Using the Landscape for Passive Cooling and Bioclimatic Control:

Applications for higher density and larger scale

STEVEN A. SANDIFER

University of California, Los Angeles, U.S.A.

ABSTRACT: Design for passive cooling in hot climates presents particular design challenges due of the magnitude of the sources of overheating versus the potential of the natural sources of cooling that are usually available. Despite the general recognition that the landscape can have a significant impact in improving comfort and reducing energy use in buildings, there is little quantified research. This paper presents the results from a series of experiments on the uses of several less well studied elements of the landscape in the cooling of buildings; vines, landscape ponds and vegetated roofs. The experiments described in this paper demonstrate that all of the strategies studied have the potential to reduce heat gain significantly and perform well as bioclimatic elements in cooling strategies for buildings. Landscape ponds and vegetated roofs were shown to be able to function as passive cooling systems as well. That is, they have the potential to reduce average indoor temperatures to below the outdoor average. Landscape strategies can be used to make new buildings perform well in hot climates, but may be even more valuable in improving the performance of existing buildings. The strategies studied here could be used on buildings of almost any size or type.

Keywords: Passive cooling, bioclimatic architecture, vegetated roof, green roof, pond cooling, plant shading, landscape

INTRODUCTION

Anyone who has sought the shade of a large tree or vine covered pergola on a hot day understands the ability of vegetation to improve human comfort. Ancient people certainly found relief from the heat in the landscape even before they began to construct shelters. Humans have been incorporating landscape elements into the built environment in order to improve human comfort for thousands of years. Despite, or perhaps because of, the intrinsic and obvious nature of the ability of plants to improve human comfort in hot conditions, there is relatively little systematic, quantified research on the topic. “The general effectiveness of vegetation, especially trees, to provide low-cost cooling is well known, there were few quantified studies,… and no handbooks” [1]. Most of the research that does exist is on the effects of trees or groups of trees. Some studies have been done on the impact of whole landscapes on the energy use of small buildings [4].

Minimizing heat gain is the first priority in bioclimatic design for hot climates. It is also one of the most economical means to produce indoor comfort both in terms of first costs and operating costs. Amongst the various means to minimize heat gain (building color, orientation, shading devices for openings, building material, etc.), landscape elements have several unique advantages. The use of landscape elements such as shade trees, vines on pergolas and vines grown on walls, are among the most economical means of providing effective shading of exterior surfaces and openings available in terms of first costs. The work can be done by anyone, not just building professionals. Landscaping can be added at any time, so plantings can be added to existing or new buildings to make them function better without the expense and inconvenience of altering the existing structure. Landscaping around buildings can also alter the external microclimate in positive ways, making exterior spaces adjacent to buildings more useful, not to mention more attractive. As living systems in the built environment, landscape elements always perform multiple functions; as living parts of any ecosystem do. They convert CO^2 to oxygen, sequester carbon in their tissues, filter surface water, provide habitat for birds and other wildlife, and can provide food for people and animals. Finally, the psychological relief and attraction that the living landscape provides for people in an increasingly urbanized world may be the most important benefit of all.

The use of the landscape as part of a passive cooling strategy for buildings at the scale of the single family home is a familiar concept to most designers. Trees and shrubs strategically placed on the lot around a house can provide shade in summer for roof and walls, allow winter sunlight penetration and block cold winter winds.

Other landscape elements can be used, along with trees and shrubs, to reduce cooling loads in higher density residential situations and on larger building types. Vines and vegetated roofs can be used effectively at the single family home scale, but become particularly useful as building density and scale increases. Vines are particularly suited to use on tall buildings. They require little root space, grow very quickly and can cover large areas of a building surface. The roof element can be the greatest source of unwanted heat gain in many building types. As the proportion of roof area to either building volume or lot size increases, the usefulness of vegetated roof strategies also increases. While most landscape strategies are generally considered bioclimatic strategies, that is they are able to reduce or at best, eliminate the sol air temperature elevation of building surfaces, vegetated roofs and landscape ponds adjacent to buildings were shown in the experiments described in this paper to be able to function as passive cooling elements.

This paper describes a series of experiments that were conducted on several less well studies elements of the landscape; vines, vegetated roofs and landscape ponds. These experiments, which include both field studies and laboratory experiments, were carried out as dissertation research in the Department of Architecture and Urban Design at the University of California, Los Angeles. Tests were conducted on: the effects of vines grown against walls on building surface temperature; the effects of vines grown on pergolas and trellis systems on both building surface and air temperature; the effect of sod and other vegetated roof types on roof temperature; the effect of aquatic vegetation on water temperature of ponds; the ability of vine shaded ponds to reduce temperature in interior spaces.

EXPERIMENTS ON VINES

Both laboratory and field studies were conducted on the use of vines to reduce building surface temperature, shade glazed openings and improve outdoor microclimate adjacent to buildings. One series of laboratory experiments measured the shading effectiveness of several different species of vines on South and West facing wall panels of two different colors; white and brown. South and West facing vertical modules were constructed. Each module consisted of two aluminium panels (one painted white and one painted brown) mounted on a sheet of styrofoam. A thermocouple was connected to the back of each panel at the center. One module for each orientation was left unshaded and vines were grown in front of the others. Another laboratory experiment measured shading effectiveness of two vines on a South facing brick wall. A series of field tests measured air and wall surface temperatures on a West facing wall that was partially shaded by a Wisteria covered pergola.

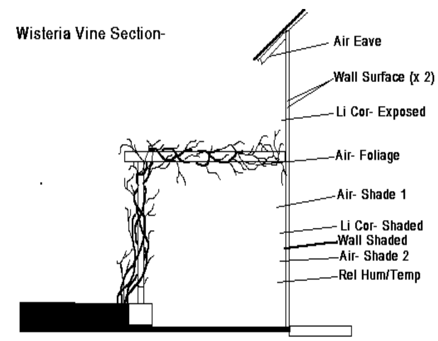

Figure 1: Pergola section showing thermocouple locations.

Figure 2: Shaded area below pergola with data collection enclosure.

To evaluate the effectiveness of vine shading in reducing building surface temperature, a formula was developed to determine a shading effectiveness ratio. Solar radiation on a south or west facing vertical plane was not always measured. The relationship between the control panel temperatures and the vine shaded panel surfaces was used to determine the effectiveness of the vine shading. The heat capacity of the aluminium panels is very small, so their temperature responds to the instantaneous changes in the ambient air temperature (DBT) and solar radiation absorbed by the plates. Therefore, the elevation of the surface temperature above the DBT can serve as the input data for the analysis of the shading effectiveness of the vining plants.

The suppression of the temperature of the experimental panels above the temperature of the controls was evaluated as a ratio of the differences between the control and the shaded panel to the control minus DBT. This ratio represents the shading effectiveness of the vines. This can be expressed in the following formula:

Shading Effectiveness =
(Control - Shaded Panel) / (Control - DBT)

It shows the degree to which a vine is able to reduce the sol-air temperature elevation of a vine shaded surface. A shading effectiveness ratio of .65 would reduce the temperature elevation of a shaded surface by 65% and a shading effectiveness ratio of 1 would reduce the temperature elevation of the shaded surface by 100%. A shading effectiveness ratio that is above 1 would indicate that there is some effect in addition to shading, such as evaporation, occurring.

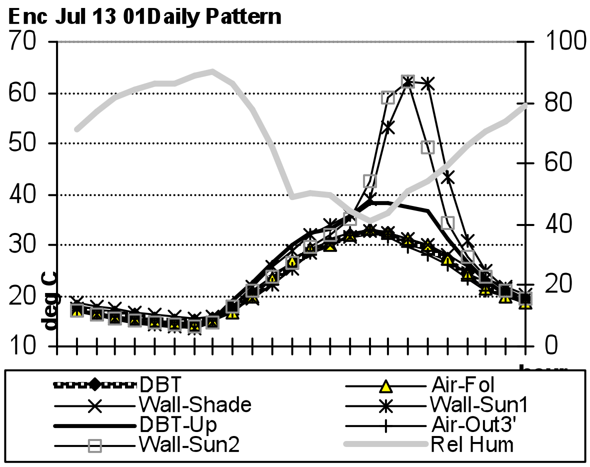

Figure 3: Chart of daily temperature patterns of a pergola shaded and unshaded West facing stucco wall.

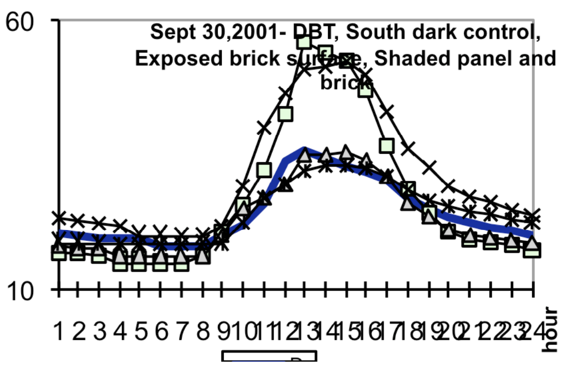

Figure 4: Chart of daily temperature pattern of unshaded and vine shaded brick wall and experimental modules showing ability of vine shading to reduce surface temperatures to ambient levels.

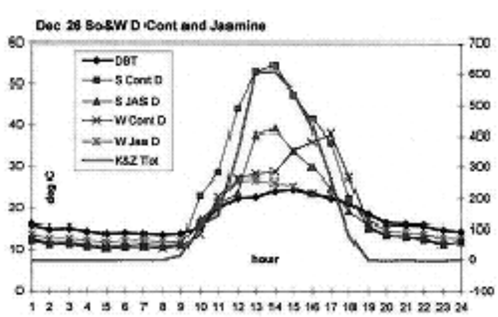

Figure 5: Chart of daily temperature patterns of shaded and unshaded South and West facing wall modules.

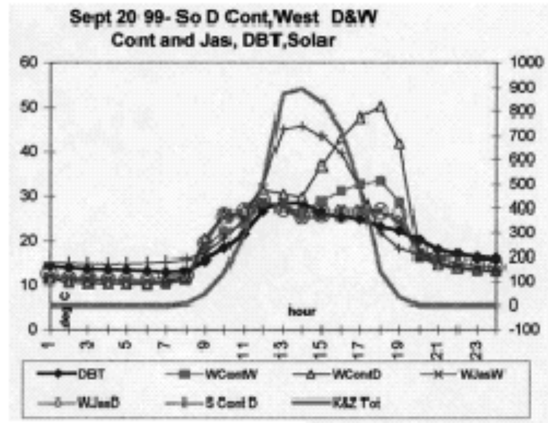

Figure 6: Daily temperature patterns of South and West facing control panels and west facing panels shaded by Jasmine vines.

SUMMARY OF THE RESULTS OF LABORATORY AND FIELD TESTS ON VARIOUS USES OF VINES

- Vines grown against a building surface at a thickness of 12-14 inches (30-35 cm) can reduce surface temperature to the level of, or slightly below, the ambient air temperature.
- Vines grown to a thickness of 12-14 inches (30-35cm) can eliminate the effect of surface color.
- Vines growing directly on walls or on pergolas can be an effective means of reducing the problem of west wall heat gain.
- A vine covered pergola can; modify surface temperature as well as surface grown vines, shade glazed openings and provide more comfortable exterior space next to buildings.
- Deciduous vines, grown against walls or on pergolas can provide summer cooling and allow winter sun to warm exterior walls and penetrate glazed openings in combination (hot summer, cold winter) climates. The foliation pattern of most vines follows the annual heat cycle providing spring and fall heating or cooling when it is usually needed most (more heating in the spring and cooling in the fall).

EXPERIMENTS ON VEGETATED ROOFS

It can be difficult to shade the roof element of a building at all hours with trees alone. A completely tree shaded roof will lose less heat at night because the tree foliage blocks the view to the night sky. A vegetated roof shades the entire roof element during daytime hours. Through shading and transpiration, the vegetation can dissipate heat that would otherwise be absorbed at the roof surface and the vegetated surface is exposed to the night sky. Unlike tree shading, vegetated roof strategies can eliminate/reduce solar load on the entire roof, at all hours of the day. Vegetated roofs can take advantage of night time radiant loss due to the exposure of the vegetated surface to the night sky. The potential cooling of the system can be transferred directly or easily into the structure below. Vegetated roofs can be differentiated from other vegetated shading strategies since the vegetated roof consists of not only the foliage, but the entire plant and the soil substrate that the plant grows in: the root system and the soil column. A vegetated roof is a complex system and the effects reflect the combination of the mass of the soil interacting with irrigation water in addition to the effects of the shading/ cooling from the foliage above the soil. One might expect performance of such a system to be similar to shaded soil/ gravel covered roof cooling systems reported by Givoni (1994).

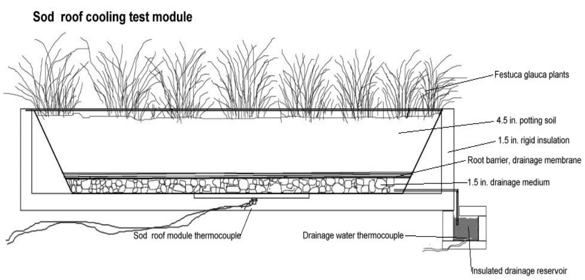

Figure 7: Vegetated roof test module diagram.

Two sample sod roof modules were constructed and temperatures beneath the sample sod roof installations were measured along with temperatures beneath standard roofing materials of two colors; brown and white. Two different planting configurations were tested; one module was planted with gray fescue grass and a second module planted with a combination of California coastal sage scrub plants. The temperature of the runoff water from one of the planted modules was also monitored.

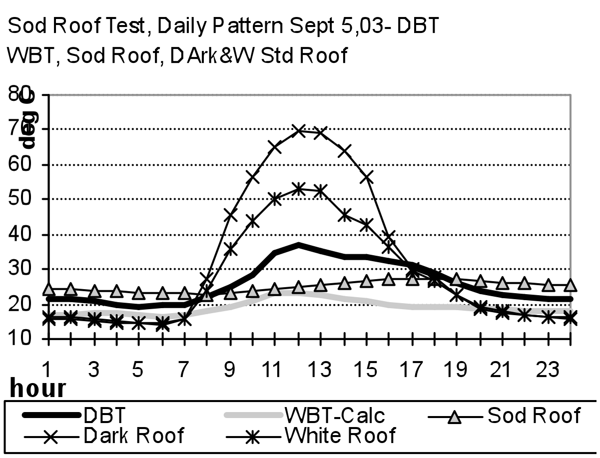

Figure 8: Chart of the daily temperature patterns of; sod roof module, light and dark standard roofing, DBT, and WBT illustrating the overall reduction in maximum temperature and suppression of the daily swing of the vegetated roof.

In order to optimize a vegetated roof to provide passive cooling for a building, the following elements are most important:

- Complete coverage of soil by vegetation
  - Dense foliage, thick turf- High LAI
  - Complete "Canopy factor"- no gaps in foliage cover
  - Soil mulch- 2" to conserve water, shade soil surface until plants shade soil surface completely
- Direct coupling of soil to interior (through heat transfer system or by using no insulating layer between interior and base of soil)
- Spray/mist irrigation system
- Light foliage color

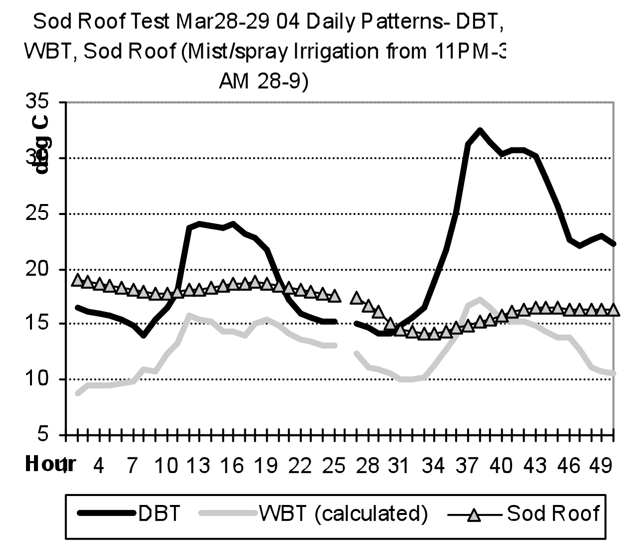

Figure 9: Chart of 2 day temperature pattern showing effectiveness of night time irrigation on roof temperature

CONCLUSIONS FROM THE TESTS OF VEGETATED ROOFS

From the point of view of potential energy savings, the results are fairly dramatic and show that vegetated roofs can function as passive cooling elements. In one test that compared temperatures beneath a sod roof module and two standard roof assemblies (one dark and the other painted white), the fescue grass roof application reduced temperatures at the roof membrane by 44 degrees compared to the dark asphalt roof surface and by 25 degrees compared to the white painted surface. The research shows that vegetated roof installations have potential to provide cooling for buildings in hot climates. Temperatures beneath the module with Fescue grass had daytime average temperatures 5 degrees C below the outdoor daytime average. Timing and method of irrigation can be used to improve the cooling potential of vegetated roof systems. One test of fine-mist night irrigation reduced temperatures beneath the sod an additional 4 degrees C. It is possible that irrigation runoff from a vegetated roof could also be used in building cooling strategies. The results indicate that the water would be at or near DBT daily minimums if irrigation was done at night. These tests also illustrate another purported benefit of vegetated roof systems; longer roof membrane lifespan. Thermal shock is one common cause of roof membrane failure and degradation. In the example shown in figure x, the daily temperature swing of the sod roof module was only 6 degrees C, while the white painted roof surface had a swing of 40 degrees and the brown surface was 56 degrees.

EXPERIMENTS ON LANDSCAPE PONDS AS PASSIVE COOLING ELEMENTS FOR BUILDINGS

Ponds occupy a special place in the landscape. A pond is usually the center of interest in gardens. In terms of comfort in hot climates the space nearest to the pond may be the most comfortable part of a garden. A pond must be very large or employ spray features in order to have a significant effect on air temperatures in an outdoor space, however [3]. The psychological effect of water visible in the garden may be hard to separate from the actual cooling provided by the water feature. Ponds can also be linked to indoor spaces to provide cooling using air or water as a heat transfer medium. The amount of cooling available from a landscape pond would be limited by the size of the pond and the degree to which the pond surface is shaded from direct sunlight. Other features that could enhance the cooling ability of the pond include; the proximity of the pond to the building, the depth of the water, strategies to increase airspeed at the water surface, fountain sprays to increase the rate of evaporation, exposure of the water surface to radiant loss to the sky. The water surface must be shaded in order to produce water temperatures that are below ambient levels.

The use of ponds and constructed wetlands for cooling of indoor spaces would be limited by available space near to buildings. The cooling capacity of the pond or wetland would be limited by the size of the pond, though deep ponds could be constructed on relatively small spaces. Based on the results from roof based ponds, it might be safe to assume that a shallow pond could provide comfort for a space equal to the pond surface area and that deeper ponds would have proportionally more heat capacity. A pond or constructed wetland could be used to cool a small building or a specific room in a larger building. Water that is shaded from direct sunlight will have a temperature close to the average wet bulb temperature. The temperature of this water can be further reduced by several means, including; increasing airspeed at the water surface, using fountain sprays and by exposing the water to the night sky. A heat transfer system must be used to transfer the cooling energy from the pond to an interior space. Both water and air can be used as transfer mediums.

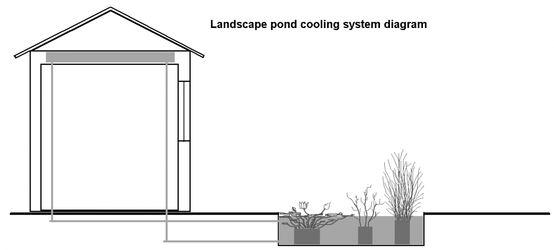

Figure 10: Diagram of a landscape pond cooling system

Previous studies have shown that the temperature of shaded roof ponds follow the average wet bulb temperature. Several configurations of roof based pond cooling systems have been tested/studied and have performed well [3]. While roof ponds require specific design and structural details, ground based ponds could be used to cool any building. Theoretically, any fountain, fish pond, or constructed wetland could also be used as a source of cooling energy for buildings as long as daytime heat gain could be minimized. In the case of ground based landscape ponds, cooling energy would have to be transferred indirectly, using air or water as a transfer medium. A functional diagram of a pond cooling system would consist of the two elements shown above in figure 5a; the cooling pond and the interior space connected by two heat exchangers. The pond would then function as a heat sink to provide cooling to the interior space.

Figure 11: Can aquatic vegetation provide sufficient shade for a pond to function in a cooling system?

Several experiments were conducted on the use of ponds as cooling systems including:

- A series of tests on the ability of various types of aquatic vegetation to shade and cool ponds,
- A test of a deep pond shaded at the surface by floating vegetation where temperature was measured at several different levels.
- An experiment where a shaded pond was used to cool a test cell. Plywood panels and vines were used to shade the pond surface. Air and water were used as heat transfer mediums. Several strategies were used to

improve the performance of the cooling ponds, including fountain sprays and increasing the airspeed at the pond surface.

In order to use a pond or constructed wetland as a passive cooling system for a building, the following elements are most important:

- Water surface that is substantially shaded
- Pond elements that are as deep as possible/ or that have deep chambers
- Ponds that are located as close to the building as possible
- Design that enhances air movement over water surface
- Fountain sprays to enhance evaporative cooling/ radiative cooling
- Heat transfer from pond to interior-
  Water/liquid heat transfer- can cool interior mass
  Air heat transfer- can improve performance of pond when operated at night.

CONCLUSIONS FROM THE TESTS OF LANDSCAPE PONDS

The experiments on the effects of aquatic vegetation on water temperatures show that water shaded by aquatic plants has temperature patterns and levels similar to water that is covered by artificial shade structures. Both the shaded control pond and the various aquatic plant types tested produced water temperatures near to WBT daily average. The pattern of temperature for the vegetated ponds was offset from the ambient air by 12 hours so that the daily minimum recorded in the plant covered ponds coincided with the maximum DBT. The artificially shaded pond had a time lag of approximately 7 hours. The amount of cooling produced by the plant shaded ponds was also sufficient to indicate potential use for passive cooling system applications. In the example shown in figure 9 the daily average temperature of the plant shaded ponds was between 5 and 7 degrees below the daytime average DBT.

The deep pond experiments show that deeper ponds or ponds with deep chambers may offer better performance than shallow (18 inches or less) plant shaded ponds. In one test, temperature levels at 9 and 18 inches deep in the plant shaded deep pond were similar to the other plant shaded ponds, but temperatures at 27 inches of depth were 2-3 degrees C lower.

The results obtained to date for the pond cooled test cell indicate that such a system could provide cooling for an interior space. The tests using an artificial shade (plywood) also show that either air or water could be used as a transfer medium. Direct comparisons of relative efficiency of the two mediums are difficult with the experimental set-up that was used since the water based system was a closed water loop between the ponds and the test cell and the air based system was a one-way cooled ventilation strategy. Outside air was drawn into a serpentine chamber beneath the ponds and then into the test cell and displaced air vented out of the cell at the opposite end from the inlet. The test of the air based system showed that the air was cooled to the level of the WBT during daytime hours and to a level just above WBT at night. The situation at night may be that the air was cooling the pond, since the pond water temperature at night was usually at or just above the DBT. Meanwhile, temperatures in the test cell were 3 degrees C (5.4 deg. F) below the daytime average DBT. The water based heat exchange system also performed well. In one four day period, both pond and circulation water had similar temperatures and patterns with very little deviation. Average water temperatures and average test cell temperatures were both 5-7 degrees C (9-13 deg. F) below average daytime DBT.

Based on the results of these tests, it appears that a pond with both air and water heat exchange could provide better performance than a pond with either one or the other. The use of the air exchange system at night could improve the performance of the pond, since night-time air temperature minimums usually fall below that of the pond water. Additionally, an air exchange system could provide cool air instantly while the high mass ceiling exchanger needs to operate for at least one day before the effects could be seen.

REFERENCES

1. Cook, J., (1989). Passive cooling. MIT Press, Cambridge, Mass.
2. Givoni, B., (1998). Climate Considerations in Building and Urban Design; Van Nostrand Reinhold, New York.
3. Givoni, B., (1994). Passive and Low Energy Cooling of Buildings; Van Nostrand Reinhold, New York.
4. McPherson, E.G., (1984). Energy-conserving site design. American Society of Landscape Architects.
5. Moffat, A.S. and Schiler, M., (1994). Energy-efficient and environmental landscaping : cut your utility bills by up to 30 percent and create a natural, healthy yard. Appropriate Solutions Press, So. Newfane, Vt.
6. Robinette, G. O., (1972). Plants/People/and Environmental Quality - A Study of Plants and Their Environmental Functions. U.S. Department of the Interior, National Park Service, Washington D.C.
7. Sandifer, S. (2007). The use of Landscape Elements in Passive Cooling Strategies for Buildings. Doctoral dissertation, University of California, Los Angeles, Department of Architecture and Urban Design.