Sustainable Urban Design in Arid Regions; Integrating Energy and Comfort

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Abstract:
Over one-third of the world's surface and an estimated 25% of the population live in desert cities located in regions using the definition of extremely arid, arid or semi-arid. While desert cities survive in a harsh environment and scarcity of natural resources they have the opportunity to confront these environmental constraints and serve as models for the solution to urban ecology problems of our time. In the Sonora desert, scientists at the University of Arizona, and in the College of Architecture, have been researching different aspects of the built environment that attribute the most to indoor and outdoor human thermal comfort conditions. Our research suggests that careful planning, design, and attention to the climatic forces can significantly improve the livability of outdoor spaces of communities from both the human comfort and the energy use perspective. This improved microclimate will have direct impact on the thermal performance and energy usage of buildings. This paper addresses the pedagogical implementation and practical applications toward sustainable design and energy conservation in the built environment while demonstrates the efficacy of a sustainable approach to extend indoor living spaces outdoors.

Desert Cities and the US Southwest:
In Arizona, we live in a desert environment that uses the definition of extremely arid, arid, and semi-arid land. Over one-third of the world's surface and an estimated 25% of the population live in similar conditions. Desert cities survive in an environment which is characterized by: 1) aridity and scarcity of natural resources, such as water, and 2) extreme climatic conditions manifested by high temperatures and heat. Other typical conditions of such arid region we can perceive as opportunities. These are: 3) abundant energy in the form of solar radiation and light and 4) plentiful clear sky conditions attributing to the large diurnal temperature swing and blackbody radiation.

Integrating A Sustainable Approach:
For many years, scientists at The University of Arizona, and especially in the College of Architecture have been researching and developing methods for energy conservation, use of natural resources such as solar and...
wind energy, passive evaporative cooling, appropriate materials including high thermal mass, and night-sky (blackbody) radiation to achieve thermal comfort indoors. These methods have also extended for the purpose of investigating and optimizing thermal comfort conditions of outdoor spaces in desert cities. Our research suggests that careful planning, design, and attention to the climatic forces can significantly improve the livability of outdoor spaces of communities from both the human comfort and the energy use perspective.

Indoor comfort is based on outdoor ambient climate conditions, envelope effectiveness, and mechanical heating and cooling efficiency. Move the outdoor climate toward comfort and building performance improves, while the adjacent outdoor becomes more useful. Our hypothesis is then founded on the following two questions:

1) “if outdoor spaces of a community can be made more comfortable by design, can we then assume that buildings would require less enclosed area and move some of their functions to the adjacent outdoor spaces?”

2) “can buildings become more energy efficient since, with a modified microclimate, they will not have to deal with the climate extremes?”

To investigate these conditions, the following objectives have been considered:

1. Improve understanding of human comfort as a mean for advancing residential and community design.
2. Increase efficiency of energy and water by designing with climate and comfort in mind.
3. Improve livability and sustainability through comfort considerations.

Pedagogical Implementation:
Our “Design and Energy Conservation” graduate program in the School of Architecture has two folds; teaching processes and methodologies that address energy and environmental concerns, as well as, explore methods of investigation through laboratory techniques. Students can choose to adopt a process for implementation toward a specific project of their interest. Alternatively, they can research and further develop new methodologies to achieve higher gain and advancement in their chosen field.

Energy and Buildings:
Earth has 6 billion people but about 72% of them live in countries that are not industrialized. During the last decade, earth’s energy consumption averaged about 400 quadrillion (400x10^{15}) Kilowatt-hours per year. The building sector consumes half of the energy that is used by human beings. If the standard of living of all people is raised to the same level, the energy needed will be three or four times greater. It is vital to consider where this additional energy will come from?

![Fig. 3: World's energy consumption by sector](image)

Energy consumption in the United States costs $450 billion dollars a year. The growing awareness of the importance of energy efficiency beginning in 1973 has improved the economy and now saves the country $160 billion per year (Harvey et al, 1991)[1]. This was achieved through existing technologies that provided opportunities to improve efficiency without reducing standards of living. But even greater advances are possible.
Studies show that cost effective energy efficiency could save 1/2 the energy now consumed in buildings, saving the country about $100 billion/Yr.

Arizona's climate and growth present particular challenging design opportunities. Arizona has both the greatest amount of insolation and the second largest population growth in the U.S.A. The total primary energy consumption in Arizona is estimated at 1,079,800 X 10^9 BTU's in 1990; this is an average 19.19% increase in consumption over the 839 X 10^9 BTU's in 1986 (AEO, 1990)[2]. The residential sector consumes 19.6% of the total primary energy. Energy consumed for space conditioning (both heating and cooling) represents approximately two-thirds of the total energy consumed in the typical home and roughly 11% of total U.S. energy consumption (DOE/EIA 0262, 1981)[3]. The House Energy Doctor© program (HED) at The University of Arizona's College of Architecture was developed in 1986 to address the energy efficiency issue.

**The House Energy Doctor:**
The HED program is an educational, research and community service program at the College of Architecture that promotes student learning of energy conservation and passive solar design through field investigation of existing buildings and through innovative sustainable design studios. While field investigation provides a no-cost energy consultation service for building owners, the sustainability focused designs studios help in the graduation of new generations of energy conscious and climate responsive architects and provide consultation to major sectors of the community such as local architects, builders, utility companies and developers (Chalfoun, 1991)[4,5].

The climate responsive design process is based on balancing the major forces acting on building envelope from the macroclimate scale, to the microclimate modifiers, and lastly to the building envelop itself. If thermal comfort is not achieved, further passive solar technologies, such as Tromb walls, sunspaces, rockbeds, cool towers, etc., could be utilized to fine tune the design before relying on mechanical system.

Investigation the energy efficiency of building envelope is mainly focused on the following impact areas:
1. Building Shape
2. Orientation
3. Insulation
4. Shading
5. Fenestration
6. Reflectivity
7. Ventilation
8. Materials
9. Efficiency/types of mechanical system
In Arizona, due to the mild winter season, passive solar energy with adequate thermal storage system can provide almost all the heating requirements for a building. The House Energy Doctor program provides students the opportunity to develop research projects related to their Masters studies, senior (capstone) design, and/or funded research. A Below-collector Tromb-wall system with low-flow fan and insulated double brick Thermal storage wall coupled with return air ducts was developed at the Mittal residence in Tucson, Arizona.

Research activity of the energy program also leads to publication of findings and opportunity for national and international travel. Over the past 10 years, the HED team has published more than 44 national and international research papers in conferences, peer-reviewed journals and magazines. Students traveled to Mexico, Europe, and other places to present their work.

The Outdoor Comfort Research:
Man-made built environment of urban development in large cities has altered the natural biological order of heat balance. The lack of evapotranspiration, the sealing off of natural evaporative surfaces, and the use of materials of permanence, like concrete, asphalt, and glass has contributed to increasing local warming. In the climatic extreme of arid regions this “heat island” phenomenon reduces the hospitality of a community by causing thermal discomfort in outdoor spaces as well as increasing the energy needed for cooling indoor spaces. Confronting the warming issue, therefore,
may have positive effects on both the quality-of-life of a community by improving comfort for outdoor interaction, and on resource conservation by improving the energy performance of a community for indoor heating and cooling.

Fig. 9: Downtown Tucson; a demonstration of urban heat island effect.

It appears from the great amount of debate in the field of sustainable development that there are few analytical tools used for thermal assessment of outdoor spaces. Almost all of the discussion involves preconceptions, empirical information and case study exemplars with little theoretical evidence to assess what the design variables and their consequences might be. For many years, scientists at The University of Arizona have been researching outdoor thermal comfort conditions for desert cities. Our research suggests that careful attention to the climatic forces can significantly improve the livability of outdoor spaces of communities from both the human comfort and the energy use perspective.

Recently, a new methodology for assessing outdoor thermal comfort in urban spaces has been developed by the author. Utilizing sophisticated tools, in-house developed software, scale models and fish-eye lens photography, the thermal performance of an outdoor space is predicted and evaluated for comfort. The methodology follows three main steps; 1) evaluation of the geometry of a location by calculating the view factors of all surrounding radiating fields, 2) collection of major microclimate data, and 3) prediction of thermal conditions utilizing a computer program named MRT© (Chalfoun, 91)[6,7].

Fig. 10: Thermal Comfort Analysis

MRT© manipulates the view factors and the natural climatic elements of temperature, moisture, solar radiation, and wind speeds, as well as reflectivity, absorptivity and radiant emissivity of surrounding natural landscape materials and man-made surfaces to predict the Mean Radiant Temperature (MRT), the Predicted Mean Vote (PMV) thermal index and the Percent of People Dissatisfaction (PPD). These indices represent the thermal comfort condition of the location.

Fig. 11: Estimation of View Factors: “The fraction of the radiant flux which strikes a person from a particular surface to that which would be received from the entire environment radiating uniformly.”

A most recent development of the method (Chalfoun, 01)[8] allowed designers to assess view factors in scale models through
fish-eye lens photography technique that was adapted from I. Watson and G. Johnson [9]. This development expands the method which was previously limited to investigation of existing outdoor spaces. Designers can easily make changes to the models and re-test different design strategies for improvement.

Theoretically, physical models of buildings and urban open spaces provide a means of accurately predicting daylight illumination but they are not suitable where the phenomenon does not scale down properly such as in the case of the thermal environment. However, in complex building geometry, physical models, when combined with fish-eye lens photography, can provide a reliable way to compute view factors of the various radiant surfaces at a reference point which otherwise would involve complex, often unmanageable, equations. To consider long-wave infrared radiation from all surfaces, methods of calculation based on the actual human figure model are too laborious to be practical. In practice, the long-wave mean radiant temperature is measured using a globe thermometer, which is considered a close approximation to the human body. By using a spherical target, whose diameter includes a 6-foot human figure, computation of the view factors is greatly simplified.

Because the fish-eye lens circular images represent the hemispheric radiating environment acting on the proposed 6 foot average human figure, we assumed that the real environment can be reduced in scale down to the limit of the sphere whose diameter is the size of the lens in use. Because we are currently using a 1" (22.5mm) lens diameter, then the scale is defined as 1" = 6'-0".

Since a person’s radiating environment is represented as a sphere, and the $180^\circ$ photograph represents only a hemisphere, the process of estimating view factor at each location requires taking two photographs; one with the lens facing up at 3 feet high above the ground level, and the other looking down, also at a 3 feet height above ground. Because the selected scale is 1" = 6 feet, when photographing the model the camera lens needs to be at $\frac{1}{2}$" from the plane of the model base. For photos looking down, a tripod is used. Photos looking up require cutting a 3" hole at each selected location.

The circular images are overlaid with a polar grid with 25 annuli and 40 radii dividing the circle into 1000 parts. Each cell in this polar grid represents 0.1 percent of the radiating environment on half of the radiating hemisphere. Therefore, combining both photographs, each cell in the polar grid will represent 0.05% of the total radiating environment.
environment at that location and corresponds to a fraction of a person's view factor.

Fig. 14: Circular images overlaid by the polar grid.

Figs. 15 & 16: Student's working models showing the circular holes that allow for fish-eye lens photography.

When view factors are calculated, the MRT program predicts the mean radiant temperature (MRT), the ASHRAE New Effective Temperature (ET*) and the Predicted Mean Vote index (PMV), which represents human thermal comfort on a scale from -5 to +5.

Fig. 7: MRT results illustrate that human thermal comfort condition was maintained throughout a typical summer day, especially with the cool tower strategy.

The presented methodology allows designers to identify the major elements that most contribute to the thermal conditions of an urban outdoor space.

References: