compatibility of the building to the local climate.

The active system simulations assess the energy performance of buildings (in energy units and in dollars) that use HVAC systems. These simulations can also run on buildings without HVAC (such as historic buildings) by simulating them as if they include mechanical systems. The results of these simulations show the building's source energy in thousand Btus per square foot (kBtu/sq.ft),[12] total energy consumption in million Btus (Mbtu), and energy cost analysis.[13] The output illustrates in detail monthly and annual heating and cooling loads, peak loads, and energy demand profiles. The more Btu's required by the building to maintain thermal comfort, the less compatible is the building to the climate. In addition, the results of this run help detect the structural components that influence the energy consumption of the building, and the areas for thermal improvement.

RESULTS

The main findings of this study demonstrate that Frank Lloyd Wright's design is environmentally conscious, and that the comfort level he had provided in his buildings complies quite well with contemporary standards. The results emphasize that Wright's buildings are designed to better accommodate the summer of the Chicago area than its winter. The findings also show that the church is more comfortable and consumes less energy than the two single family houses.

The results of the simulations of each building are described in three segments: the comfort level; the energy performance; and areas for thermal improvement.

The Energy Performance of Unity Temple

The results of the passive system simulations of Unity Temple in its original design show a discomfort level of 62,882 annual DDH. Most of this climatic discomfort can be attributed to the cold weather (62,537 DDH-C; 345 DDH-H). In addition, the results of this simulation show that the building is comfortable (between 68°F - 79°F) during 46 percent of the annual occupancy hours. It is too cold (less than 68°F) during 53 percent of the annual occupancy hours, and too hot (more than 79°F) only in one percent of the annual occupancy hours.

The active system run simulated Unity Temple as if it included a HVAC system. This simulation assessed how much energy the building would consume to achieve a designated climatic comfort. The results show an annual source energy of 129.6 kBtu/sq.ft. This energy value is better than the BEPS (Building Energy Performance Standard) for this type of building in Chicago (141 kBtu/sq.ft.). Thus, the energy performance of the church can be acceptable even by today's standards. The findings also show how much energy is required to cool/heat the building. The annual heat loads are 951.43 MBtu, and the annual cooling loads are 125.58 MBtu. These results correspond to the findings of the annual cold and hot DDH and demonstrate the major impact of Chicago's cold winters on the building's thermal conditions.

Further investigation of the energy loads in the church shows that the major contributor to the cooling loads is the solar heat that radiates through the windows (124.2 MBtu). However, the thermal mass effect of the concrete walls decreases the cooling load by 146.22 MBtu, thus, neutralizing the solar effect. The major contributors to the heating loads in the church are the roof (724.5 MBtu), exterior walls (524.6 MBtu), and infiltration/ventilation (292.77 MBtu).

Although Frank Lloyd Wright did not use insulation materials in the Unity Temple while experimenting with concrete, it is interesting to note that he became aware of this type of thermal improvement later in his career. In his writings on 'insulation and heating' (1954: 158-160) he mentions the importance of insulated roofs: "The overhead is where insulation should occur in any building ... whereas the insulation of the walls and the air space within the walls becomes less and less important ... overhead insulation is extremely important: heat rises and if it finds a place overhead where it can be cooled off and dropped, you have to continuously supply a lot of heat. If however, the overhead is reasonably defensive against cold, you can heat your house very economically." To corroborate these more recent ideas of Frank Lloyd Wright, the study simulated Unity Temple with an insulated roof (U-Factor of 0.069) and a reduced infiltration rate (1.0 ACH). The simulations resulted in an improvement of 12 percent in climatic comfort (55,393 annual DDH) and 21 percent in energy performance (102.2 kBtu/sq.ft. source energy).

The Energy Performance of Mrs. Thomas Gale House

The passive system simulations of Mrs. Gale House in its original design resulted in 110,309 total annual DDH (108,783 DDH-C, and 1,526 DDH-H) and in comfortable conditions during 31 percent of the annual occupancy hours. It is too cold during 64% of the annual occupancy hours and five percent too hot. These findings demonstrate that Mrs. Gale House, similarly to the church, is climatically more comfortable in the summer than in the winter. Yet, it is less comfortable than Unity Temple. The active system run simulated Mrs. Gale House as if it included a HVAC system. The results show annual source energy of 142 kBtu/sq.ft. This energy value is worse than the BEPS for this type of building in Chicago (103-110 kBtu/sq.ft.). This simulation mode also indicates that the source energy of Mrs. Gale House is worse than that of Unity Temple. In addition, the findings show annual heat loads of 190.50 MBtu, and annual cooling loads of 23.43 MBtu. These results correspond to the findings of the annual cold and hot DDH, and demonstrate again the major impact of Chicago's cold winters on the building's thermal conditions. These findings support the proposition that Frank Lloyd Wright's designed his buildings to better accommodate the summer of the Chicago area than its winter.

Further investigation of the energy loads of this house points out that the major contributors to the annual cooling loads are the solar heat that radiates through the windows (11.75 MBtu), and the infiltration/ventilation (6.59 MBtu). However, the wall effect of the house decreases some of these contributions by 7.26 MBtu. The major contributors to the annual heating loads are the walls (119.27 MBtu), and infiltration/ventilation (86.59 MBtu). Simulating Mrs. Gale's House with some thermal improvement such as reducing the infiltration rate (1.0 ACH) and insulating the walls (U-Factor: 0.046) resulted in an improvement of five percent in climatic comfort (104,693 annual DDH), and 18 percent in energy performance (source energy: 116 kBtu/sq.ft.).

The Energy Performance of Frank Lloyd Wright Home (1889)

The findings of ENER-WIN simulations of Frank Lloyd Wright Home show that this house is climatically less comfortable than Mrs. Gale House and the Unity Temple, but similarly to them, it is more comfortable in the summer than in the winter. The results of the passive system simulations show 121,230 total annual DDH (120,061 DDH-C, and 1,169 DDH-H). The house was found to be comfortable only in 26 percent of the annual occupancy hours. Seventy percent of the annual occupancy hours are too cold and four percent are too hot.

The results of the active system simulations of Mr. Wright Home as if it included a HVAC system show an annual source energy of 153.6 kBtu/sq.ft. This energy value is worse than the BEPS for this type of building in Chicago (103-110 kBtu/sq.ft.). Analyzing the energy loads show annual heat loads of 190.50 MBtu, and annual cooling loads of 23.43 MBtu. These results are in line with the findings of the annual cold and hot DDH, and replicate the major impact of Chicago's cold winters on the building's thermal conditions.

This simulation revealed that the solar heat that radiates through the windows (5.21 MBtu) and the infiltration/ventilation (3.37 MBtu) are the major contributors to the cooling loads. However, the mass effect of the building (5.26 Mbtu) and the walls (3.05 Mbtu) neutralize these contributions by reducing the cooling loads. The major contributors to the annual heating loads are the walls (94.91 MBtu), and infiltration/ventilation (57.29 MBtu). Simulating Mr. Wright's House with a reduced infiltration rate (1.0 ACH) and insulated walls (U-Factor of 0.046) resulted in a small increase of 0.6 percent in climatic comfort (120,469 annual DDH) and an improvement of 9.5% in energy performance (source energy of 139.0 kBtu/sq.ft.).

CONCLUSION

The summary of this project draws three major conclusions. First, Frank Lloyd Wright considered climate as an important factor in architecture not only in his publications, but also in the design of his buildings. Although the writings of Wright include relatively very few direct comments on the issue of climate and architecture, Wright's design demonstrates sensitivity to thermal properties of his buildings. For example: he experimented with construction materials utilizing thermal mass effects of thick concrete walls; he designed a horizontal cantilevers system that serves as a shading device for specific sun angles; he designed an open plan and walls of windows to provide natural ventilation and light. Wright's architectural passive cooling/heating methods as well as his development of effective heating systems freed his architecture from traditional forms while maintaining a comfortable shelter.

Figure 5 illustrates the energy performance in source energy (kBtu/sq.ft) of the three buildings of this study as compared to BEPS. It shows that Unity Temple is compatible with the climate of Chicago area even by today's standards. The results of the energy simulations of the other two residential buildings somewhat exceed current standards. Thus, these buildings are less compatible with the climate, requiring more energy to achieve a designated comfort level. Yet, this comparison should take into consideration that today's standards require different levels of comfort than could have been aspired for almost 100 years ago.

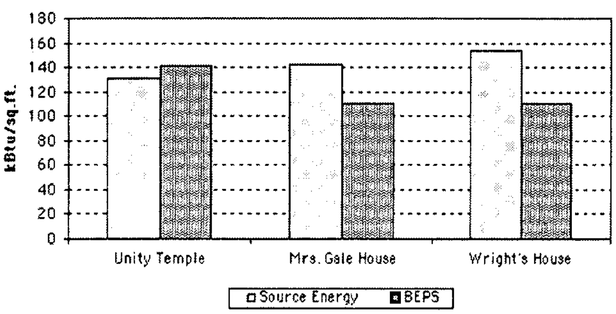

Fig. 5. A comparison of the Source Energy of each building with BEPS

The second conclusion of this project addresses Frank Lloyd Wright's climatic considerations in the design of two different building types: a church and a single family house. Wright's conceptualization of architectural forms as a shelter did not differentiate among building types. Thus, it is expected that all three buildings (the church and the two houses) will be equally comfortable. In contrast, studies of 19th century American vernacular architecture show that the climatic comfort level of houses was higher than churches where very often comfort was sacrificed in order to express heritage (Geva 1995).

Although Wright's houses were influenced by vernacular architecture (Banham 1969; Harrington 1996), the results of this study show that they were climatically less comfortable than the church (see Figures 5, 6). These results can be interpreted in two ways. One possibility is that the Unitarian congregation supported Wright's new ideas of the relations between faith and form and allowed him to explore a non-traditional design of the Unity Temple that departed from the conventional design of churches. Another option is that Wright was more concerned with climatic comfort when a building was to be used by a larger number of people. Since there is no evidence for these explanations in the literature, and the project's sample of only one church and two houses is too small, it is difficult to draw a decisive conclusion.

The third major conclusion of this study is that Frank Lloyd Wright designed his buildings to accommodate the heat of the Chicago area better than the cold windy days. Figure 6 illustrates the percentages of the 'too cold' (less than 68°) and 'too hot' (more than 79°) annual occupancy hours in each of the three buildings. The small percentage of 'too hot' annual occupancy hours may suggest that Frank Lloyd Wright developed an effective passive cooling system. As for the cold conditions, it is plausible that Wright was fascinated with the "new" technologies of water heating systems that he exploited it more extensively than evolving a design of effective passive heating systems (Wright 1910/1985).[14]

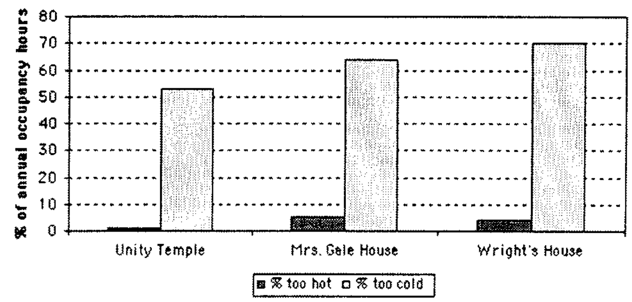

Fig. 6. The percentage of 'too hot' and 'too cold' annual occupancy hours in each building

The simulations also point out that Wright's buildings are designed well enough that simple and inexpensive measures, such as weathering the windows, or adding insulation to the roof improve the comfort level in the winter (e.g., the buildings consume less energy for heating). As mentioned before, Frank Lloyd Wright acknowledged the need to include these thermal improvements in design (Wright 1953).

Naturally, the above conclusions focus on energy issues and isolate them from Frank Lloyd Wright's additional design intentions. However, this study specifically tested the climatic considerations as one aspect within Wright's multidimensional architectural world. The study shows that Frank Lloyd Wright's architecture can be considered as an environmentally conscious design. Furthermore, the study demonstrates the utility of computerized energy simulations in testing the linkage between environmental theory and practice. This methodology helps assess climatic comfort and energy performance of the buildings, identify areas for thermal improvement, and test environmental propositions. Yet, to further validate and refine the propositions of how Frank Lloyd Wright organic architecture dealt with climate, and to increase generalizability of the current empirical approach, this line of research should expand to include a broader spectrum of climate areas and building types.

NOTES

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[1] An exception to the above is Estoque study (1981) that used also simulations and climatic measurements of the Robie House. Though, his study dealt mainly with retrofitting the house for a function different from that designed by Frank Lloyd Wright.

[2] McCarter (1997a) points out that Wright traveled to Japan only six years later.

[3] For a list of microcomputer energy software useful at the design stage see:
http://www.eren.doe.gov/buildings/tools_directory/energy_simulation.htm

[4] The envelope-material catalogue and numerous user profiles are based on ASHRAE 90.1 energy
efficiency standards.

[5] For some of the program limitations see Al-Homoud (1994); Soebarto (1996a).

[6] The life cycle information is irrelevant to this project; however, it is a required component for running the simulation. The study used the program default data.

[7] I would like to acknowledge the Research Center of the Frank Lloyd Wright Home and Studio Foundation, and the Historical Society of Oak Park for their help in obtaining information on the project's buildings.

[8] Decrement factor is a function of time lag and thermal resistance of a wall (Mackey and Wright 1944)

[9] The MATERL4 program was developed by Degelman (1978) at Texas A&M University. This program calculates different thermal factors of walls and roofs built of several layers of materials

[10] The Thermal Comfort Zone as defined by ASHRAE ranges between 68°F - 79°F. For a graphic illustration of the deviation of building's internal conditions from the comfort zone see Figure 3.2 in AlHomoud (1994).

[11] For detailed equations and calculations of the passive system simulations see Al-Homoud (1994) description of the Floating Space Temperatures simulation and Discomfort Degree Hours.

[12] Source Energy: energy consumed by the power plant to produce the total energy used by the building.

[13] The cost analysis is not relevant to this study.

[14] Most of Wright's later houses were typically heated by hot water circulating in pipes beneath the slab (Streich 1972, and Pope 1948, in Brooks 1981 p.42, 56).

REFERENCES

Al-Homoud, M S. "Design Optimization of Energy Conserving Building Envelopes." A Dissertation. College Station, TX: Texas A&M University, 1994.

ASHRAE. ASHRAE Handbook 1985 Fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1985.

Banham, R. "Frank Lloyd Wright as Environmentalist," in Allen Brooks (Ed.) Writings on Wright. Cambridge, MA: The MIT Press, 1981, pp.155-162.

Banham, R. The Architecture of The Well-tempered Environment (2nd edition). London: The Architectural Press, 1969.

Brooks A H. Writings on Wright. Cambridge, MA: The MIT Press, 1981.

Brooks, A H. Frank Lloyd Wright and The Prairie School. New York: George Braziller, Inc., 1984.

Degelman, L O. ENERCALC: A Weather and Building Energy Simulation Model Using Fast Hour-by Hour Algorithms. Tucson, AZ: The Fourth National Conference on Microcomputer Applications in Energy, 1990.

Degelman L O, Andrade G, Miranda V. ENERCAD User Manual. College Station, TX: Department of Architecture, Texas A&M University, 1991a.

Degelman L O, Kim B, Kim Y. ENERCALC User Manual. College Station, TX: Department of Architecture, Texas A&M University, 1991b.

Degelman L O, Soebarto V I. ENER-WIN: A Visual Interface Model for Hourly Energy Simulation in Buildings. E&R '94 Symposium. Prairie View, TX: Prairie View University, 1994.

Degelman, L O. ENER-WIN: User Manual. College Station, TX: Department of Architecture, Texas A&M University, 1995.

Estoque, J. "Heating and Cooling Robie House." APT Bulletin V.19 No. 2 (1981): 38-51.

Fitch, J M. American Building: The Forces That Shaped It. Boston, MA: Houghton Mifflin Co., 1948.

Geva A, Soebarto V I, Degelman L O. "Maintaining A National Image of A Fast Food Chain in Different Climates: Energy Conservation Strategies." Journal of Architectural and Planning Research (1997, in Press)

Geva, A. "A Computer Simulation of Energy Performance of Historic Buildings: St. Louis Catholic Church, Castroville, Texas." APT Bulletin, The Journal of Preservation Technology. Vol. XXIX, No. 1 (1998): 36-41

Geva, A. "The Interaction of Climate, Culture, and Building Type on Built Form: A Computer Simulation Study of Energy Performance of Historic Buildings." A Dissertation. College Station, TX: Texas A&M University, 1995.

Harrington E, Hedrich-Blessing. Frank Lloyd Wright Home and Studio, Oak Park. Stuttgart, Germany: Axel Menges, 1996.

Hildebrand, G. The Wright Space: Patterns and Meaning in Frank Lloyd Wright's Houses. Seattle, WA: university of Washington Press, 1991.

Hitchcock, H R. In The Nature of Materials. New York: Da Capo Press, Inc., 1942.

Hoffmann, D. Understanding Frank Lloyd Wright Architecture. New York: Dover Publications, Inc., 1955.

Hoffmann, D. Frank Lloyd Wright: Architecture and Nature. New York: Dover Publications, Inc., 1986.

Johonnot, R F. The New Edifice of Unity Church, Oak Park, Illinois. Oak Park, IL.: The New Unity Church Club, 1906.

Kaufmann E, Raeburn B. Frank Lloyd Wright: Writings and Buildings. New York: Horizon Press, 1960.

Lechner, N. Heating, Cooling, Lighting: Design Methods for Architects. New York: Wiley & Sons, Inc., 1991.

Levine, N. The Architecture of Frank Lloyd Wright. Princeton, NJ: Princeton University Press, 1996.

Mackey C O, Wright L T Jr. "Periodic Heat Flow - Homogeneous Walls or Roofs," ASHVE Transactions 50 (1944): 293-312

McCarter, R. Frank Lloyd Wright. London: Phaidon Press Ltd., 1997a.

McCarter, R. Unity Temple: Frank Lloyd Wright. London: Phaidon Press Ltd., 1997b.

Pope, L. "The Love Affair of a Man and His House," in Allen Brooks (Ed.) Writings on Wright. Cambridge, MA: The MIT Press, 1981, pp. 51-57.

"Scientific Computing CAD-Building Load Software Review," Engineered Systems. June (1995): 50-56

Siry, J M. Unity Temple: Frank Lloyd Wright and Architecture for Liberal Religion. Cambridge: Cambridge University Press, 1996.

Soebarto, V I. Development of A Calibration Methodology for Hourly Building Energy Simulation Models Using Disaggregated Energy Use Data From Existing Buildings. A Dissertation. College Station, TX: Texas A&M University, 1996a.

Soebarto V I, Degelman L O. "A Calibration Methodology for Retrofit Projects Using Short-Term Monitoring and Disaggregated Energy Use Data," Proceedings of the 10th Symposium on Improving Building Systems in Hot Humid Climates. May (1996b): 38-47.

Solomon, N B. "Software from the Schools," Architecture 8 (1996): 153-157

Storrer, W A. The Frank Lloyd Wright Companion. Chicago, IL.: The University of Chicago Press, 1993.

Streich, E R. "An Original-Owner Interview Survey of Frank Lloyd Wright's Residential Architecture," in Allen Brooks (Ed.) Writings on Wright. Cambridge, MA: The MIT Press, 1981, pp. 35-45.

Wright, F L. "In the cause of Architecture (1908)," in Frederick Gutheim (Ed.) In the Cause of Architecture: Frank Lloyd Wright. New York: Architectural Record, 1975, pp. 53-119.

Wright, F L. Ausgefuhrte Bauten und Entwurfe, Berlin, 1910. Reprinted in English Studies and Executed Buildings. New York: Rizzoli International Publication, Inc., 1986.

Wright, F L. "In the Cause of Architecture (1914)," in Frederick Gutheim (Ed.) In the cause of Architecture: Frank Lloyd Wright. New York: Architectural Record, 1975, pp. 121-129.

Wright, F L. Modern Architecture. Princeton: Princeton University Press, 1931. Renewed by Southern Illinois University Press, 1959.

Wright, F L. "Prairie Architecture (1931)," in Edgar Kaufmann and Ben Raeburn. Frank Lloyd Write: Writings and Buildings. Horizon Press, Inc., 1960, pp. 37-170.

Wright, F L. An Autobiography. New York: Duell, Sloan and Pierce, 1932. Reprinted by Horizon New York, 1943; 1977.

Wright, F L. The Future of Architecture. New York: Horizon Press, 1953.

Wright, F L. The Natural House. New York: Horizon Press, 1954.

Wright, F L. "The New Architecture: Principles (A Testament), 1957," in Edgar Kaufmann and Ben Raeburn. Frank Lloyd Write: Writings and Buildings. Horizon Press, Inc., 1960, pp. 304-326.