Novel Sustainability: An Exploration of Systemic Architectural Structure and Form Through Fractal Geometry

Introduction

Within the broad discourse of creating a more sustainable built environment, a particular aspect of architecture is often largely ignored: a building's structure. *How Buildings Learn: What Happens After They're Built* by Stewart Brand offers an interesting view of structure suggesting a building is comprised of layers that are periodically sheared (renovated): site, structure, skin, services, space plan, and stuff.[1] Aside from site, structure maintains the longest life, whereas tenants/users, skins, and services change over time based on technological advances, façade whim, and economics.[2] Brand's introduction of adaptability as a critical aspect within the greater context of sustainability reveals a need for a reinterpretation of structure and form.

Significant technological strides have been made in the areas of skins, materials, and energy and resource-related systems. While laudable, all too often implementation of these systems/technologies does not result in fully systemic buildings; extinct carcasses (structures) are being up-fitted with these breakthrough efforts. These are fine for renovations of existing buildings, but what about the structure and form of new designs and constructions? Sustainable architecture should be fully systemic. This leads to the question: can a structural system leave itself open enough to evolving uses, services and skins as part of a systemic architecture?

An emerging biological paradigm in the areas of history, sciences, economics, and architecture realizes the systemic nature of all aspects of our world and expects systemic solutions. Perhaps a methodology for initiating, ordering, and developing systemic, sustainable architectonic solutions can emerge through an examination of natural-sourced models and their generative, emergent potential.

In 1977, Benoît Mandelbrot published the English version of his seminal work *Fractals: Form, Chance and Dimension*, giving geometrical expression to cascading, repetitive patterns found throughout nature. Geometry and patterns have been interlaced with architectural design throughout history. Due to the systemic nature of fractals, I posit that structure and forms generated through a geometric methodology based on fractals might result in more successful and meaningful, sustainable design solutions than are typically created for the built environment. In this paper, I will explore a path through historical research and analysis, case studies, and experimentation as to how a systemic architecture (structure, form, and ornament) might be organically "grown"/geometrically derived from fractal geometry.

New Paradigm: Novel Structures?

Artist and philosopher Manuel De Landa provides an intriguing concept in *A Thousand Years of Non-Linear History* (2000), where he asserts that both classical thermodynamics and Darwinism are limited to single outcomes: at thermal equilibrium, or at Darwin's most fit design, a static solution results and any historical processes are invalidated.[3] In the 1960's, thermodynamics was revolutionized when it was proved that classical thermodynamic results only came from within closed systems where energy quantities remain preserved; an intense flow of energy, in or out of system, (i.e far from equilibrium) produces a greatly increased number and type of potential outcomes.[4] In both the natural and artificial world, phenomena of great complexity can be observed. However, the basic components of many of these systems are often rather simple. The second law of thermodynamics implies that initial order progressively breaks down as a system evolves; the end result is a state of maximal disorder. According to physicist and mathematician Stephen Wolfram:

> *Many natural systems exhibit such behaviour. But there are also many systems that exhibit quite opposite behaviour, transforming initial simplicity or disorder into great complexity. ... Biology provides the most extreme examples of such self-organization.*[5]

A simple addition of the same set of constituent parts culminates in repetitive, deterministic results. Novel structures can only be generated in a different manner: a bottom-up approach, rather than the traditional top-down approach where parts are dissected from a whole. The concept of *emergence* concerns itself with the collective behavior of systemic components; the complex interactions of forms, structures, patterns and even properties, spontaneously emerging within a complex system, from smaller scales to larger ones.[6] Working within this new paradigm, nonlinear, self-organizing combinations can yield certain emergent and synergistic properties.

Fractals

Mandelbrot refers to his book, *The Fractal Geometry of Nature*, as being able to reveal "a totally new world of plastic beauty".[7] To simplify Mandelbrot's more technical definition[8], a fractal is a highly irregular geometric shape, object or quantity that displays self-similarity across a multitude of scales. Mandelbrot himself might simplify it as an object whose dimension is not an integer. Euclidean geometry provides us with point, line, surface and solid, with topological dimensions of zero, one, two and three, respectively. The non-integer, topological dimension of fractal geometry portends the emergence of great complexity.

A fractal is typically developed through repeated, fixed-scale iterations of the same initial form. No matter how small the subdivision of the fractal object, the subsection will contain as much detail as the whole. (Fig. 1). An initial geometric shape acts as initiator, a generator modifies the initiator to create a new initiator, and the pattern (iteration) is repeated indefinitely. By their nature fractals are self-organizing and infinitely scalable: similar forms and a similar degree of complexity can be found at every level. Fractals have myriad counterparts in nature such as trees, mountains, clouds, coastlines and snowflakes. Across a certain limited range of scales, physical objects and structures (leaves, tree branching, even buildings) can exhibit fractal properties.

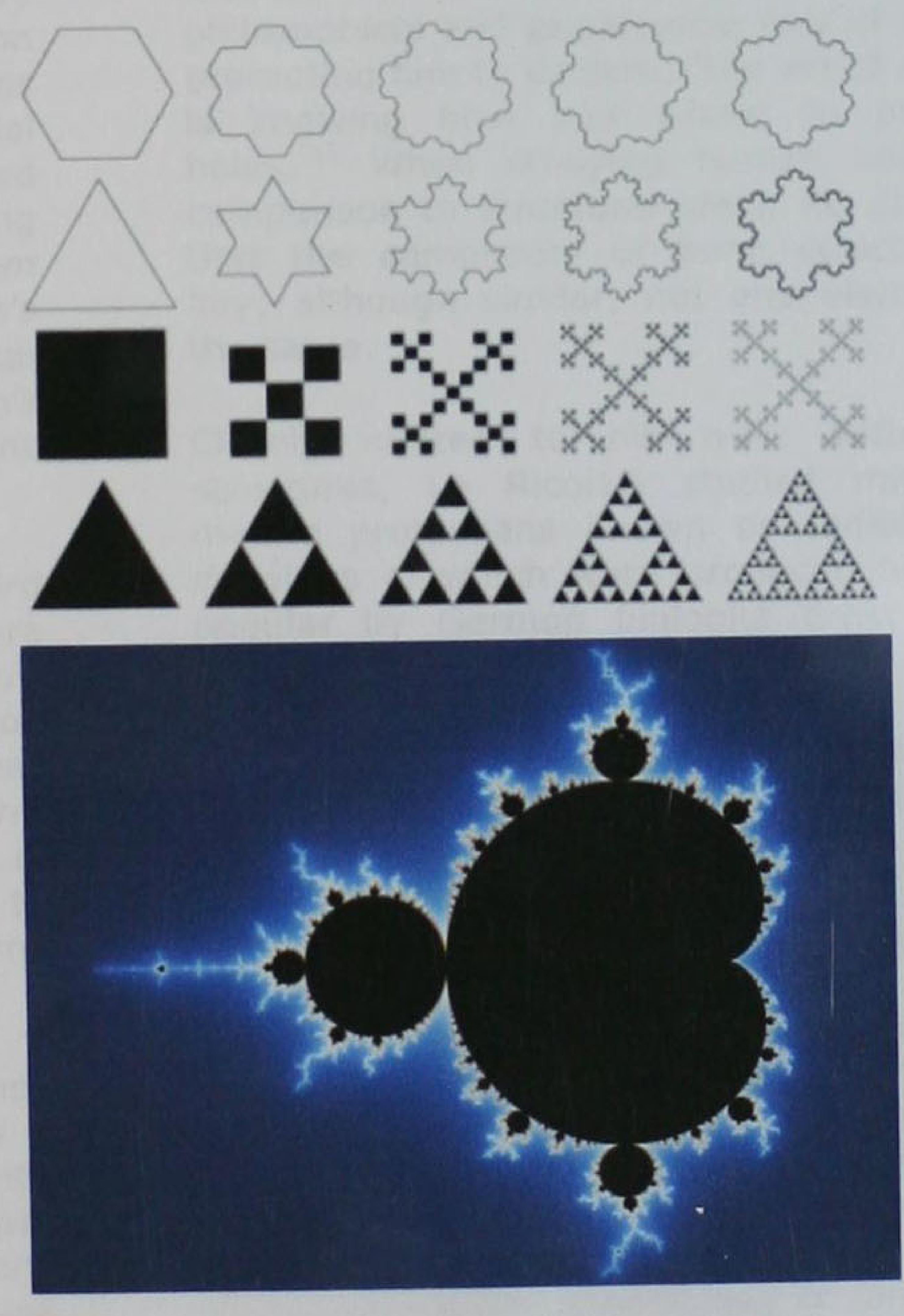


Fig. 1. Top: Basic fractal geometries; the same geometric shape is repeated at multiple scales. Bottom: The famous Mandelbrot set.

Carl Bovill introduces fractal geometry as a powerful tool for architects in *Fractal Geometry in Architecture and Design* (1996). He identifies two primary ways in which fractal concepts can be utilized in architecture and design: as analytical tool, and "to generate complex rhythms for use in design."[9] Although Bovill's first suggested application is interesting, the second is rich with possibilities and is pertinent to the exploration of systemic solutions in this paper.

Historic Precedent: Geometry and Nature as Systemic Impetus

Perhaps the most accessible example of a systemic architecture can be found in the work of Frank Lloyd Wright. His mentor, architect Louis Sullivan, published *A System of Architectural Ornament According with a Philosophy of Man's Powers* (1924). Sullivan's book is a compelling manifestation of an organic idea based on a compact geometric identity, influenced by late 19th century theories of composition based on observation of the laws of nature.[10] In an elaborate series of drawing plates, Sullivan places an initial geometric center (or seed) with its projected axes, and embellishes them with stunning botanical imagination. Plate 17 in *A System* exhibits a striking similarity to Sullivan's Grinnell, Iowa bank front window. Although literally sculptural in result, Sullivan's ornament is largely limited to two dimensions in its architectonic role.

Wright was able to push beyond to the third dimension[11] to create an organic architecture with the plastic continuity of Sullivan's ornamental forms, by predicating it on generative rationale. As a child, Wright was instructed in the Froebel Kindergarten system, in which children learn to see the world in geometric abstractions. This enabled Wright to abstract representative forms and patterns found in nature.

Comparing the plan of Wright's Robie House with a plate from Sullivan's book reveals a formal geometric development with remarkable similarities. A square grid determines both plan and all proportions throughout. Compositionally, the Robie House reads as a three-dimensional conceptual manifestation of Sullivan's "Manipulation of Forms in Plane Geometry" in *A System,* in terms of utilizing the block-shaped brick as his seed germ.[12] Wright extends it throughout the house as his Froebelian block, composing space, component forms, overall massing, rectilinear windows, and numerous details. Wright utilizes a part-to-whole relationship to achieve a systemic solution, where structure, form, and ornament emerge through the use of organic design principles. In this respect, fractals are relatable to the *systemic* nature of organic design principles in terms of scalability, similarity of form, and complexity.

French born and educated structural engineer Robert Le Ricolais, although not as well known as his American counterpart and contemporary Buckminster Fuller, is often referred to as the "father of spatial structures".[13] Throughout his career, he maintained a curiosity for exploration and a meticulous observation of nature when experimenting with structure stating, "I've found no better discipline in this unpredictable problem of form than to observe the prodigies created by nature."[14] Le Ricolais utilized a philosophical and paradoxical way of thinking, prompting him to declare, "the art of structure is knowing how and where to put [the] holes."[15] When studying human bone as a comparison to structural steel, he discovered that the complexity of bone structure was key; although similar, not one element was the same.

Closely related to his work with spatial structures, Le Ricolais studied microscopic marine protozoans known as radiolarians;[16] drawings of which were produced and made popular by German biologist Ernst Haeckel during the 1870's. The tension networks inherent in radiolarians allowed him to understand the dynamic properties of skeletal structures. Of radiolarians, Le Ricolais writes:

> *[O]ne peculiar species ... is the one looking very much like the little Chinese ivory things you find in antique shops --- where you have a ball inside a ball inside another ball ... it's kind of a prodigy, to see in another sphere another sphere and so forth ... this principle is what in our jargon we call automorphism: some kind of geometric assemblage of forms which go into one another, repeating themselves.*[17]

Le Ricolais' description of *automorphism* focusing on repetition and self-similarity when discussing radiolarians could almost be a substitute for a general description of fractals. Although he may have unknowingly developed an intuitive grasp of fractals, there appears to be no direct acknowledgement of Mandelbrot's work.[18] However, some of his spatial structure studies do begin to exhibit fractal qualities, if only extended a few iterations: the Polyten truss for example. (Fig. 2).

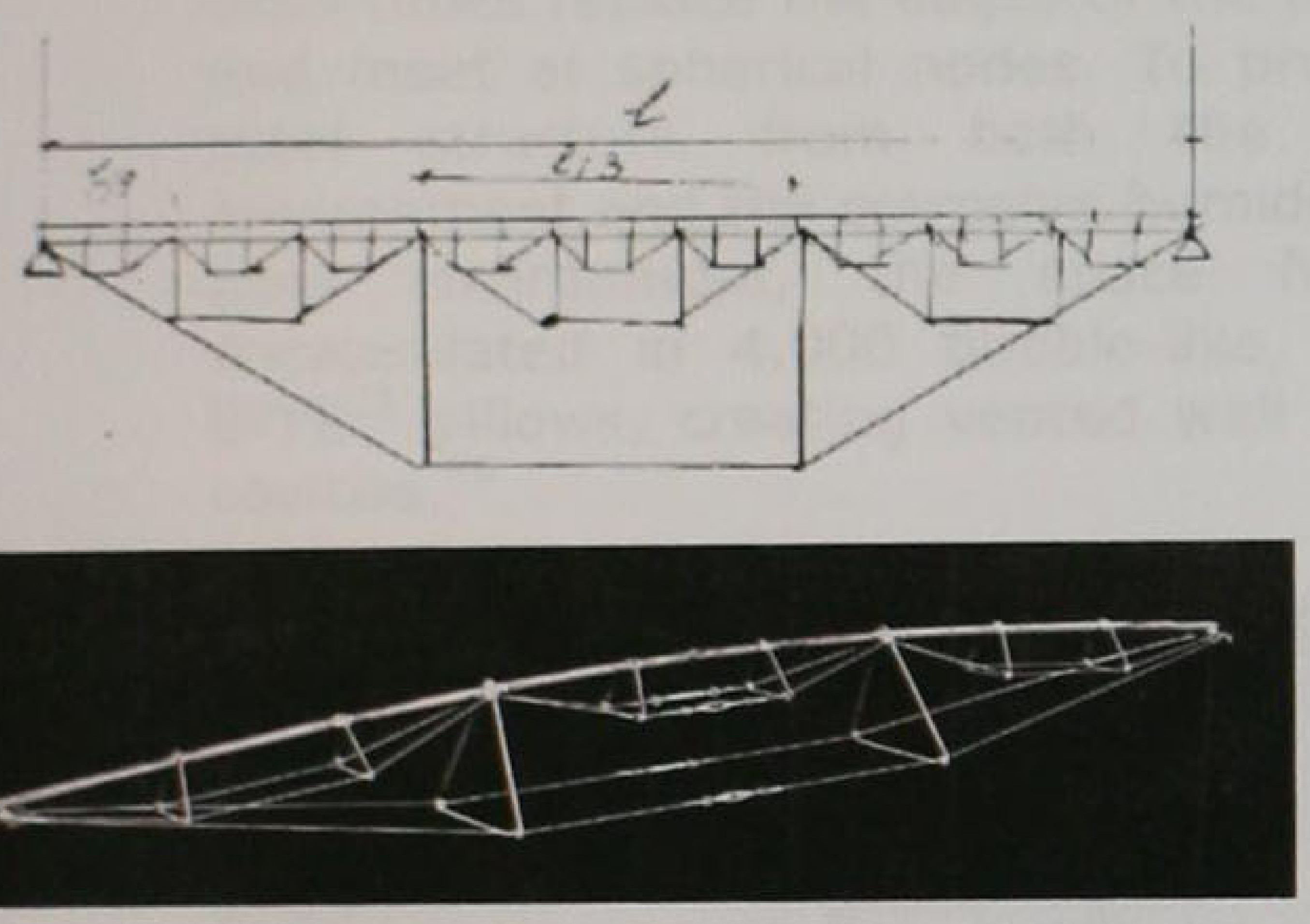


Fig. 2. Study sketch (top) and model (bottom) of Le Ricolais's Polyten truss.

Historically, architects and structural engineers have turned to nature for inspiration when designing improved shell and spatial structures: the spider web with its high strength-to-weight ratio has inspired cable net structures, vaults based on eggs and shells comprised of hard, curved materials, pneumatic structures are modeled after soap bubbles, and geodesics derived from radiolarians are amongst the most common. Even as these examples reference nature, exhibit automorphism in form, or are biomimetic, they are not necessarily fractal. Although a naturally occurring phenomena, fractals have had limited application in architecture and structure. The following discussion on adaptability and systems theory will offer some architectural examples that begin to approach a fractal quality.

Adaptability in Structure

Adaptability in a structure can infer a number of traits including, being transformable, moveable, and interactive. Within the constraints of this paper, the discussion shall be limited to structure that can be adapted through transformation, although not kinetically.[19]

Man has sustained himself in the natural realm via the capacity for change and adaptation. Our survival depends on the same within the realm of the built environment, by reason of a conservative use of resources. Change and adaptation are functions of diversity and efficiency of form. For the most part, we do not build that way. According to Peter Pearce, "Technological man's pervasive reliance upon standardized undifferentiated form minimizes the possibility for diversity."[20] In his book, *Structure in Nature is a Strategy for Design* (1978), Pearce attempts to reconcile standardization principles and the necessities of diversity and adaptation. He proposes the notion of a system of component standardization, advocating an efficiency of distribution and conservation of natural resources, referring to them as *minimum inventory/maximum diversity* systems. He writes, "Systems can be envisaged which consist of some minimum inventory of component types which can be alternatively combined to yield a great diversity of efficient structural form."[21] Pearce provides an extensive investigation into geometry and, more importantly, polyhedra (three-dimensional geometry) and the role they play in space filling. The concept of closest packing of spheres[22] (via polyhedra) is explored towards reaching the ultimate goal of three-dimensional space. Closest packing of both spheres and polyhedra also creates a repeated pattern of triangulation. According to Pearce, "Triangulation imparts strength to structures even before the physics of materials is taken into account."[23]

Case Study: The Water Cube

A contemporary architectural solution utilizing a systemic approach to structure and form based on repetitive geometry occurs at the National Aquatics Center, commonly known as the "Water Cube". Although boxlike in form, the building's aesthetic and structure is inspired by the natural formation of soap bubbles, and uses a highly integrated envelope and structure combination. Team members explored the geometry of soap bubbles grouped as "foam", studying the work of Irish physicists Denis Weaire and Robert Phelan. The Weaire–Phelan structure is a complex 3-dimensional structure comprised of two kinds of cells of equal volume with slightly curved faces. During the design process, the designers wrote a computer script allowing them to develop the theoretical foam structure into a building structure. This allowed them to compose numerous combinations of the Weaire-Phelan units, rotate them three dimensionally, then cut the cells to create a box form.[24] The Water Cube "foam" is made up of a combination of polyhedra with either 12 or 14 faces. (Fig. 3). A Vierendeel space frame is created where steel tubes replace the edges of the polyhedra and meet at spherical nodes. To protect the steel structure from both the exterior environment and the corrosive humidity of the pool environment, the space frame is encapsulated in 4,000 bubble-like, air-filled ETFE[25] pillows, creating vented wall and roof cavities.[26]

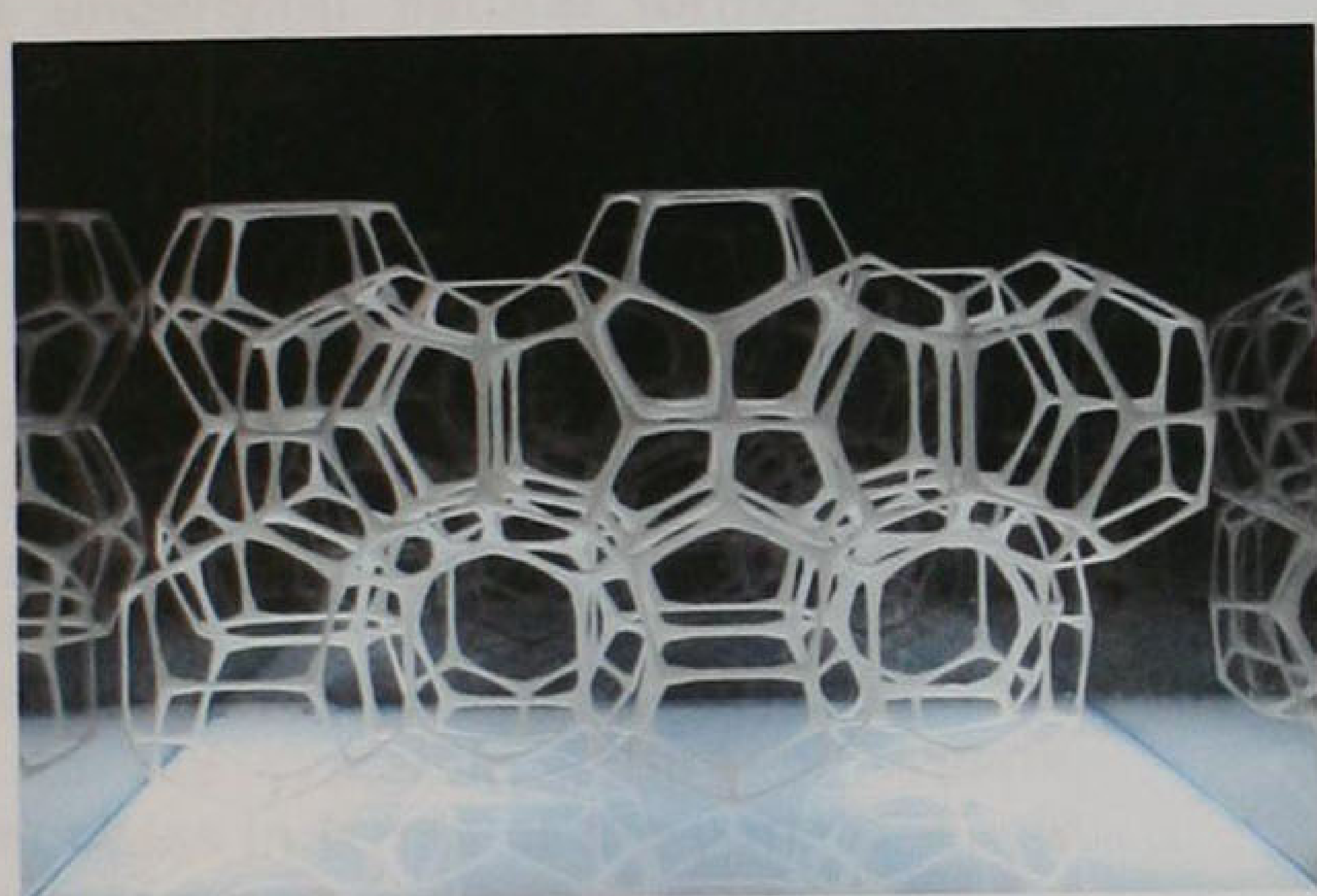


Fig. 3. Structural model developed for The Water Cube.

Writing in 1978, Pearce exhibits an array of possible structures and resulting forms in his *minimum inventory/maximum diversity* system studies of modular spatial frames. However, complexity is limited to one scale. Adaptability is largely limited to linear repetition, as opposed to nonlinear *iterative* growth: sameness persists without diversity. While Pearce's studies and The Water Cube project are not fractal in their result, one can imagine the potential for generating three-dimensional, fractal structure and form. Pushing these polyhedral geometries to multiple iterations of increasingly smaller scales, and placing them at every vertex, would produce an interesting fractal. The result would resemble the three-dimensional equivalent of an Apollonian gasket; an Apollonian sphere packing.[27]

Adaptability through Systems Theory

A systemic structure provides the benefits of efficiency through repetition and modularity. If a structure is to be adaptable, it should more fully reflect a dynamic, living organism, which according to Sir D'Arcy Wentworth Thompson, "represents, or occupies, a field of force which is never simple, and which as a rule is of immense complexity".[28] Inspired by Thompson, Pearce suggests that structural form (in nature) is the result of two fundamental forces: extrinsic and intrinsic. Extrinsic forces are those influences that are external to any structural system, largely environmental. Intrinsic forces "are those governing factors which are inherent in any particular structural system ... which govern its possible arrangements and its potential performance ... and the nature or character of its infinitely varied patterns".[29]

Systems theory is an interdisciplinary theory from within the biological paradigm, regarding the nature of complex systems. It advocates that a loose coupling of system components be maintained to create flexibility. As a contributing author to *Construction Ecology: Nature as a Basis for Green Buildings*, ecologist Garry Peterson writes:

> *This principle can be applied to buildings by designing structures so that parts or components of a structure can be modified and replaced without destroying the integrity of the structure as a whole.*[30]

If a structural system were based on a systemic, generative methodology that exhibits dynamic growth potential, it can be more adaptable; parts or components could be modified or replaced while maintaining an intrinsic force. The self-organizing characteristic of fractals is intrinsic; fractals are complex and dynamic.

Fractals in Architecture

Implementation of fractal geometry should be apparent in architecture; scale, self-similarity, organization and complexity exist as components of architectural language.[31] Mandelbrot himself made a foray into the use of fractals in architecture, stating, "A Mies van der Rohe building is a scale-bound throwback to Euclid, while a high period Beaux Arts building is rich in fractals."[32] Since Mandelbrot, architectural implementations of fractals have not been extensive, often limited to surface treatment or other tentative gestures.[33] Historical examples such as the Hindu Temple of Kandariya Mahadeva, various Gothic cathedrals, and even some buildings designed by Wright exhibit varying degrees of fractal quality. Although a half-century and older now, some have analyzed Wright's buildings to find implementation of fractal geometry. Whether intentionally or intuitively placed, Wright proposed a generative design methodology to produce a systemic architecture across multiple scales; he considered environment, site, building and furnishings inextricably linked.[34] Bovill suggests Wright's organic architecture "emphasized the understanding of the deep principles underlying natural forms. One of these deep principles is a cascade of detail from the large to the small scale. Nature virtually never flattens out."[35]

Although architectural forms cannot maintain self-similarity across all scales and are thus not true fractals, buildings can possess fractal properties in their progression of self-similar detail, as the focus moves closer or further away. As previously stated, fractals are relatable to the *systemic* nature of organic design principles in terms of the part-to-whole relationship of structure-form-ornament.

Case Study: Federation Square

LAB Architecture Studio's Federation Square in Melbourne, Australia does appear to utilize fractal geometry, albeit in a significantly limited manner. Triangulated fractal-like forms based on the Penrose pinwheel[36] establish a systemic lexicon for the entire scheme. (Fig. 4). Plaza surface, structure, building façade, and ornamentation all emerge as a triangle is turned and shifted to compose and organize the design.[37] The building façade fractal "tile" system, executed in sandstone, zinc or glass only, permits building individualism while maintaining collective site coherence. The facades of the main buildings utilize a double-layer rain screen: the panels being comprised of five triangular tiles, grouped together as part of five panels forming one mega-panel. The larger panel is attached to a triangular galvanized steel frame. The use of an integrated cladding and structural system as building envelope informs the character and form of the interior spaces.

Of particular importance in this project, is the glazed atrium space. Here the same triangular geometry is utilized to create its galvanized, open structural frame system. The folded, three-dimensional system is glazed inside and out, acting as a thermal chimney, evacuating the build-up of hot air. More importantly, as a frame it accepts a variety of skins and being comprised of individual struts/members, the structural system appears open to intelligible adaptation. The coherence from skin to structure at Federation Square begins to establish a more systemic architectonic solution. Of the Federation Square project, Nina Rappaport writes:

> *A structure with an underlying coherence from the whole to the fragmentary assemblage, this pattern pervades the project from the ornamental, or accessory elements of the tiled skin through to the structural skeleton.*[38]

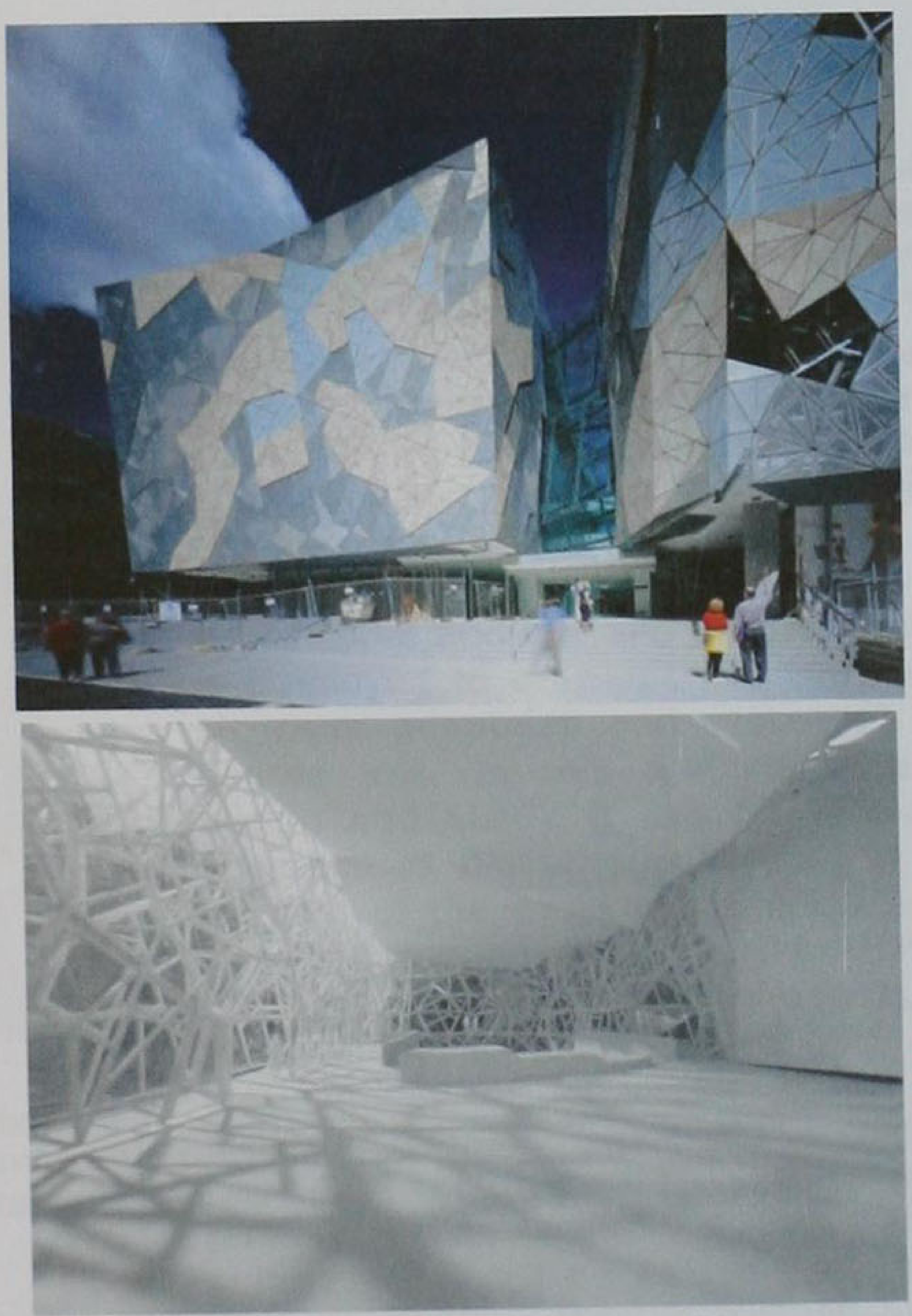


Fig. 4. Top: Exterior view of Federation Square. Bottom: Model detail of south atrium interior.

Experimentation: Fractal Structures

To begin exploring the potential of fractal geometry as a generative source of systemic structure and architecture, I began a series of varying studies. Working through the sequence of initiator, generator, and new initiator, a series of two-dimensional studies resulted in a variety of complex images. These patterns can be readily transformed through simple Euclidean extrusion as plan or cross-section profile. Concerned that these held innate limitations due to simple extrusion, I began to experiment with three-dimensional geometries as initiator. (Fig. 5).

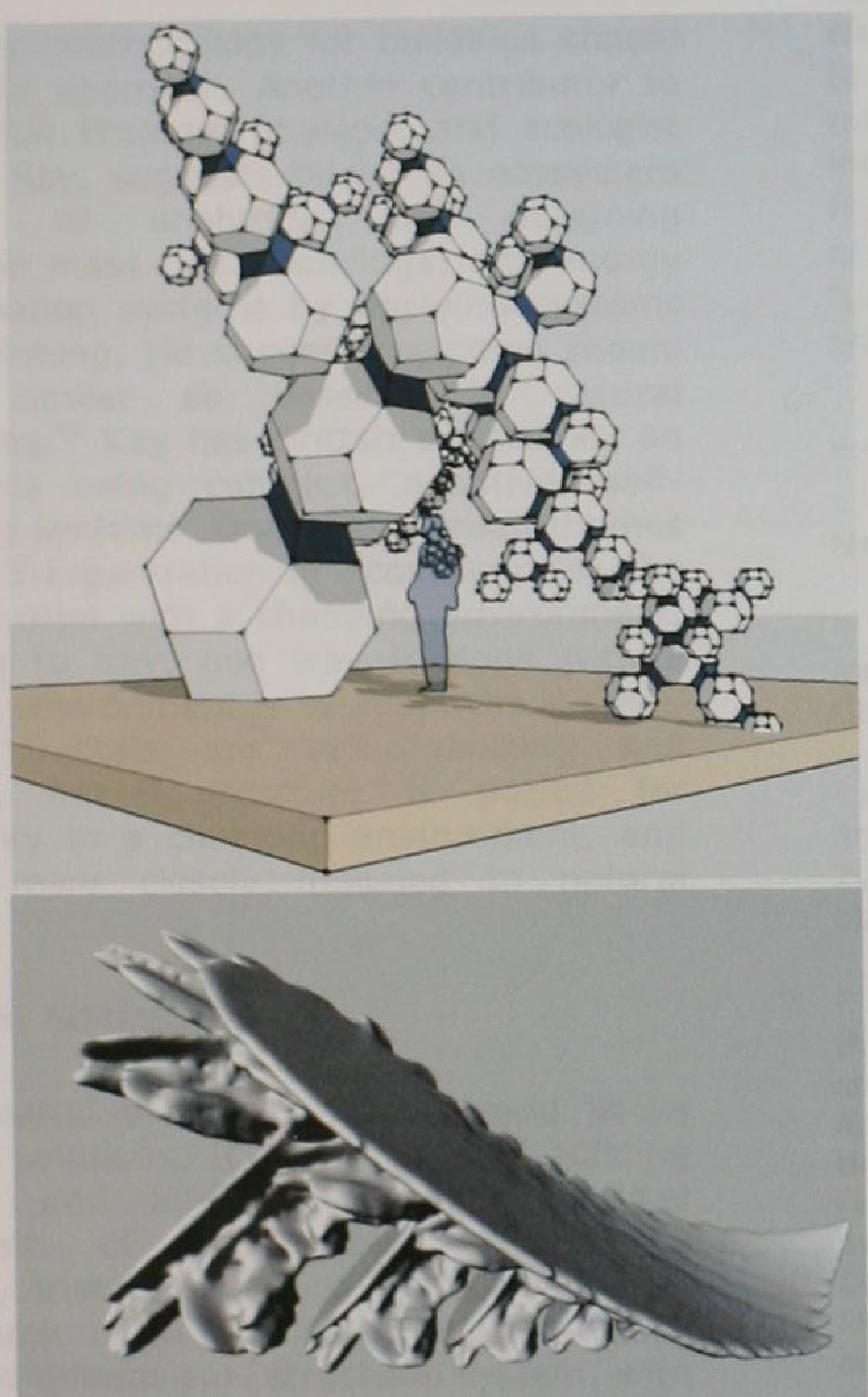


Fig. 5. Fractal structure study utilizing truncated octahedron as initiator (top) and "shell" structure generated utilizing the three-dimensional, fractal-generating software XenoDream™ (bottom).

These studies, while resembling the structure of the Water Cube and Federation Square projects to a degree, exhibit much more interesting potential due to being pushed to higher iterations of their initial geometries. I was able to guide the generative factors to create larger/smaller units as desired and influence direction of growth, resulting in spatial frames/cells on a range of scales: from habitable space, to structure, to minute and complex ornament. The addition or removal of units, or change in density/scale while maintaining self-organizational characteristics, creates opportunities for openness or enclosure. The spatial nature of the three-dimensional cells, or frame structure, linked to the character of the emergent form, presents an opportunity to extend towards a systemic culmination of architectural structure, form, and ornament. Pushing further in experimentation with three-dimensional, fractal-generating software resulted in a series of rather complex forms. Like the three-dimensional initiator studies, the repetition and self-similarity of forms at varying scales produced here bode well for systemic architectural implementation. This last series of studies appear to exhibit good potential as shell structures.

Aren't we there already?

The structure of a building is similar in concept to the human muscular-skeletal system; it is most readily interpreted as a frame in building construction. The most prevalent example of a building frame is a gridded, geometric extrapolation as a series of columns and beams extended ad infinitum to support floor and roof loads. Conceptually, services and space plan are free to move about amongst the forest of columns, building users come and go, and a curtain wall (skin) is employed to envelope the exterior. Is this structure adaptable and systemic? To some degree yes. Is this a sustainable way to design and build? It can be. However, this approach to design and building is a simple addition of the same set of constituent parts culminating in repetitive, deterministic results; it is not dynamic and is limited in its response to the natural environment. The top-down methodology of Modernist purity does not allow for the emergence of the complexity of novel structures. Le Ricolais offers reinforcement toward a non-deterministic approach to the design of structures, suggesting two opposing methodologies. One course is the subtractive carving of an initial "block"; the other being an additive approach toward a definitive form, through the repetitive arrangement of a "germinal cell".[39] There is a change in perspective in moving towards a self-organizing view of the universe, and away from a mechanistic one. Peterson writes:

> *The construction phase of a building is the one that brings in most of the*

> *materials and a lot of energy into a site. It is the stage in which the ultimate form and possibilities for future growth and adaptation are locked in. I argue that construction methods that allow future growth and adaptation are critically important.*[40]

The design methodology for buildings should mirror that approach. Another contributor to *Construction Ecology*, physicist and ecologist James J. Kay, suggests taking an ecosystem approach to analyzing and designing biophysical mass (viz., buildings) and energy transformation systems by applying systems theory thinking. He suggests systems should be as similar as possible to natural ecosystems.[41] Kay has written extensively on ecosystems being complex, adaptive, self-organizing systems. One of the broad themes to the self-organization of ecosystems is the ability to cope with a changing environment. According to Kay, one way to cope with a changing environment is to adapt the system. Because fractals are self-organizing and systemic, fractal structure is poised for adaptability in a changing environment, and can be more closely modeled to natural systems.

Emergent Structures

The biological paradigm of our world seeks systemic solutions. If adaptability of building structure and form is to be a critical component of sustainable architectural solutions, that paradigm should be explored for systemic inspiration. Growth or decrease of a three-dimensional structural system, with an accompanying change in density of pattern — fewer or greater, or larger/smaller "holes" — to accommodate modified spatial or loading requirements can be imagined. Planning ahead with structure for adaptive re-use, or using "open building" principles are "fully complementary with the pressing issues of environmental ethics, cradle-to-grave embodied energy, recycling, use of non-toxic materials and other vital issues in the worldwide sustainability agenda".[42] A complex structural system, spatial or otherwise, based on the self-organizational aspects of fractal geometry, would exhibit a coherent organizational behavior, and allow for openness and flexibility to freely respond to changing conditions.

Too often, the static Cartesian box is prescriptively dressed in sustainable components, top-down. Reductive design methods typically result in less dynamic building forms: forms less free to respond. Could fractal-generated building forms elicit a true response to their environment? Perhaps even provide for "real-time" adaptability to changing conditions? Moving forward, I hope to investigate how such patterns of growth might be nuanced and informed by the introduction of ecological/contextual factors. Fractal growth, responding to wind, water and/or solar input might push a system further from equilibrium where novel building structure and forms might emerge.

Notes and References

[1] Stewart Brand, *How Buildings Learn: What Happens After They're Built* (New York: Penguin Group, 1994), 12-13.

[2] According to Brand, structure life may range from 30 to 300 years, whereas, skins change on cycles of 20 years or less, and services wear out or become obsolete in 7 to 15 years. See Brand, 17-23.

[3] During the 19th century, the science of thermodynamics introduced a systemic paradigm of study and presented the idea of irreversible historical processes. Thermodynamics investigates the relationship of heat and mechanical energy (work) and the conversion of one into the other over time, within a state of equilibrium. Concurrently, evolutionist Charles Darwin's theory illuminated that plants and animals were the accumulative results of adaptation occurring in reproductive isolation. Manuel De Landa, *A Thousand Years of Non-Linear History,* ed. by Jonathon Crary, Sanford Kwinter, and Bruce Mau (New York: Swerve Editions, 2000), 13-14.

[4] Alternative thinking to these theories gained momentum in the 1960's with the work of physical chemist Ilya Priogogine. Ilya Priogogine (1917-2003) was a physical chemist and Nobel Laureate noted for his work in his work on dissipative structures, complex systems, and irreversibility. Priogogine discovered that an intense flow of energy, in or out of system, (i.e far from equilibrium) produces a greatly increased number and type of potential outcomes.

[5] Stephen Wolfram, "Complex Systems Theory," in *Emerging syntheses in science: proceedings of the founding workshops of the Santa Fe Institute, Santa*

Fe, New Mexico, Vol. 1., ed. David Pines (Redwood City, California: Addison-Wesley, 1988), 183-184.

[6] In 1984, the Santa Fe Institute was founded to "discover, comprehend, and communicate the common fundamental principles in complex physical, computational, biological, and social systems that underlie many of the most profound problems facing science and society today." Fractals, emergence, nonlinear dynamics, and self-organizing systems are among the many areas of devoted research occurring there. http://www.santafe.edu/about/mission/

[7] Benoît B. Mandelbrot, *Fractals: form, chance, and dimension*. (San Francisco: W.H. Freeman, 1977), 6.

[8] Mandelbrot offers a shortcut definition of a fractal as an object whose Euclidean dimension differs from its Hausdorff Besicovitch dimension, writing, "A fractal is by definition a set for which the Hausdorff Besicovitch dimension strictly exceeds the topological dimension." Benoit B. Mandelbrot, *Fractals: form, chance, and dimension*. (San Francisco: W.H. Freeman, 1977), 15.

[9] Carl Bovill, *Fractal Geometry in Architecture and Design*. Design science collection (Boston: Birkhäuser, 1996), 6.

[10] During the late 19th century, new theories of composition for architectural ornament and the decorative arts developed, based on a scientific attitude toward design. Archaeological expeditions by English and French historians and architects resulted in several publications of drawing plates and written material on ornament and decoration. These works consisted of carefully developed lifelike drawings and analysis of flowers, animals, and other natural forms. In *The Grammar of Ornament* (1856), English theorist Owen Jones published one hundred color plates of geometric patterns, intricacies and etchings of natural elements, based on abstracted and modeled indigenous natural forms. Mark B. Orlowski states that "[a]esthetic theorists endeavored to find an analogy between science and art. Much the way scientists were discovering fundamental laws of biology and botany, aesthetic theorists sought similar principles of composition." Mark B. Orlowski, "Frank Furness: Architecture and the Heroic Ideal." (Ph. D. diss., University of Michigan, 1986), 250.

[11] According to Tom Beeby, Sullivan's protégé pushed beyond. "Wright solved the one ornamental aspect which Sullivan never completely resolved; the exact relationship between ornament and construction. In Sullivan's mind the ornament was articulated from the structure ... Wright perceived the possibility of raising this same ornamental methodology from surface to volume, in three dimensions. He attempted what Sullivan was reluctant to contemplate: to make the structure follow the rules of ornamental design". Tom Beeby, "Flowering Grid," *Architectural Review* 162 (October 1977): 224.

[12] Sullivan speaks of the "Extension of form along lines or axes radiating from the center and (or) Intention of form along the same or other radials from the Periphery toward the Center". Louis H. Sullivan, *A System of Architectural Ornament.* Foreword by John Zukowsky and Susan Glover Godlewski, essay by Lauren S. Weingarden. New York: Press of The American Institute of Architects, Inc., 1924; reprint ed., (New York: Rizzoli International Publications, 1990), 124.

[13] As a practicing engineer (as well as a painter and poet), Le Ricolais (1894-1977) introduced the concept of corrugated stress skins to the building industry in 1935 and was awarded the Medal of the French Society of Civil Engineers. In 1940, his work on three-dimensional network systems introduced many architects to the concept of space frames. Le Ricolais taught in the United States primarily at the University of Pennsylvania alongside architect Louis Kahn.

[14] Robert Le Ricolais, "Things Themselves Are Lying, and So Are Their Images," in *Structures implicit and explicit*. ed. James Bryan, and Rolf Sauer (Philadelphia: Graduate School of Fine Arts, University of Pennsylvania; distributed by Wittenborn, New York, 1973), 88.

[15] Perhaps the most famous of his paradoxes is his declaration that "the art of structure is knowing how and where to put [the] holes. It's a good concept for building, to build with holes, to use things which are hollow, things which have no weight, which have strength but no weight.", Le Ricolais, 88.

[16] Radiolarians are any of various marine protozoans having rigid skeletons usually made of silica, typically spherically symmetrical and structurally complex, containing elaborate patterns of perforations (through which needle-like pseudopods extend) and often spicules. Skeletal remains of radiolarians sink to form ooze on the ocean floor, and prehistoric radiolarian ooze has fossilized to become chert and flint. Source: The American Heritage Science Dictionary, Houghton Mifflin, 2002.

[17] Le Ricolais, 91.

[18] Le Ricolais' death occurred in 1977, the same year Benoît Mandelbrot published the English version of his *Fractals: Form, Chance and Dimension*.

[19] According to Robert Kronenburg, "A transformable building is therefore one that changes shape, volume form, or appearance by the physical alteration of structure, skin or internal surface, enabling a significant alteration in the way it is used or perceived. This is architecture that opens, closes, expands or contracts". Robert Kronenburg. *Flexible: Architecture that Responds to Change*. (London: Laurence King Publishing Ltd., 2007), 146.

[20] Peter Pearce. *Structure in Nature is a Strategy for Design*. (Cambridge, Massachusetts: MIT Press, 1978), xii.

[21] Pearce, xii.

[22] In geometry, the close-packing of spheres is the dense arrangement of equal spheres in an infinite, regular arrangement. Carl Friedrich Gauss proved that the highest average density – that is, the greatest fraction of space occupied by spheres – that can be achieved by a regular lattice arrangement is 0.74048. Many crystal structures are based on a close-packing of atoms, or of large ions with smaller ions filling the spaces between them. Source: http://en.wikipedia.org/wiki/Close-packing_of_spheres

[23] Pearce, 2.

[24] Joann Gonchar, "Inside Beijing's Big Box of Blue Bubbles," *Architectural Record*, July 2008, 150.

[25] ETFE (ethylene tetrafluoroethylene) is a kind of plastic designed to have high corrosion resistance and strength over a wide temperature range. Technically ETFE is a polymer, and has a very high melting temperature, excellent chemical, electrical, and high-energy radiation resistance properties.

[26] Nina Rappaport, "Deep Decoration," In *Decoration*, edited by Emily Abruzzo and Jonathan D. Solomon, 306090 Books, Vol. 10 (Summer 2006): 97-103.

[27] An Apollonian gasket (or Apollonian) net is initially generated from three circles, any two of which are tangent to one another. A circular triangle is formed between the three original circles. A circle of maximum radius, tangent to the original three circles, is placed within the triangle. Three new circular triangles are formed between the orginal three circles and the fourth, and the process repeats itself infinitely, packing ever-smaller circles tighter and tighter, resulting in a net-like gasket. The three-dimensional equivalent of an Apollonian gasket is known as Apollonian sphere packing. Benoit B. Mandelbrot, *Fractals: form, chance, and dimension*. (San Francisco: W.H. Freeman, 1977), 187.

[28] D'Arcy Wentworth Thompson, *On Growth and Form*. (Cambridge, U.K.: Cambridge University Press, 1942), 1030.

[29] Pearce, xiv-xv.

[30] Peterson elaborates, "Complicated systems are more difficult to maintain as everything in them is connected to everything else. However, a well-designed complex system that reduces the number of cross-connections among subsystems and separates systems design into relatively autonomous systems components may degrade more slowly than a complicated system". Garry Peterson, "Using ecological dynamics to move toward an adaptive architecture," in *Construction Ecology: Nature as the basis for green buildings,* ed. Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy (New York: Spon Press, 2002), 144-145.

[31] Andrew Scott Maletz, "Developing a Fractal Architecture." (M. Arch. thesis, Miami University, Department of Architecture, 1999), 23.

[32] Benoît B. Mandelbrot, *The Fractal Geometry of Nature*. (New York: W.H. Freeman, 1982), 24.

[33] Simmons Hall at MIT by Steven Holl Architects has been referenced to fractal geometry because of a resemblance to the Menger sponge. The building's exterior openings have a fractal-like distribution and it does utilize a cast-concrete exoskeleton structure with commensurate patterning. However, the sponge analogy is the result of dealing with the concept of "porosity," and the structure was not part of the original concept. Yannick Joye, "Fractal Architecture Could Be Good for You." *Nexus Network Journal*, Vol. 9, No. 2, (2007): 314.

[34] Wright stated that, "[t]he spirit in which these buildings are conceived sees all these together as the work of one thing. All these should become mere details of the character and completeness of the structure". Frank Lloyd Wright as quoted in Ulrich Conrads, *Programs and Manifestoes on 20th-Century Architecture* (Cambridge, Massachusetts: MIT Press, 1964), 25.

[35] Bovill, 134.

[36] Roger Penrose discovered the Penrose pinwheel. It comprises a set of a-periodic tiles with five-fold symmetry, and has been used to explain the structure of certain "quasi-crystal" substances.

[37] Rappaport, 97.

[38] Ibid., 97.

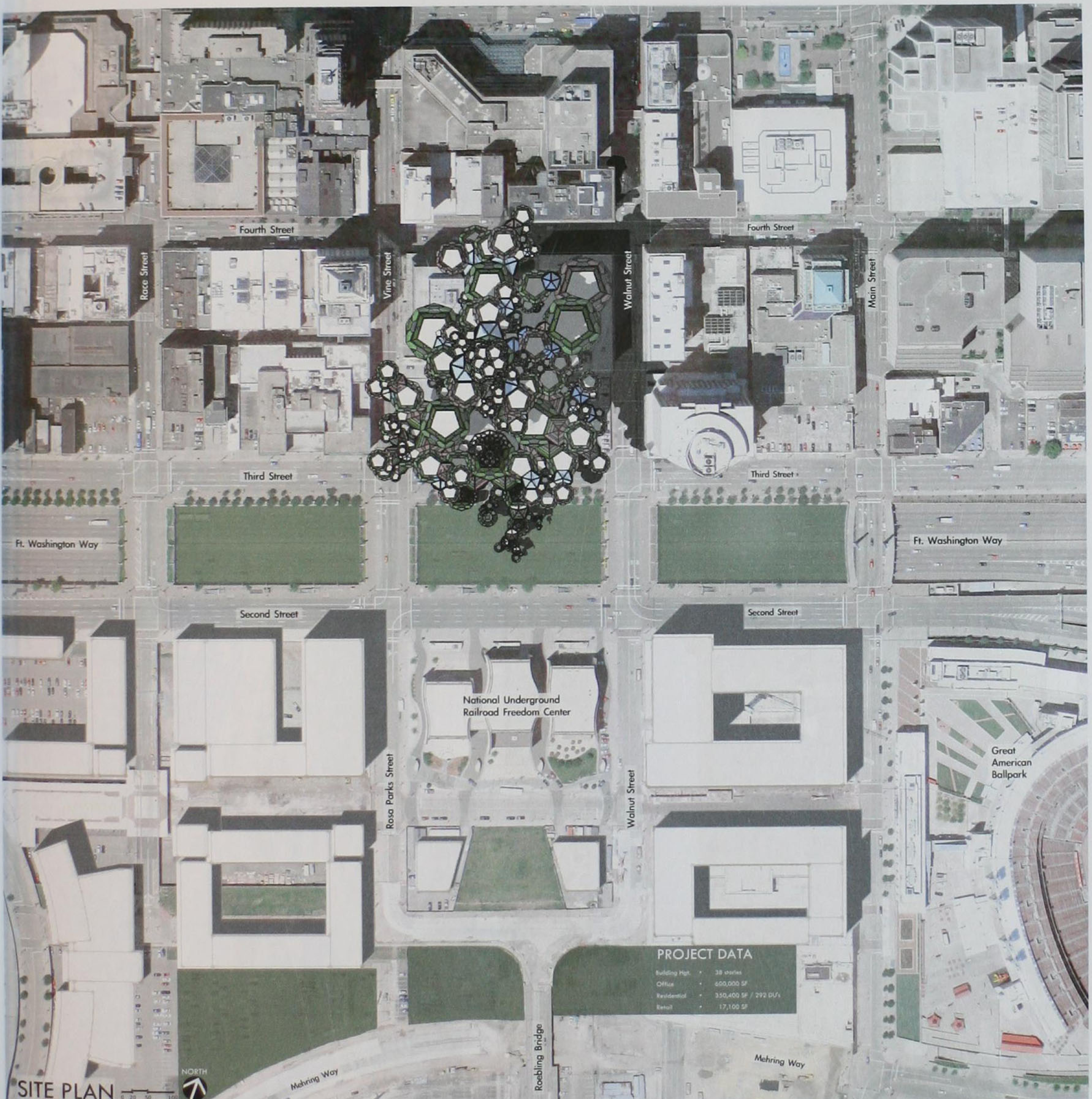
[39] Le Ricolais, 101.

[40] Garry Peterson, "Using ecological dynamics to move toward an adaptive architecture," in *Construction Ecology: Nature as the basis for green buildings,* ed. Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy (New York: Spon Press, 2002), 143.

[41] James J. Kay, "On complexity theory, exergy, and industrial ecology," in *Construction Ecology: Nature as the basis for green buildings,* ed. Charles J. Kibert, Jan Sendzimir, and G. Bradley Guy (New York: Spon Press, 2002), 93.

[42] Stephen Kendall, "Open Building: An Approach to Sustainable Architecture," *Journal of Urban Technology*, Volume 6, Number 3, (1999): 1.


Fourth Street
Fourth Street
Race Street
Vine Street
Walnut Street
Main Street
Third Street
Third Street
Washington Way
Ft. Washington Way
Second Street
Second Street
National Underground
Railroad Freedom Center
Rosa Parks Street
Walnut Street
Great
American
Ballpark
PROJECT DATA
Office
Retail
17,100 SF
Roebling Bridge
Mehring Way
Mehring Way
NORTH
ITE PLAN


Fourth Street
Fourth Street
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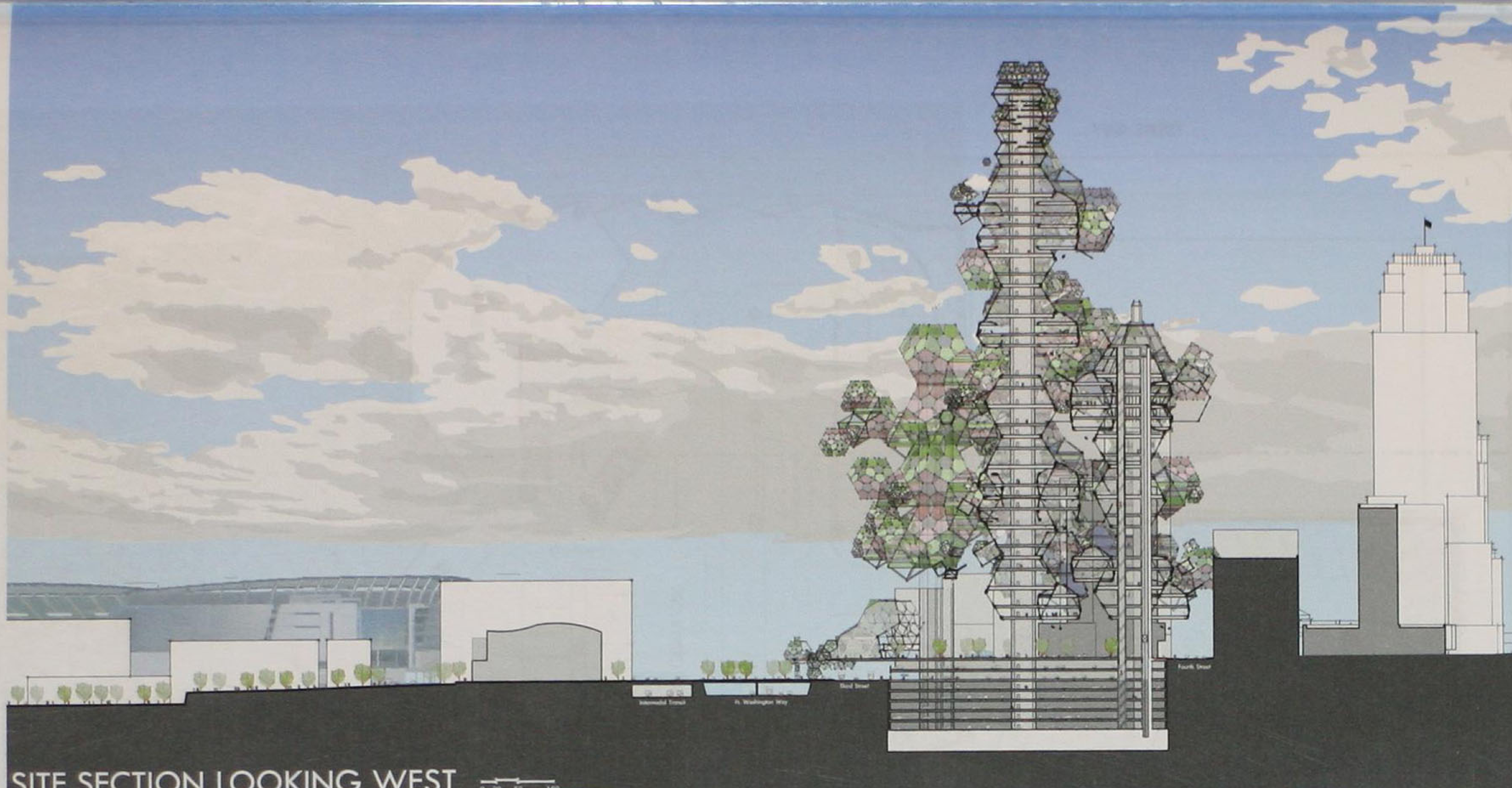
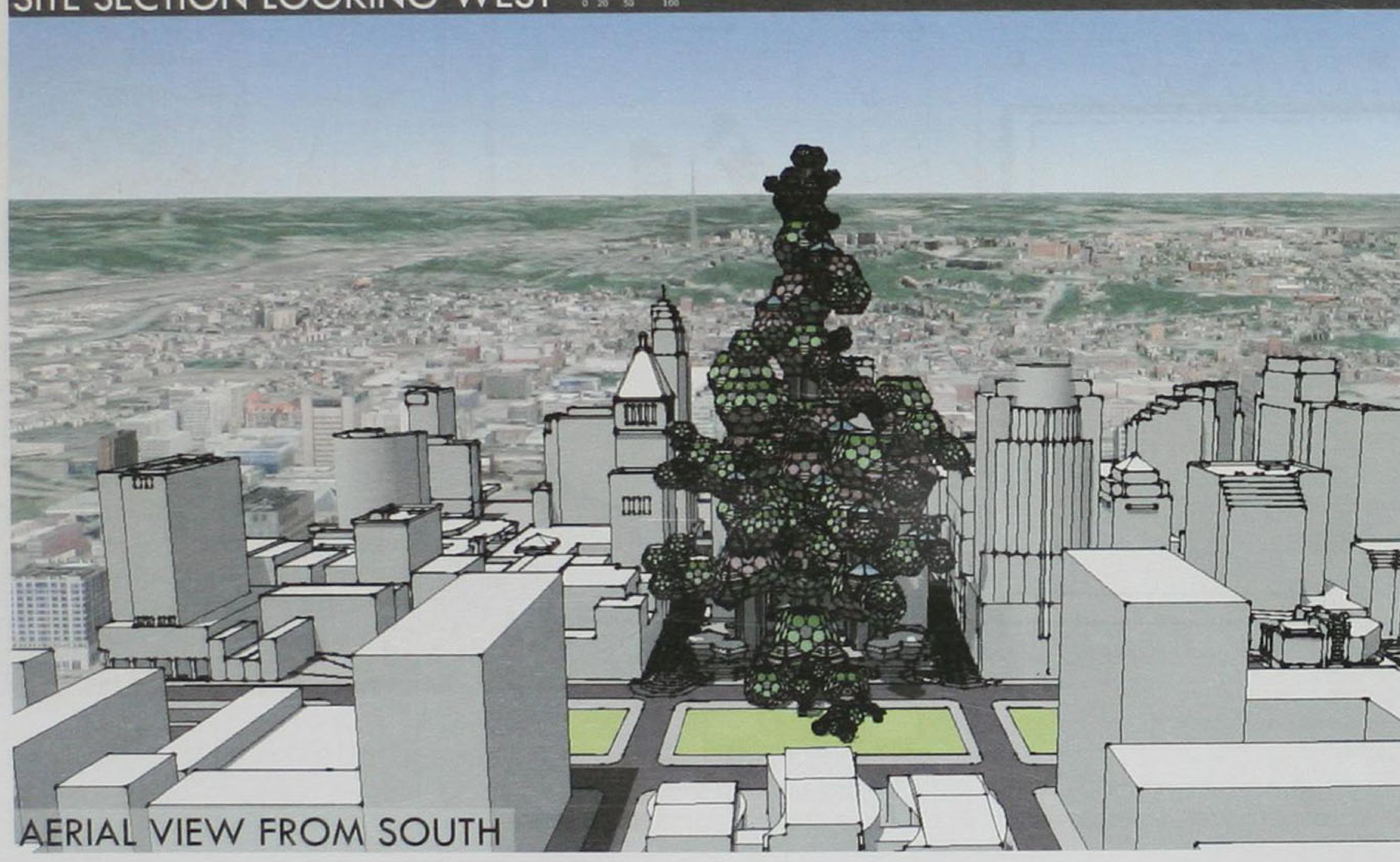
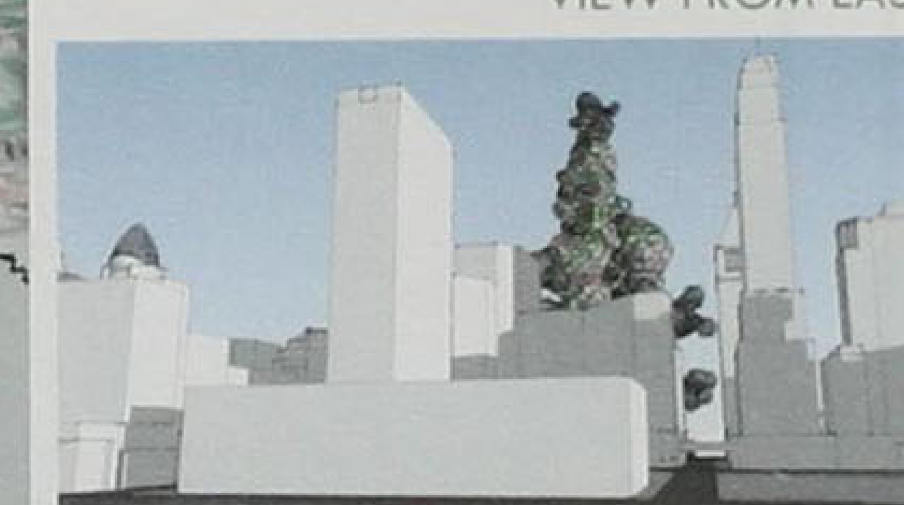
Walnut Street
Main Street
Third Street
Third Street
Ft. Washington Way
Ft. Washington Way
Second Street
Second Street
National Underground Railroad Freedom Center
Rosa Parks Street
Walnut Street
Great American Ballpark
PROJECT DATA
Building Hgt. • 38 stories
Office • 600,000 SF
Residential • 350,400 SF / 292 DU's
Retail • 17,100 SF
Mehring Way
Mehring Way
Roebling Bridge
SITE PLAN
0 20 50 100
NORTH

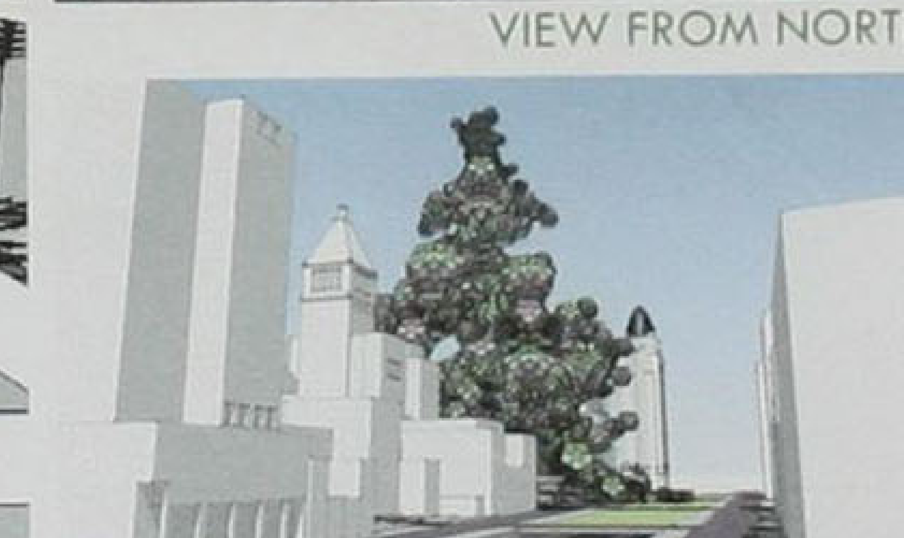


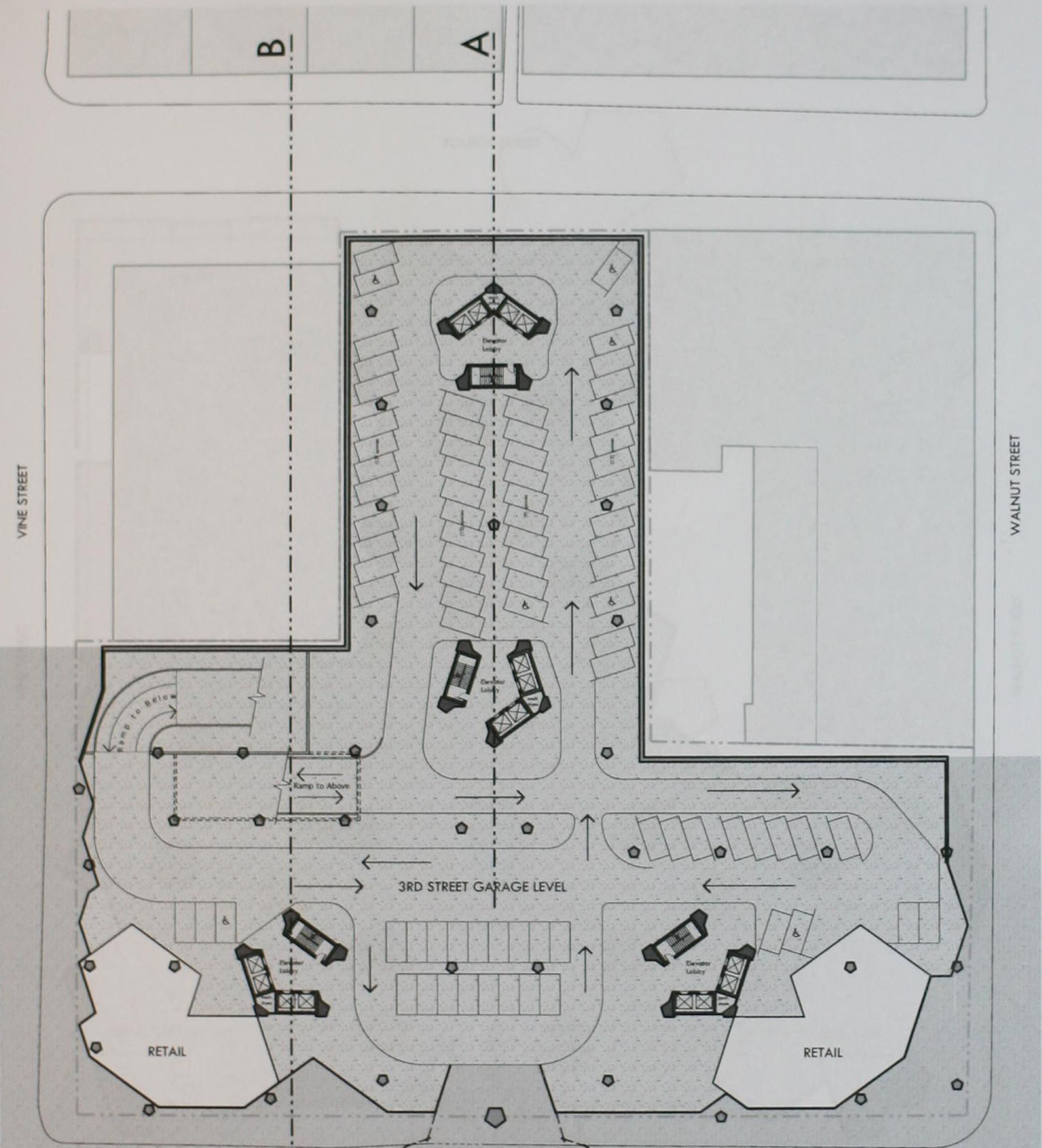
SITE SECTION LOOKING WEST


AERIAL VIEW FROM SOUTH


VIEW FROM EAST


VIEW FROM NORTH

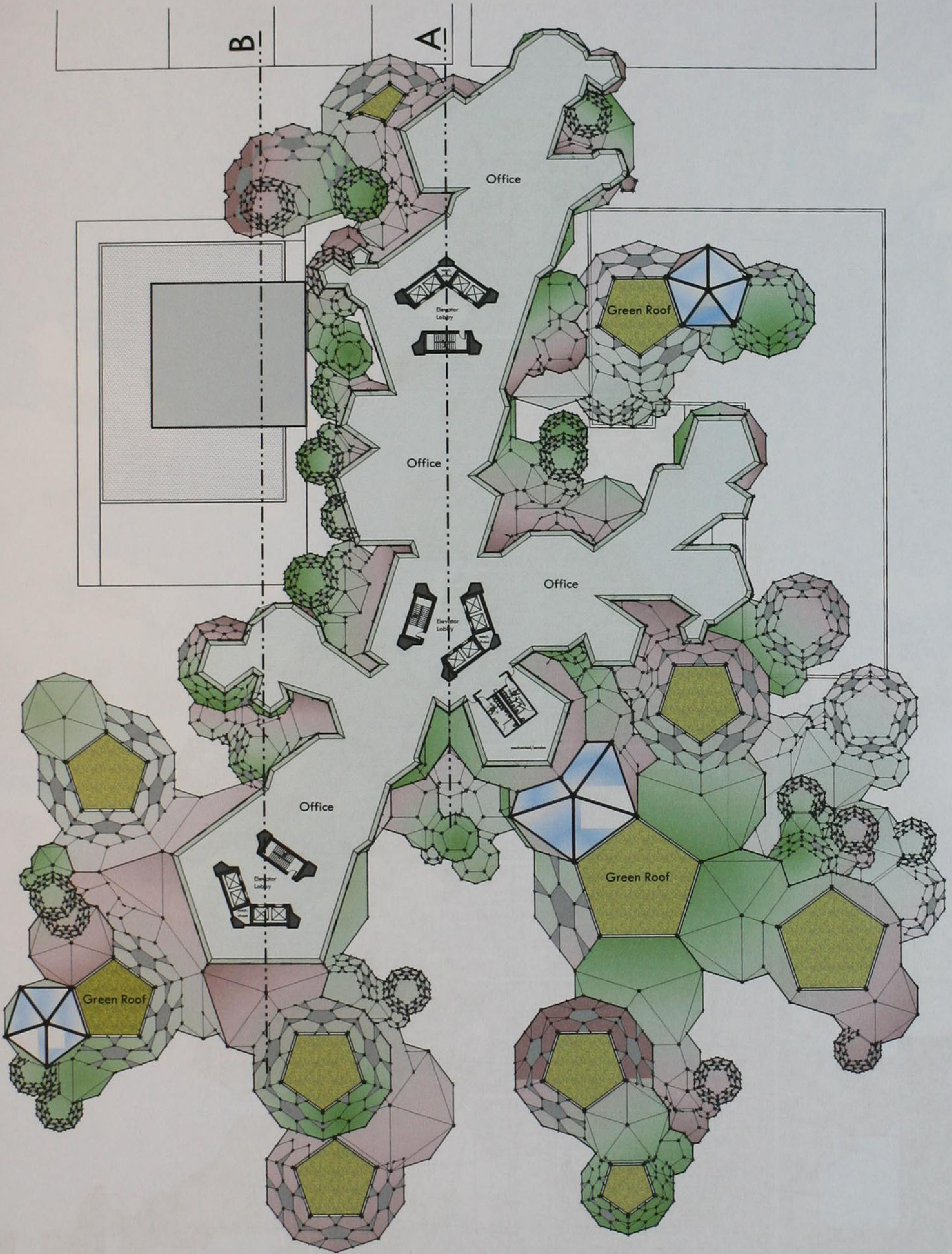

VIEW FROM WEST



B
A
VINE STREET
WALNUT STREET
Ramp to Below
Ramp to Above
Elevator Lobby
3RD STREET GARAGE LEVEL
RETAIL
RETAIL
THIRD STREET
GARAGE LEVEL PLAN
NORTH

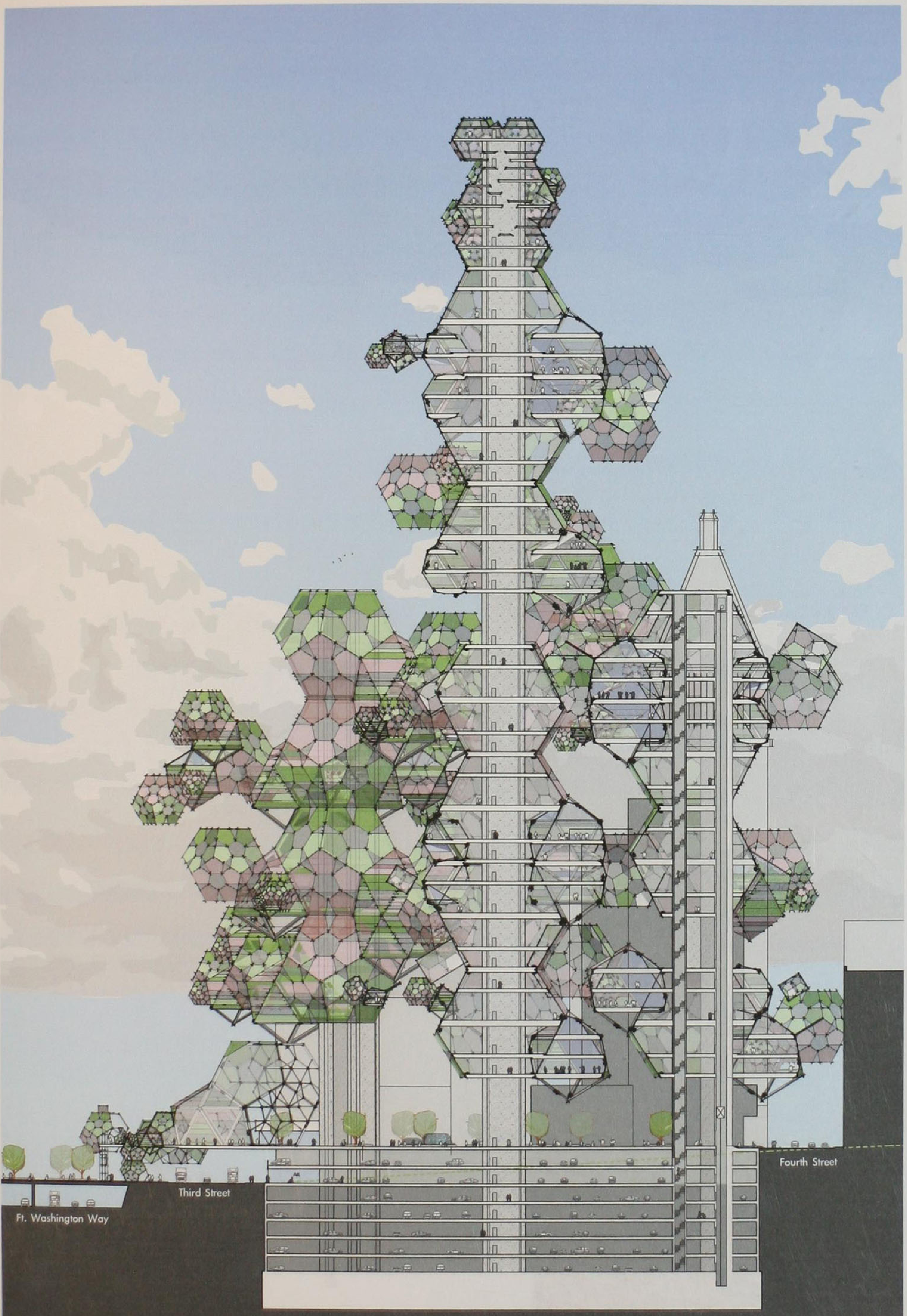

B
A
FOURTH STREET
Elevator Lobby
Elevator Lobby
RETAIL
VINE STREET
WALNUT STREET
Fountain
PLAZA
Elevator Lobby
Elevator Lobby
RETAIL/RESTAURANT
RETAIL/RESTAURANT
Overlook
Pedestrian Bridge
Elevator
PLAZA LEVEL PLAN
NORTH


B
A
Office
Office
Office
Office
women
men
jan.
mech.
Lobby
Residential Unit
2,200 SF +/-
Residential Unit
1,900 SF +/-
Residential Unit
1,800 SF +/-
bath
bath
bedroom
bedroom
kitchen
living/dining
office
1,800 SF +/-
RESIDENTIAL UNIT PLAN
1/8" = 1'-0"
LOWER ZONE PLAN
NORTH
10 5 0 20 50 100

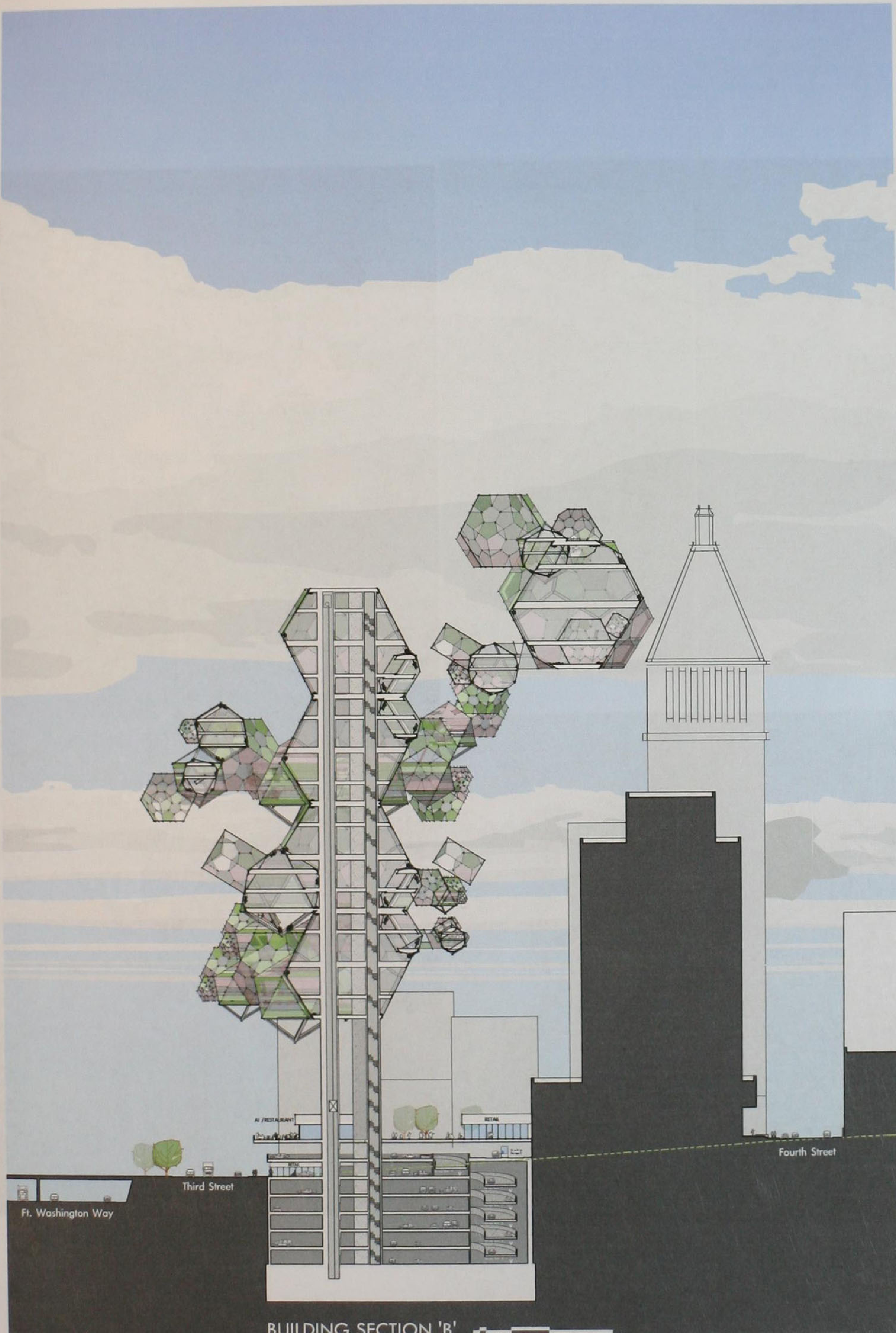


UPPER ZONE PLAN

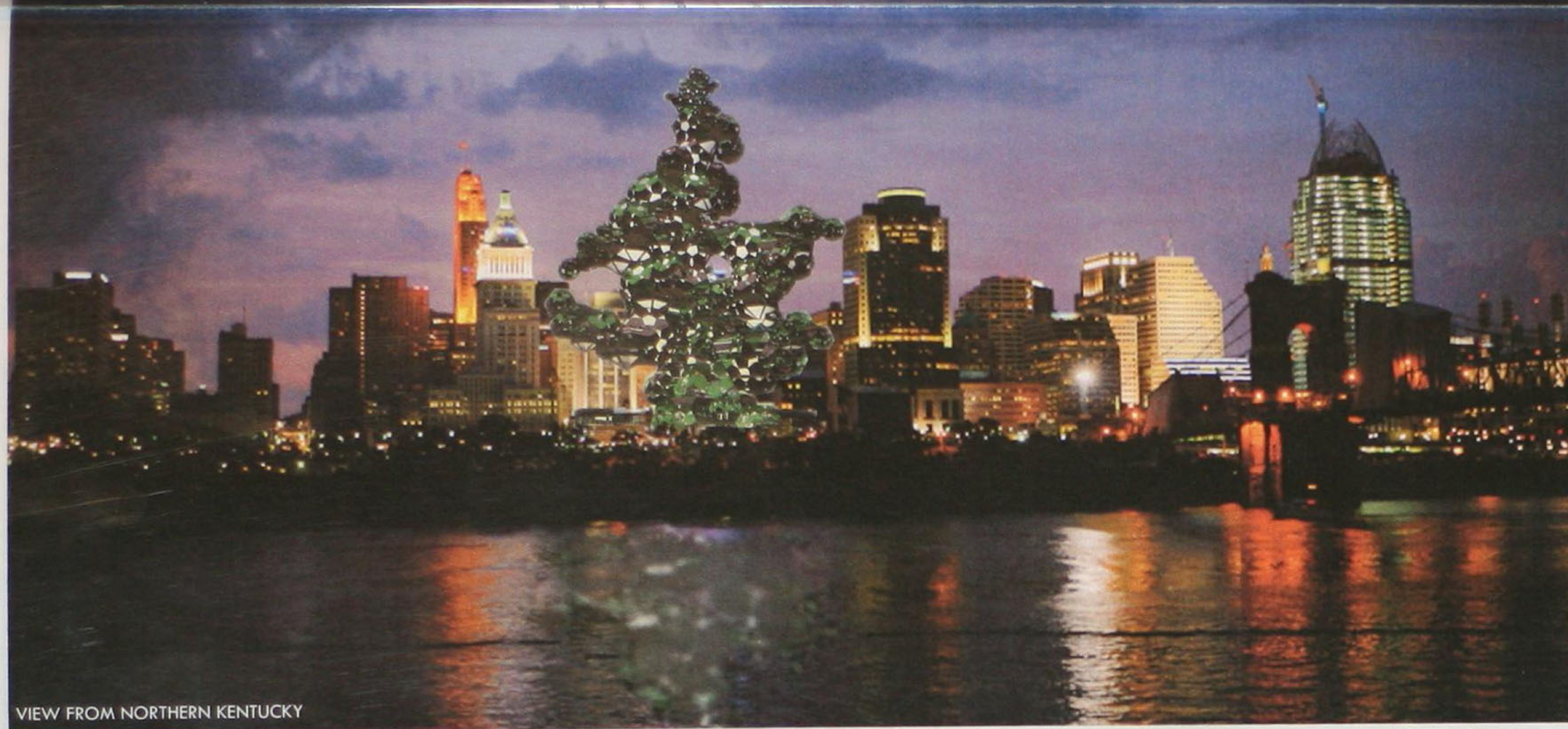
NORTH

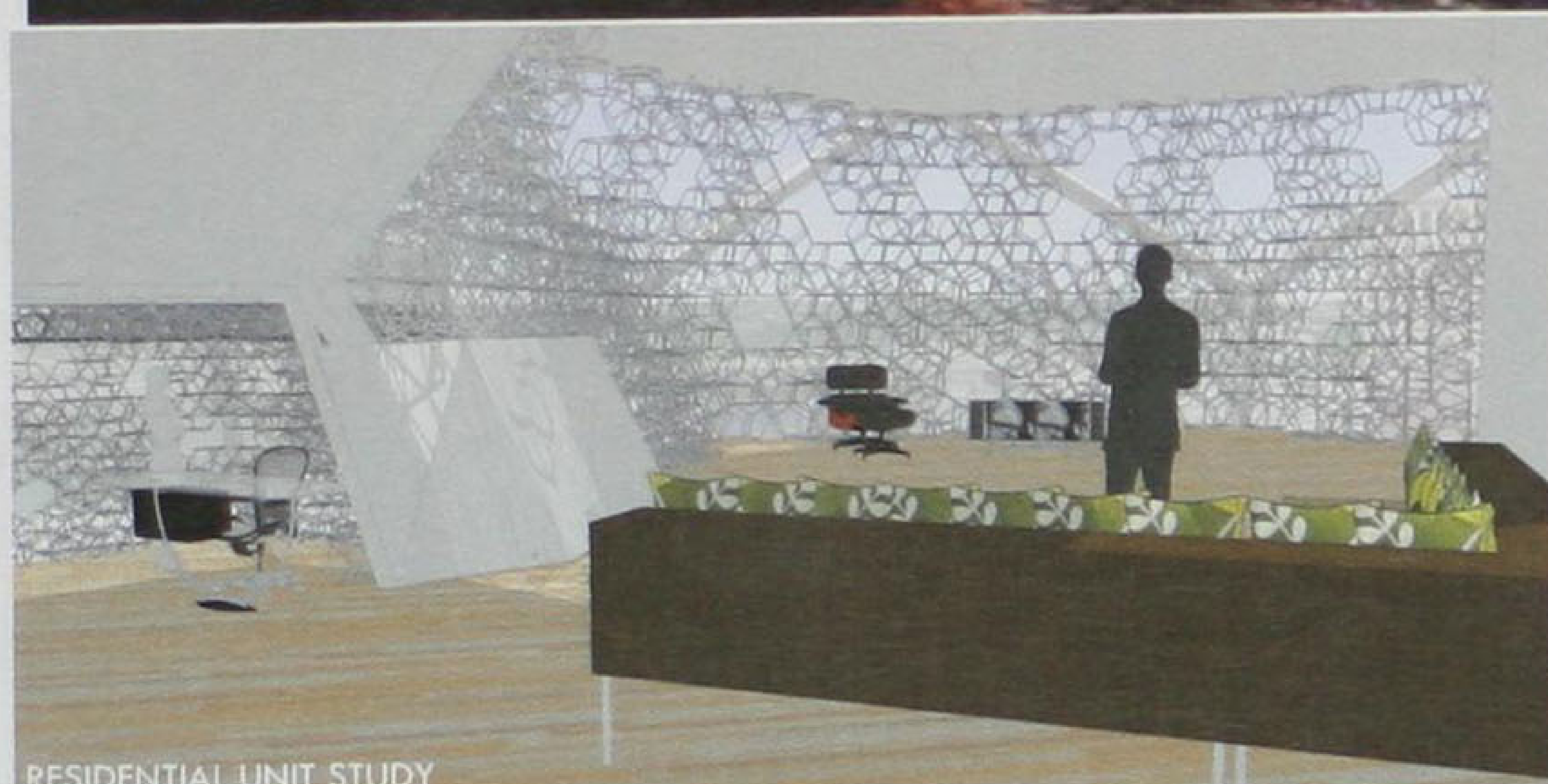


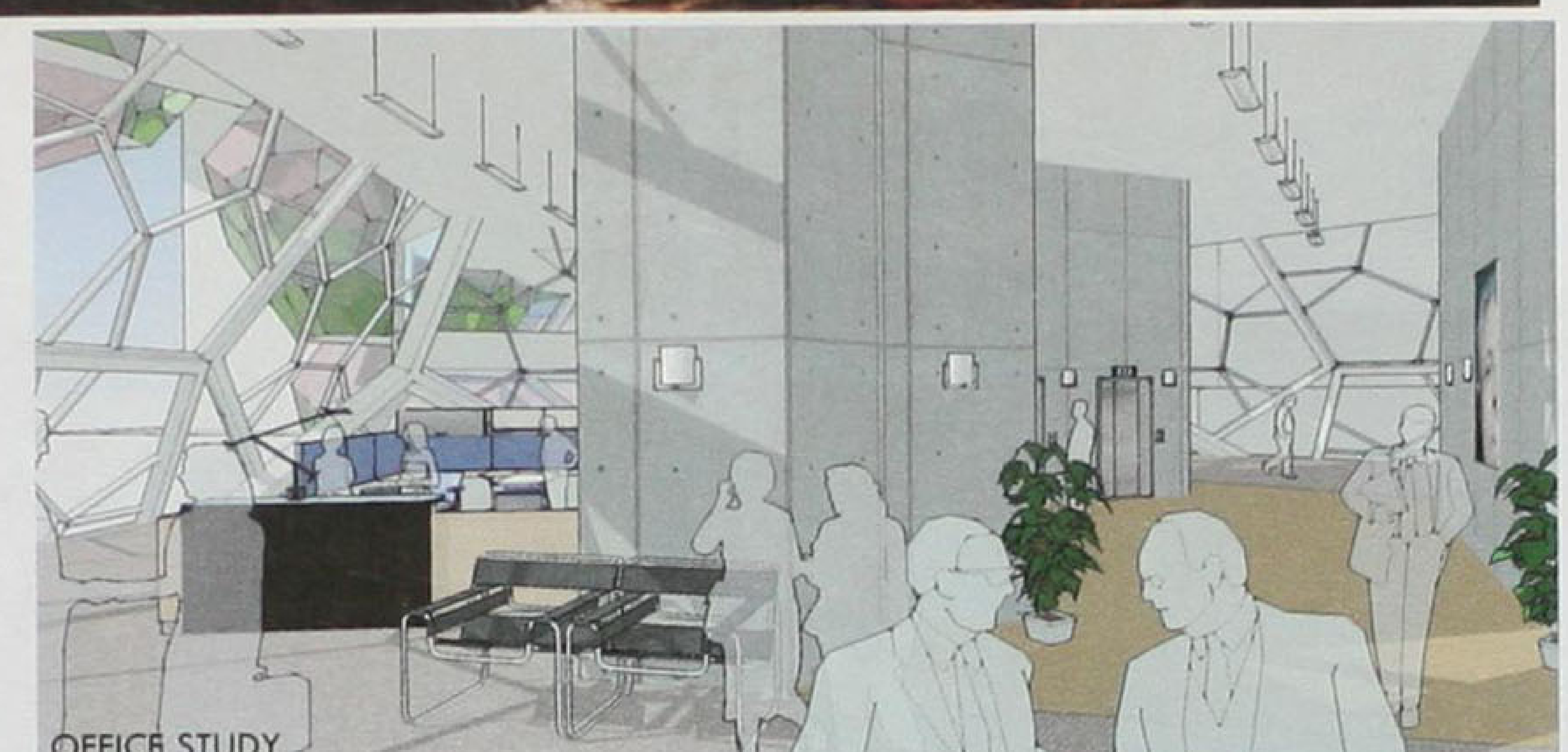
BUILDING SECTION 'A'



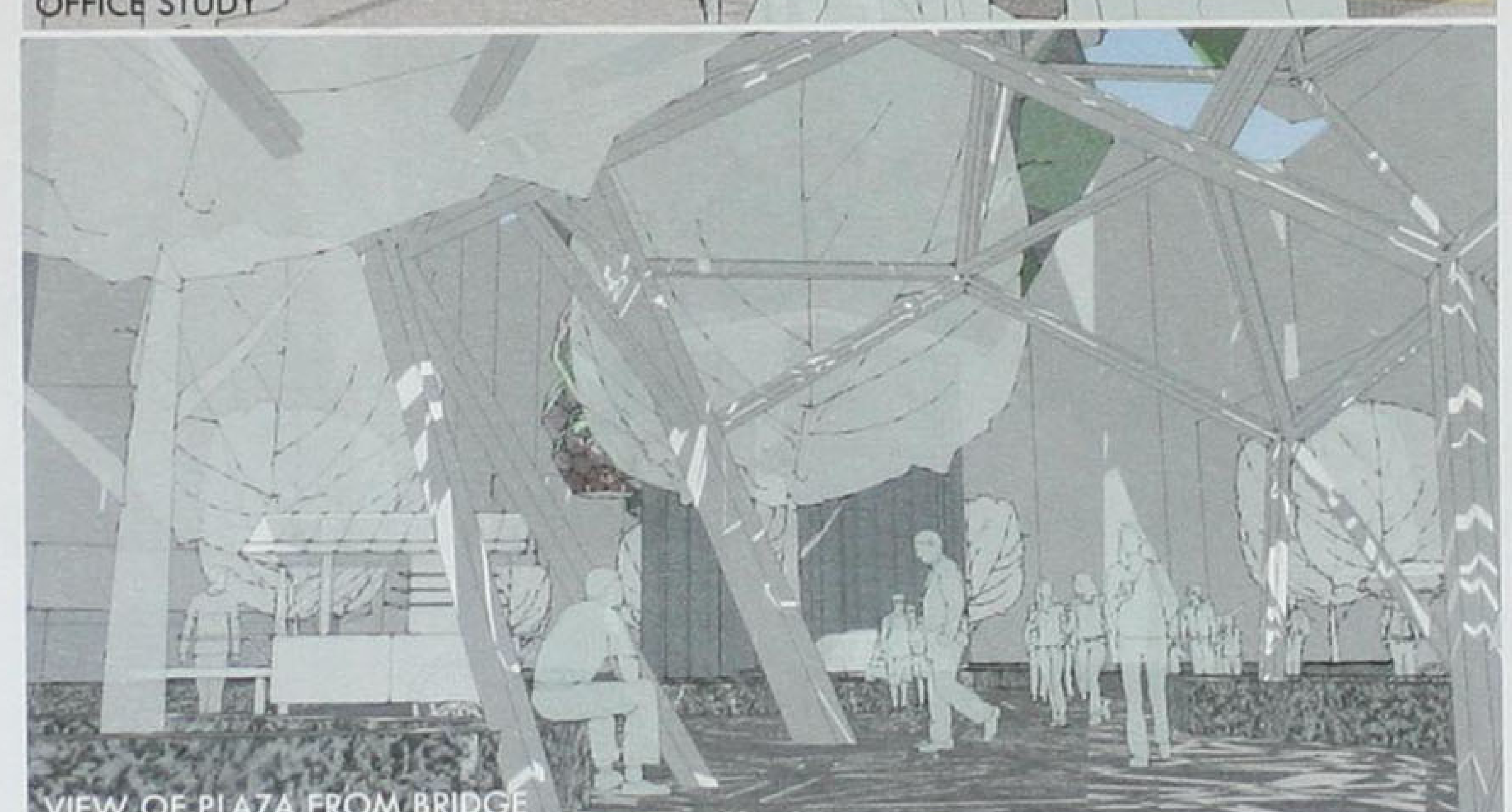
BUILDING SECTION 'B'


VIEW FROM NORTHERN KENTUCKY

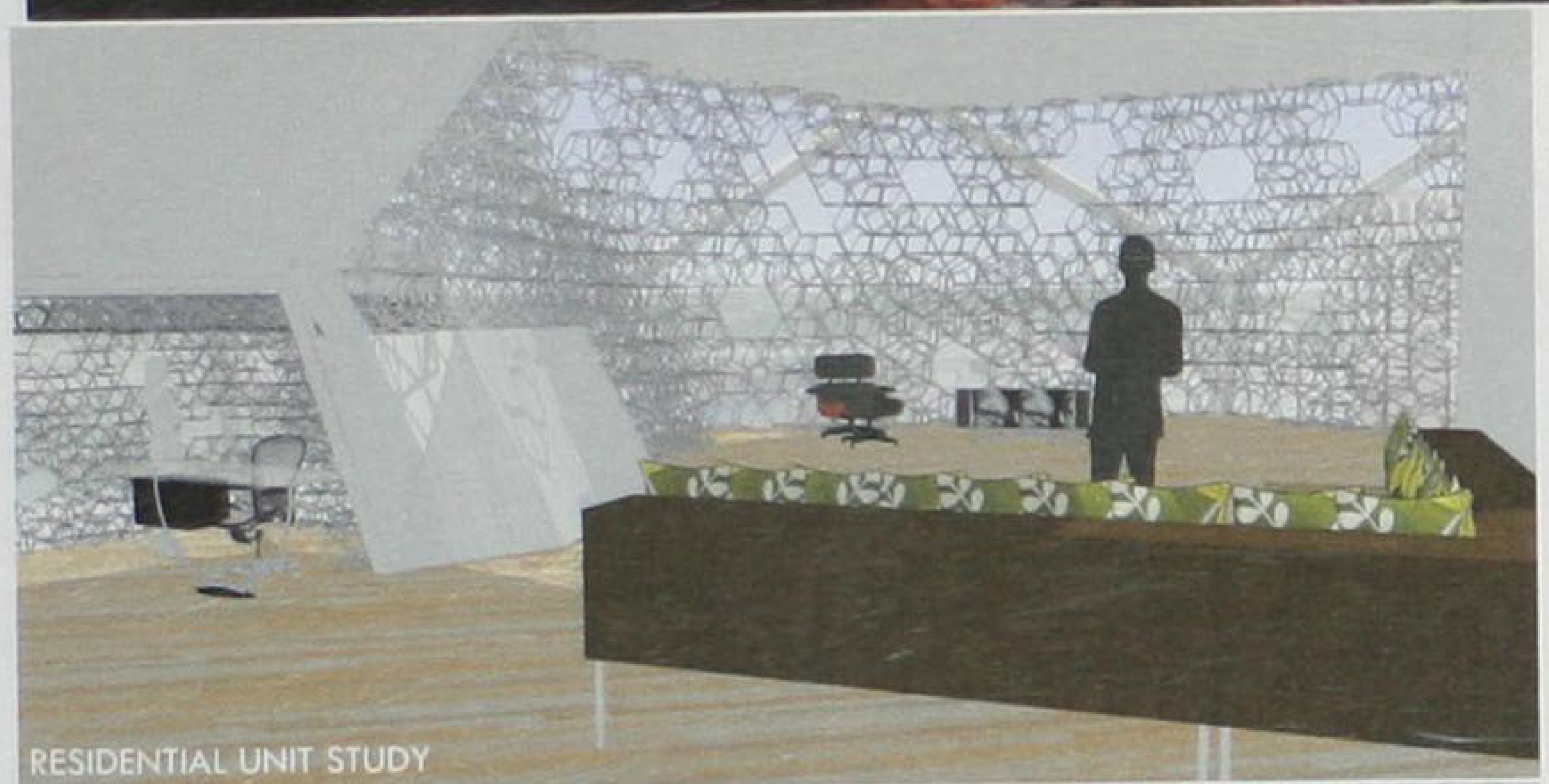

RESIDENTIAL UNIT STUDY


OFFICE STUDY


VIEW OF BRIDGE FROM PLAZA


VIEW OF PLAZA FROM BRIDGE


VIEW FROM NORTHERN KENTUCKY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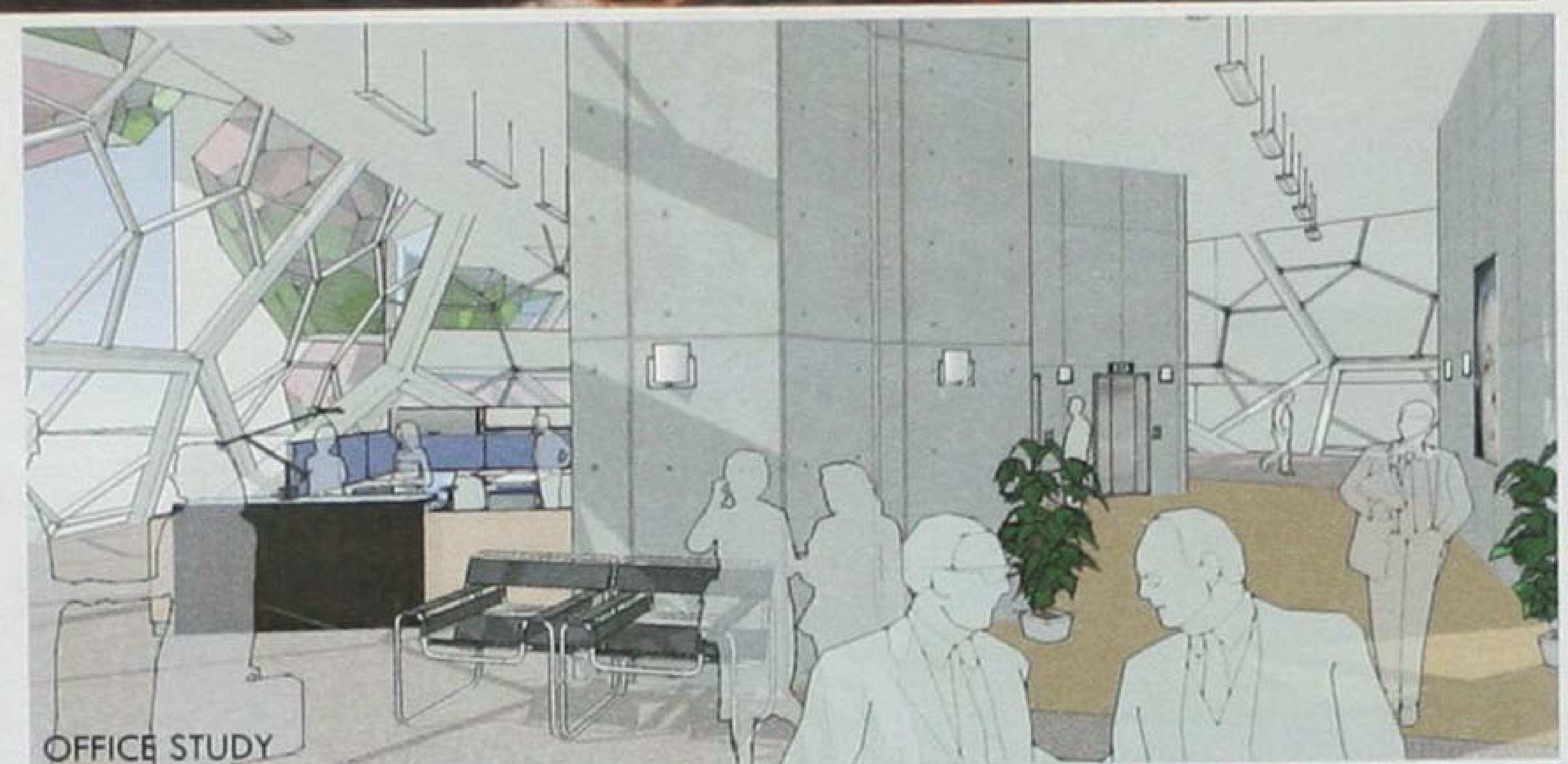
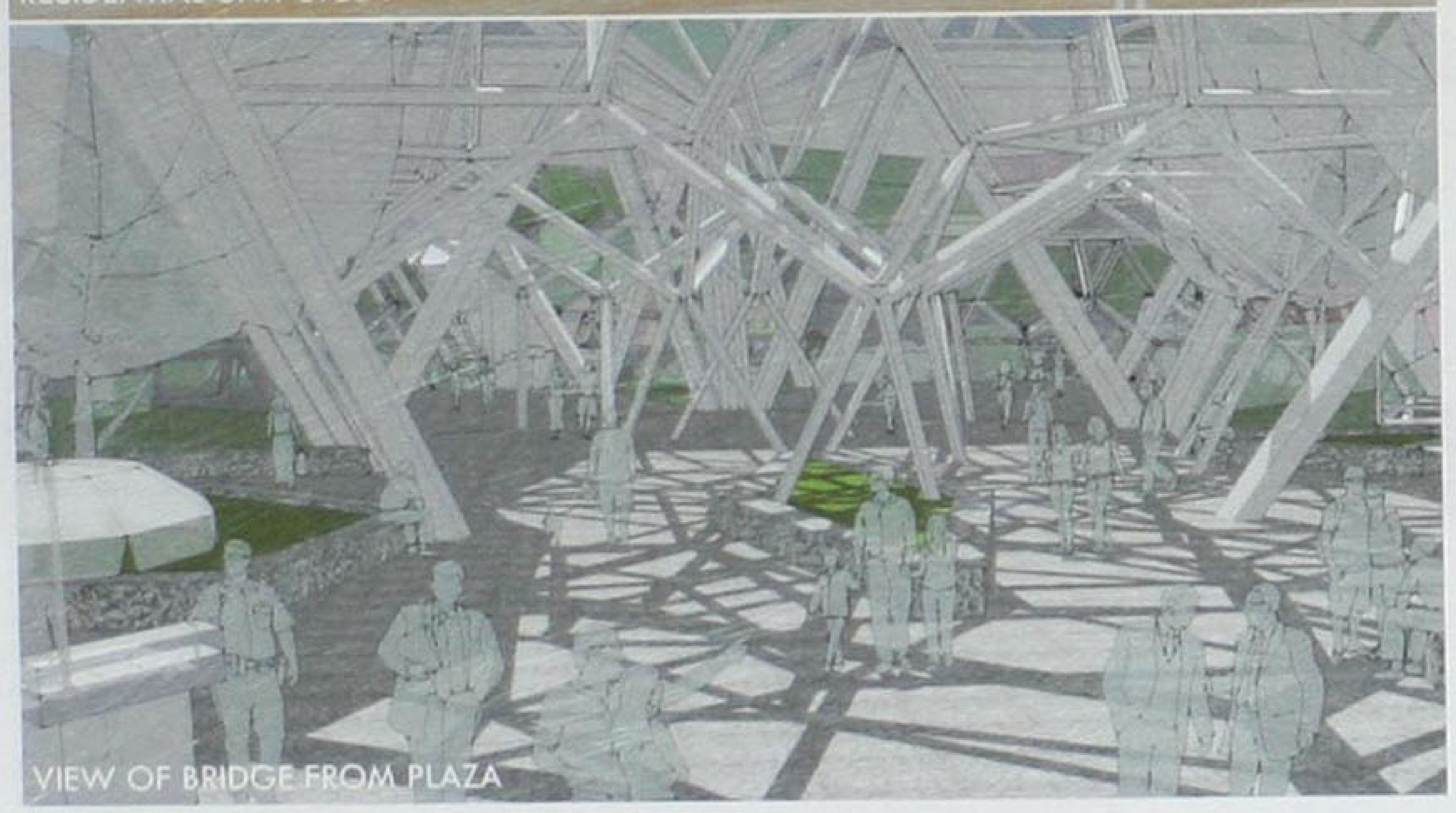
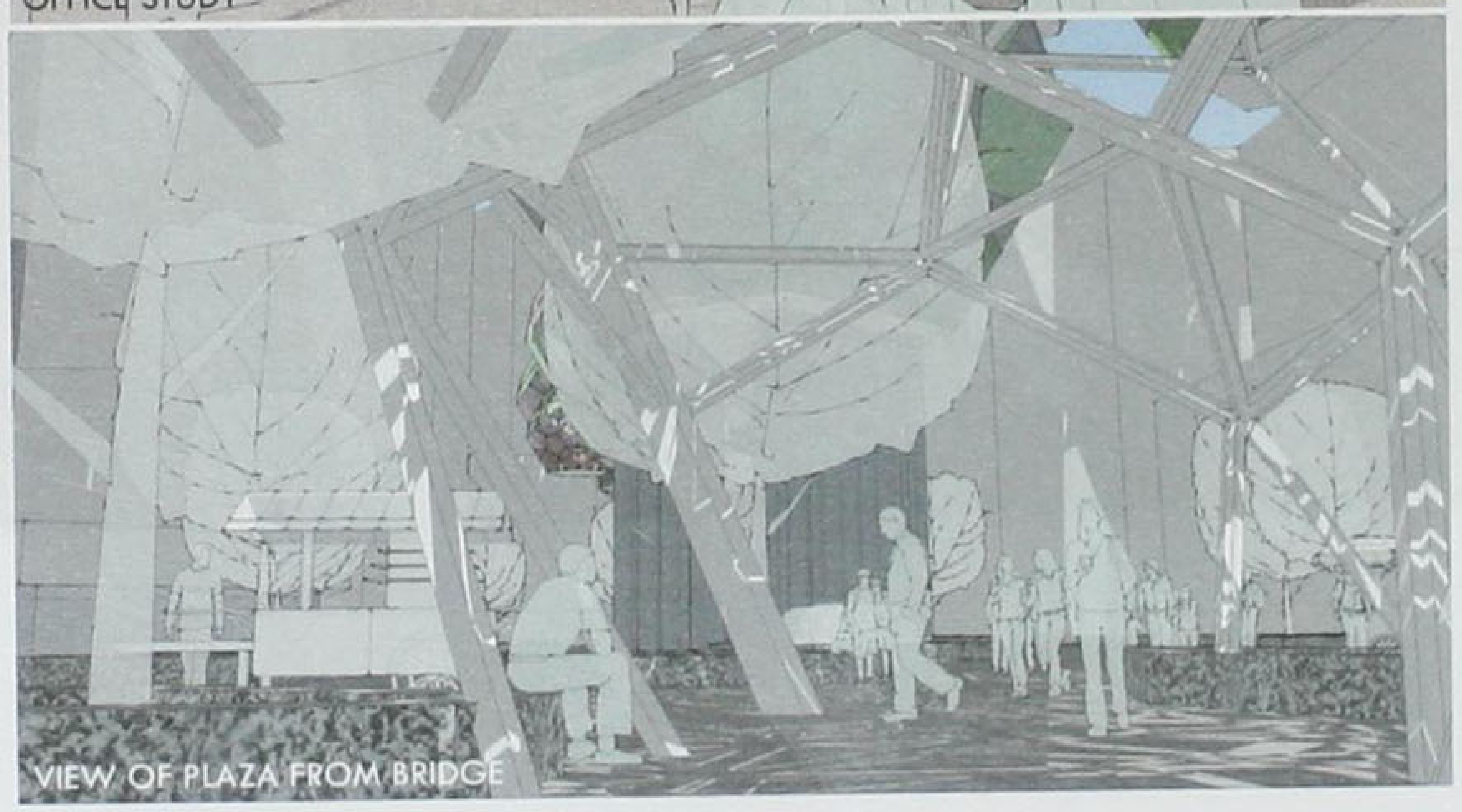
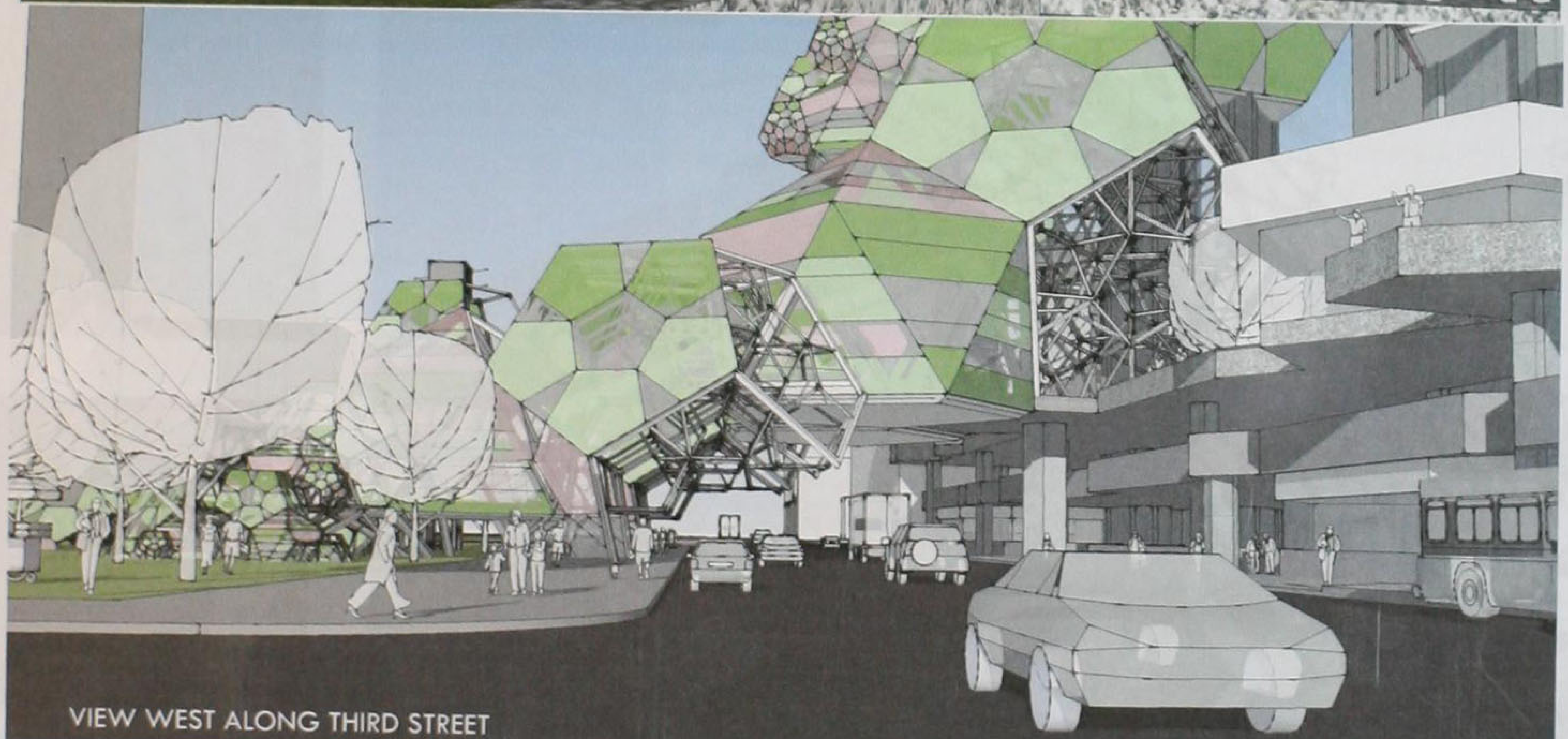

OFFICE STUDY


VIEW OF BRIDGE FROM PLAZA

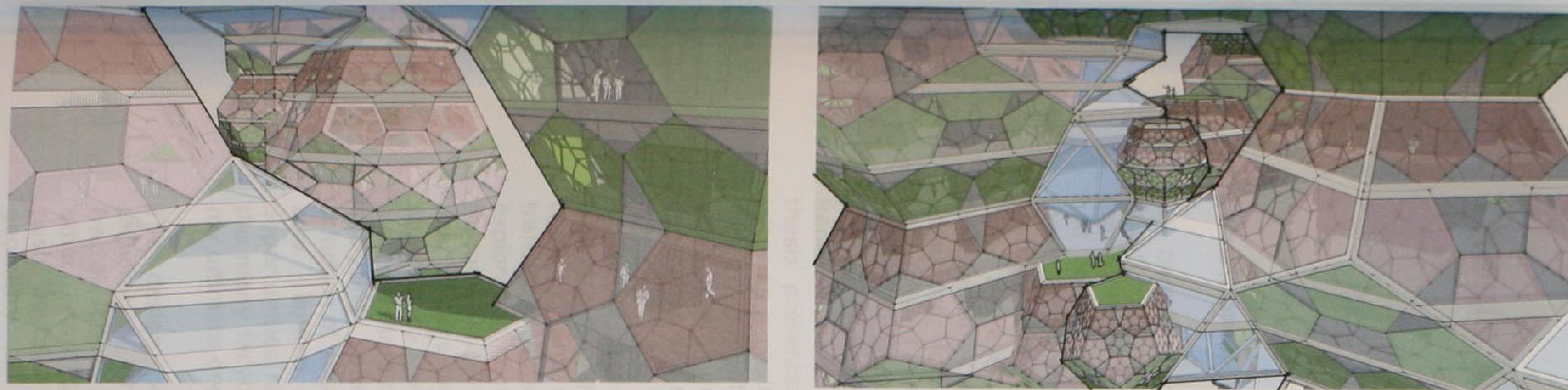

VIEW OF PLAZA FROM BRIDGE

PLAZA VIEW FROM FOURTH STREET

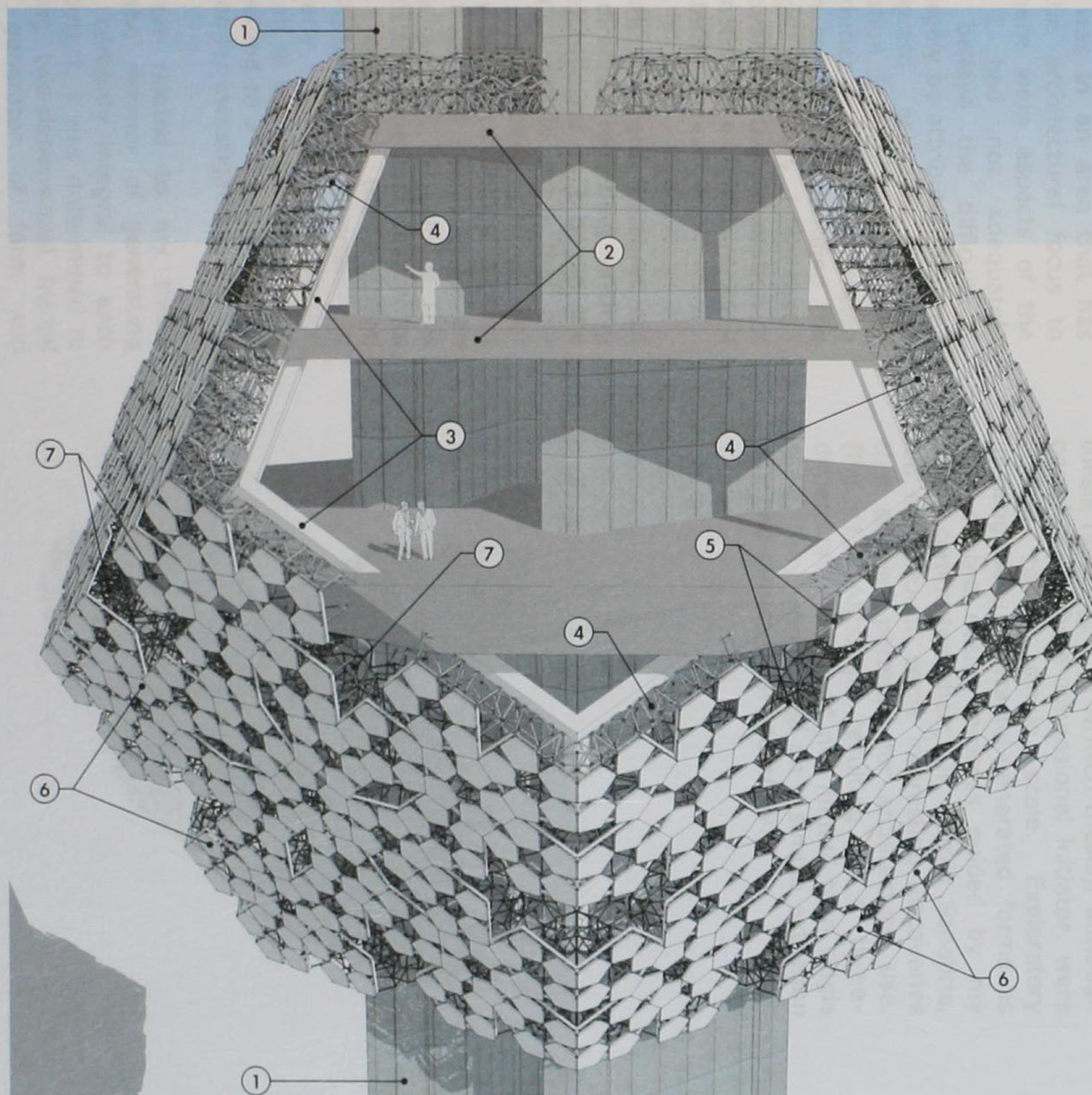


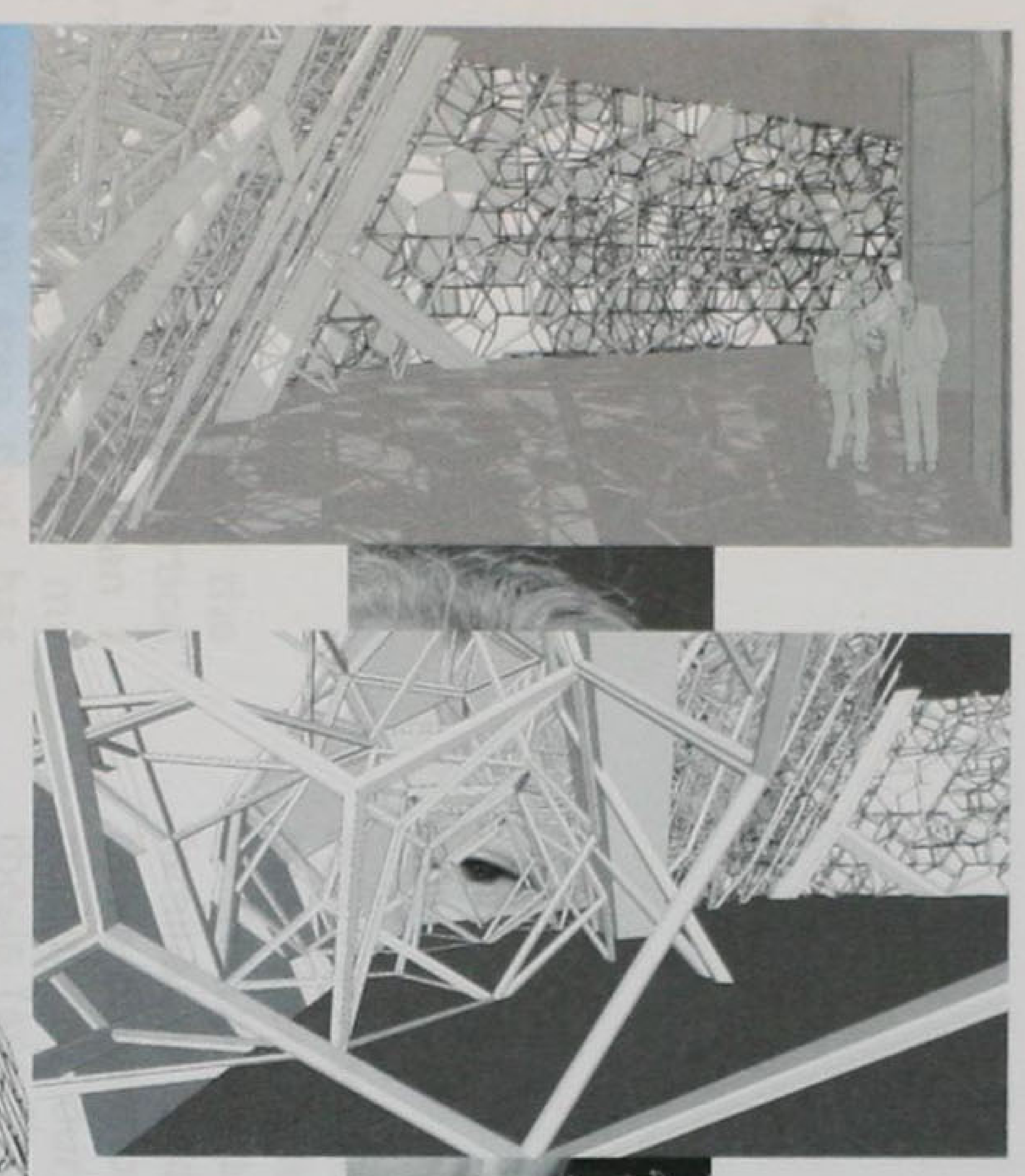
VIEW WEST ALONG THIRD STREET

VIEW NORTH FROM SECOND STREET



EXTERIOR VIGNETTES





STRUCTURAL SYSTEM CONCEPT

LEGEND

1 • Reinforced Concrete Structural Core

2 • Reinforced Concrete Floor Slab

3 • Tubular Steel Dodecahedron Frame

4 • Dodecahedral Space Frame

5 • Cladding Sub-Frame

6 • Alucobond Cladding Panels

7 • Glazing Opening

Thesis Addendum

Transition: Writing to Design

The transition from the written portion of the thesis exploration to the design portion proved to be even more challenging than I had anticipated. I was well aware that my thesis exploration was in an area that has seen relatively little architectural focus to date. However, there were aspects of the exploration that I had not adequately accounted for. I believe the difficulty I encountered can largely be attributed to three aspects: site/program selection, design process and generation. Ironically, guest juror Renee Chow's comments from the written thesis presentation in the fall identified the latter as a challenge. Ultimately, I feel that I met my goal of advancing the exploration of using fractal geometry in architecture as a generative and systemic device.

As is the case with hindsight, I regret not having a stronger direction regarding building typology (and site) in mind as I began the transition. Although I would argue that my exploration could have been carried out through almost any building typology, a great deal of time was dedicated searching for an appropriate experimental "vehicle". This placed a more restrictive time limit devoted to analyzing various sites and the eventual selection of such. Perhaps more importantly, it also limited early design exploration opportunities related to building typology and the many facets related to a "tall building" as my ultimate decision for investigation.

The design process related to my thesis exploration and the manner of generating fractal forms are certainly integral to each other. From the outset, I was determined to push beyond using two-dimensional fractal geometry as a generator of form and structure. I spent a great deal of time during the previous summer, the fall, and into December exploring various computer applications to be used as possible form generators. Ultimately, I chose to work with SketchUp based on time constraints, and my familiarity and comfort level.[1] Some early three-dimensional fractal structure studies completed during the written portion of the thesis (see Fig. 1 in written thesis), although based on a three-dimensional initiator, were limited to a single scale. Exploratory investigations of fractal-generated forms as part of the design process guided by my thesis committee chair, Dr. Sergio Sanabria, led me through some interesting discoveries that showed potential for architectural use. (Fig. 1). Although resulting in a three–dimensional form and not limited to a single scale, they were based on a simple extrusion of a two-dimensional geometry.

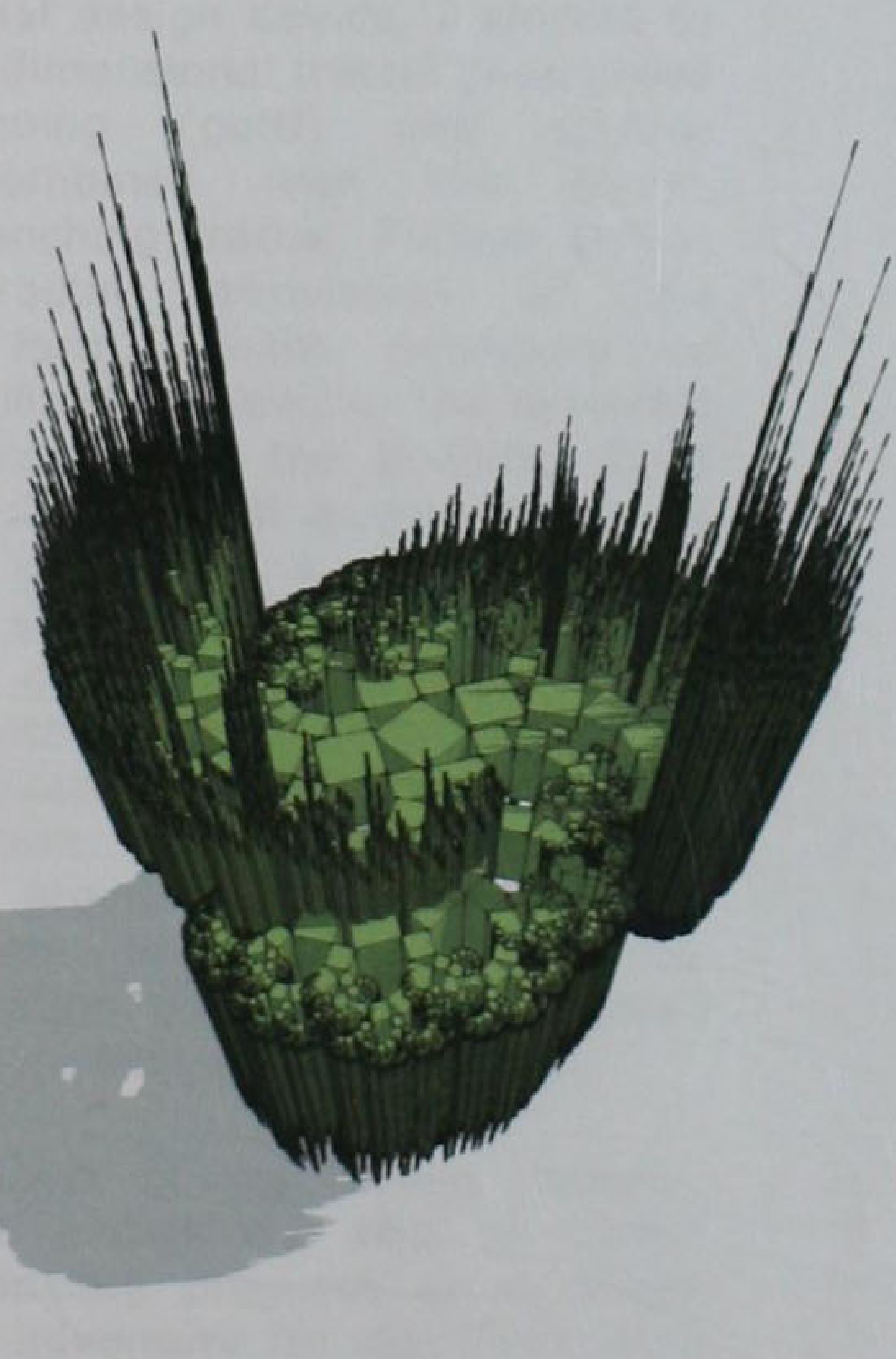


Fig. 1. A simple three-dimensional extrusion and repetition of a two-dimensional branching fractal resulting in a dynamic form.

To remain dedicated to exploring the use of a three-dimensional initiating geometric form (initiator) rather than a two-dimensional one, I continued by investigating the use of Platonic solids as an initiator. This was consistent with an early concept of a three-dimensional initiating form that worked on multiple scales: as both defined, habitable spatial form and as that which could become structural forms, or that which defined other spaces. In a more simplistic sense, one could be inside or outside of the initiating three-dimensional form of the fractal geometry. I felt this also more fully-addressed the systemic nature that I was interested in as part of my exploration.

After exploring numerous three-dimensional fractal studies, I eventually discovered a combination of the regular dodecahedron, its geometric dual the icosahedron, and two reduced-sized dodecahedron that resulted in a fractal form that branches/extends directionally, and which realized the multiple scale aspect described above. (Fig. 2). The branching/extension followed the established fractal rules while also allowing for my intervention to responsively guide the form's growth where necessary.

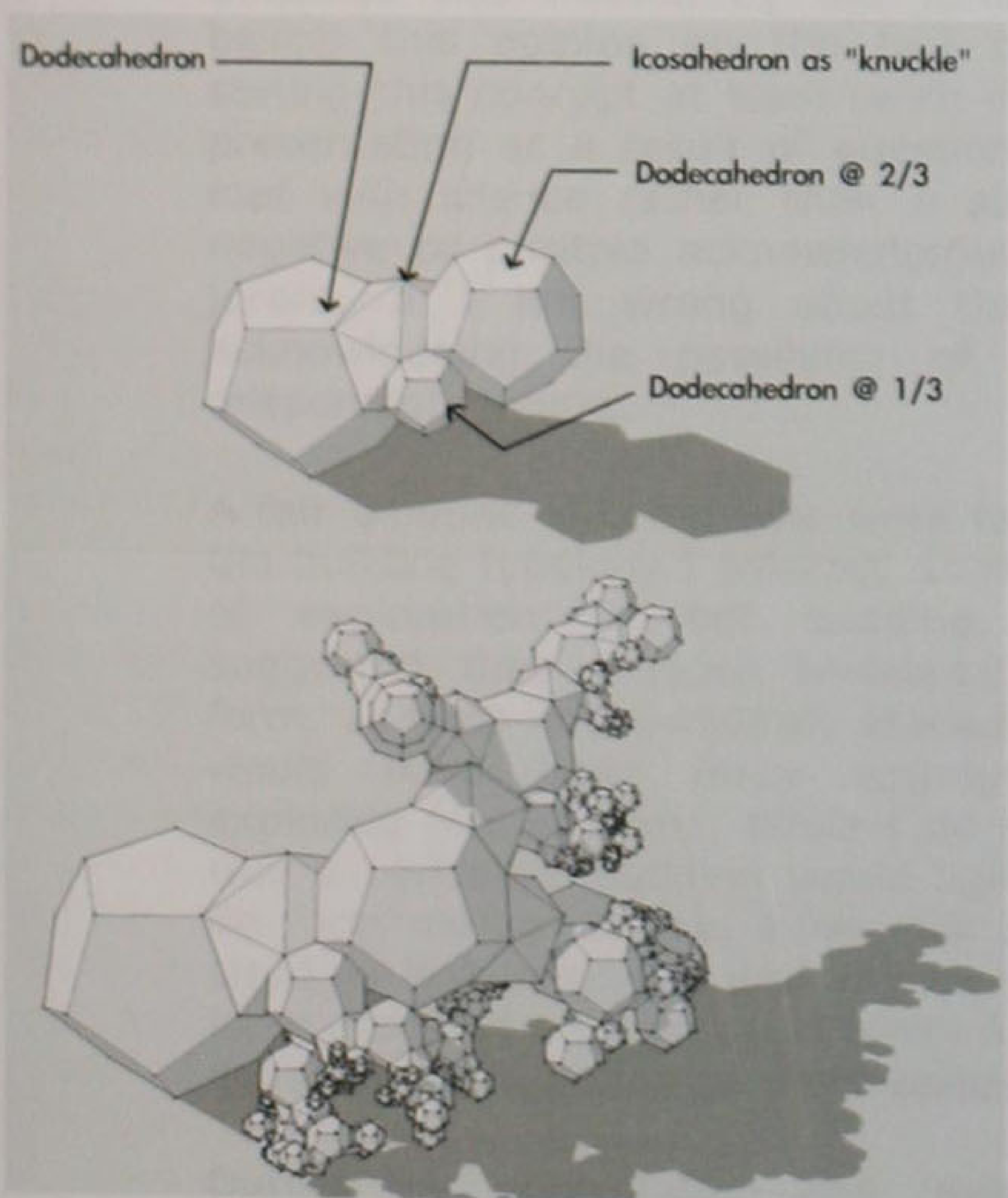


Fig. 2. Branching fractal form based on employing a dodecahedron, its dual the icosahedron, and reduced dodecahedrons.

My selected site was the bulk of a city block that borders Ft. Washington Way, a highway in Cincinnati, Ohio. The east-west oriented highway parallels the Ohio River, isolating the main city grid and the bulk of downtown from the river. My design solution attempts to extend existing master plan goals and current design and construction efforts to bridge the concrete river (highway) and connect the city with its natural amenity, the water. I had envisioned other nearby tall buildings and the potential of my design as metaphorical sycamore trees situated along a (concrete) river. I then conceptualized a tall building design as a series of connected buildings rather than a single, monolithic form. Multiple trunks (structural/functional cores) with branches hosting habitable space raised above the ground (plaza) below opened for views, light and movement. My proposed building program entails a mixture of office and residential uses (above), retail space below (plaza level), and includes a pedestrian bridge that reaches from the plaza out to the highway and city-proposed "decks" to be constructed over the highway. A parking garage is situated below the plaza and main building(s) to round out the project.

As a generational design device, I elected to implement two-dimensional fractal geometries for site planning (parti) and surface articulation, combined with the three-dimensional branching fractal. Further three-dimensional fractal articulation of the dodecahedron form, where necessary or desired, was utilized to develop the systemic architectural language of the building. Both two and three-dimensional geometries were based on the pentagon, a geometry that circumscribes a sycamore leaf. The result was an attempt to create an intelligent, three-dimensional fractal *diagram* for architectural design or exploitation. Basing the building's form and structure, literal and figurative, on the diagram provides opportunities for dynamic growth and adaptability; my systemic exploration goal as a novel (new) way to create more sustainable buildings.

As a major aspect of my design process, working almost exclusively with a three-dimensional modeling program as a design tool was a new adventure for me. Combining that with an effort to base as much as of the design as possible on three-dimensional fractal geometry definitely pushed me way

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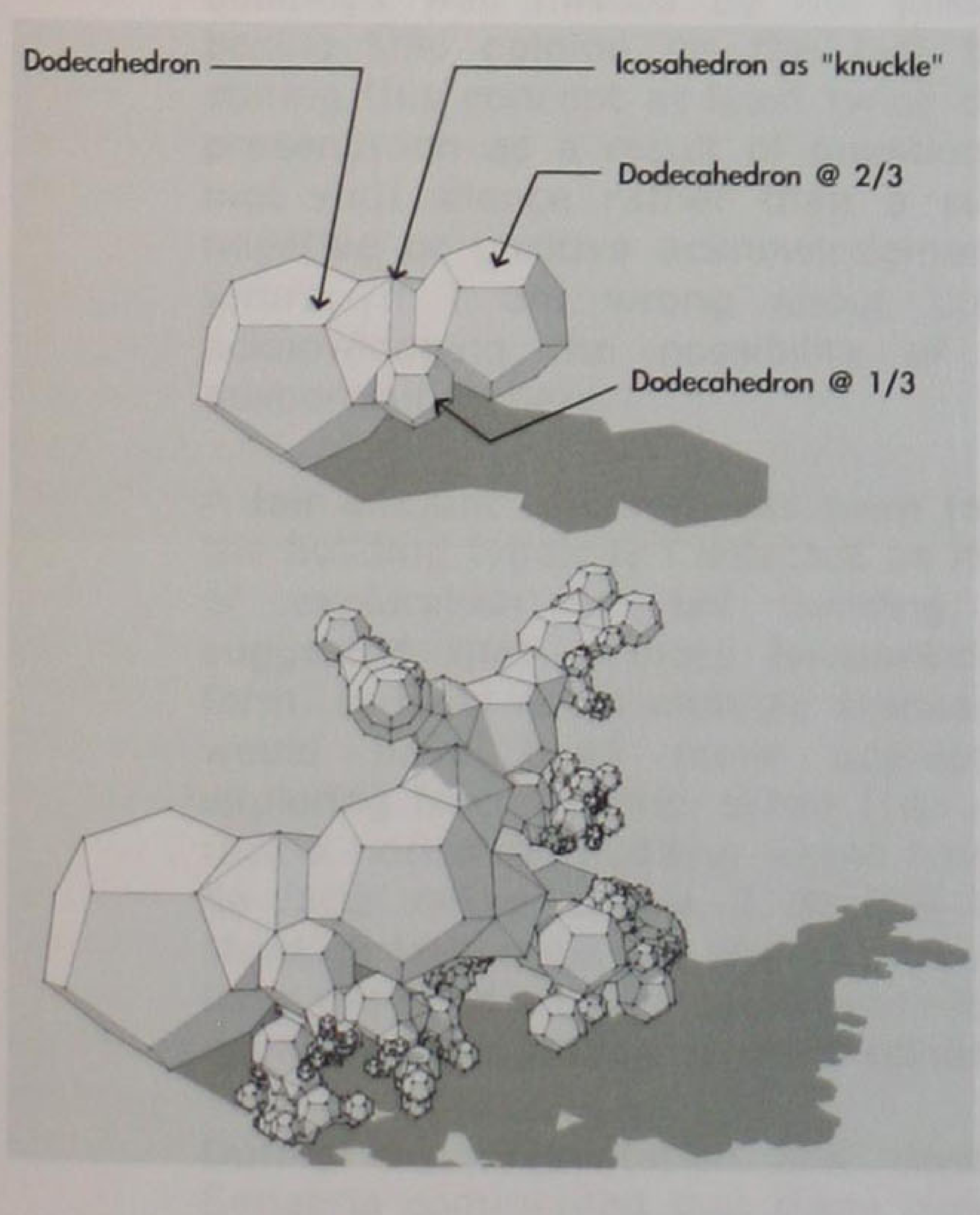

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As a major aspect of my design process, working almost exclusively with a three-dimensional modeling program as a design tool was a new adventure for me. Combining that with an effort to base as much as of the design as possible on three-dimensional fractal geometry definitely pushed me way beyond my comfort level. I soon discovered it virtually impossible to work in the normal orthographic, two-dimensional conventions of plan, section and elevation to which myself, and most, are accustomed.

Review Comments

Overall, I found the comments received during the presentation to be rather mixed in nature. Many of the critical comments and subsequent discussion were quite good, accurate and beneficial. However, I feel some of the comments and discussion were based on confusion. Although I believe that fractals can be relatively easily understood by most on a superficial level with a little explanation, working with them in an architectural undertaking is entirely different. I feel my inclusion of the words "Novel Sustainability" as the leading words of my title set me up for criticism and confusion by some. It is my opinion that most, if not all, of the jurors at the review did not grasp the concept of fractal geometry acting as an intelligent diagram for architectural design. In that respect, the idea of using this diagram as a way to create systemic form and structure to potentially create adaptability and flexibility of form in buildings was missed by the jurors. I am basing this opinion on the fact that after stating this concept at least twice during the presentation as a result of questions, it was met with silence rather than a subsequent negative or positive acknowledgment by the jurors. If I am wrong about this, I am acknowledging the possibility of my own misperception here.

A fair amount of comments were focused on the building typology I selected as my vehicle of exploration; a tall building. It was suggested that a more horizontal building form, at least not a multiple storied building, would have been more appropriate for exploring fractal forms. While I do not agree that a horizontal building would have been a de facto better choice, I do feel a smaller sized, or less ambitious project program might have provided a better opportunity for a more developed exploration on more scales.

During my presentation and review, Prof. Sanabria commented that there was a rather awkward resolution between the vertically extruded cores and the horizontal branching fractal forms that were utilized. I can certainly acknowledge this shortcoming; admittedly, the dodecahedral branches were simplistically skewered onto the vertical cores. The cores themselves were rather brutal and relatively undeveloped in their expression as they were an extrusion of the two-dimensional planning fractal utilized. Had I developed a more elegant and sophisticated solution where the cores were based on a related three-dimensional geometric initiator, the results would have likely been more visually interesting and fraught with more potential to exploit architecturally.

Some of the review comments and the subsequent discussion focused on what appeared to be "conventional" aspects of the design project, specifically the idea of an urban plaza and parking garage below the primary building, and what was described as "typical office floor arrangements" vertically. (Fig. 4).

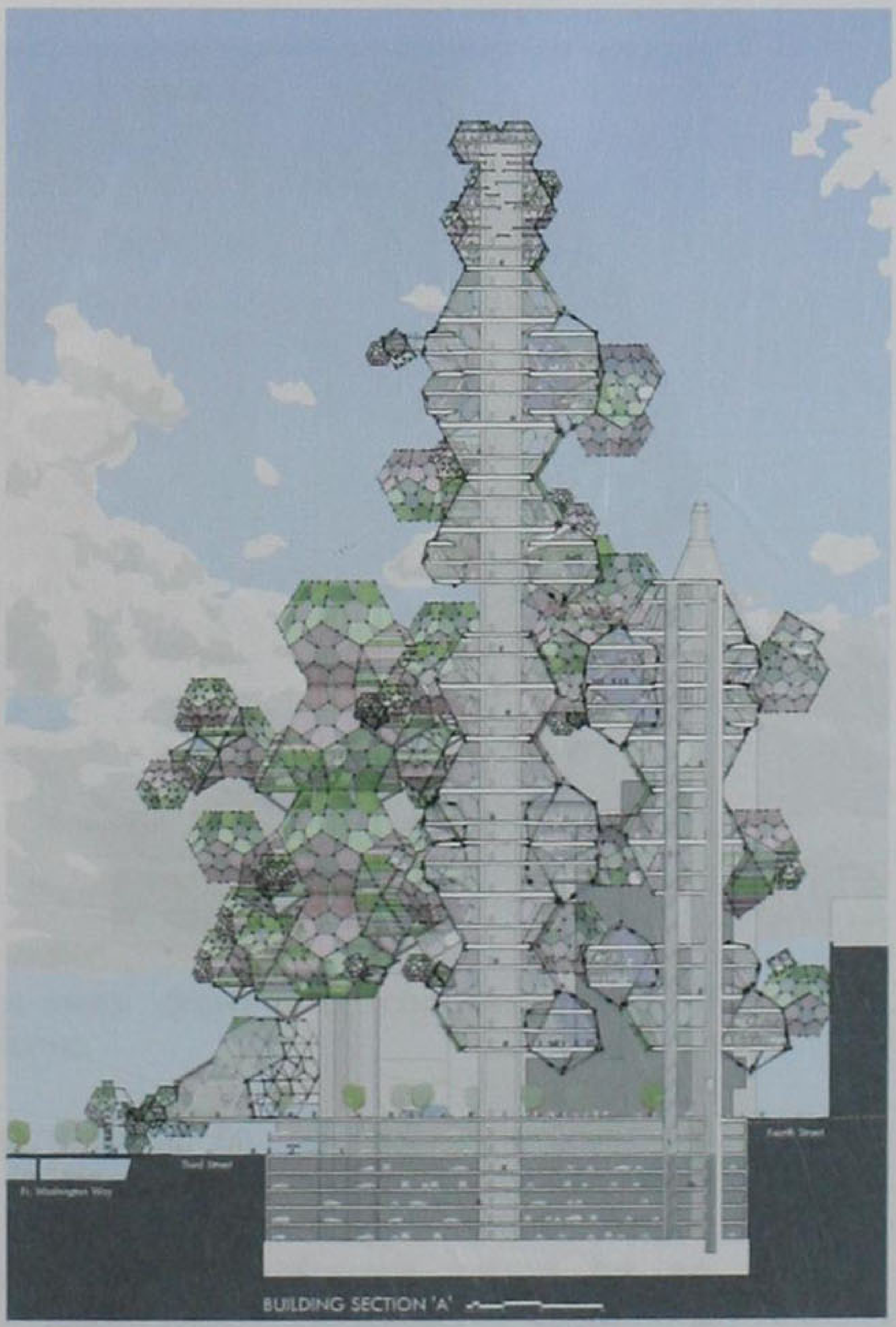

Fig. 4. Building section design drawing.

Given the theoretical nature of my design exploration, they were indeed perhaps more conventional than one might initially expect given the exploration of fractals. At one later point during the design project portion of the thesis, Prof. Sanabria, my reader Mary Ben Bonham and I discussed possible directions with the arrangement of the building design regarding meeting real-world constraints of building codes, handicap accessibility, and existing technologies such as human conveyance. One possible path would have required a reinterpretation of accessibility, elevator operation, etc., and perhaps construction material limits. The other path would have more existing building conventions integrated into the design.

For the most part, I opted to pursue a more conventionally rooted direction in terms of structural and functional feasibility based on currently available building technologies. The cores skewering the dodecahedral branches are perhaps the most visible result of that decision. Albeit less liberating design-wise, I felt that this path afforded a better chance of the design exploration resulting in something closer to a "building", given the limitations of time and generational (design/modeling) capabilities. The general overall complexity of the project, the challenge of working with fractal forms, the limitations of the modeling software, and twenty-five odd, ingrained years of being a practicing architect also contributed to keeping me on the more restrained path.

Related to "conventionality" regarding the reviewer's comments and my own choice, was the opportunity to work with Dr. Herb Bill from the University of Cincinnati's College of Engineering and Applied Science. Dr. Bill is a structural engineer is experienced in tall buildings, space frames, structural forensics, and structural modeling analysis. He acted as a structural engineering consultant in this process and he afforded me a great opportunity to test and potentially integrate a measure of structural feasibility into the design project. Dr. Bill provided feedback on the written thesis and forward through the design project. His input and help, like my committee, was invaluable during the entire thesis process.

The upper image in Fig. 2., of the first fractal iteration I developed was designated as a basic structural "module". It was hoped that structural modeling analysis software would be able to be implemented and the results presented. Some early simplistic modeling analysis was conducted on the module yielding some preliminary results. A determination of feasibility of the basic module was possible, albeit with continued development of the structural system design requiring some measure of complexity. Unfortunately, software compatibility issues were encountered along the way as the project and module complexity progressed.[2] Through several meetings, the portion of workable software data, and manual determination, it was concluded that a spatial frame system, based on the module was possible. In addition to internal attachment to horizontal floor/roof structure and the vertical cores, each face of the platonic solids required stiffening to carry transverse loading and bracing requirements. Each face would become a space frame or space truss based on smaller-scaled versions of the three-dimensional geometry. (Fig. 4).

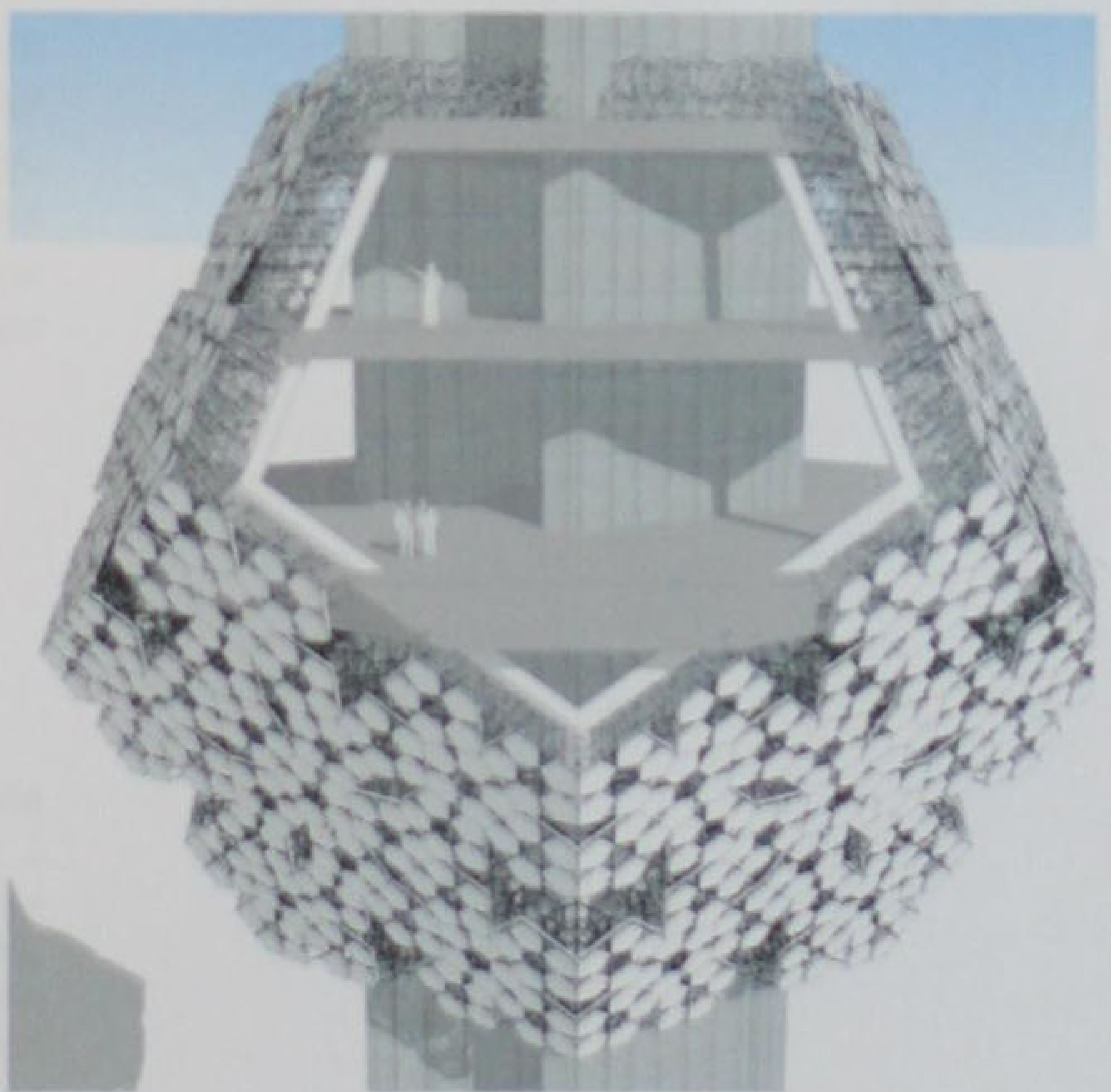

Fig. 4. Cut-away drawing of complex structural system concept.

Given the chance to re-visit this topic or pursue it further in the future, I can say with certainty that proficiency with more sophisticated design software would be an absolute minimum necessity from a technical/design standpoint. As with any master's thesis work, or any design project for that matter, not every aspect can be completely and/or successfully explored. Although certainly far from completely satisfied, I do feel that I met my goal of advancing the exploration of using fractal geometry as an architecturally generative and systemic design device, while experiencing personal growth as an architect along the way. Moving from two-dimensional initiator to three-dimensional as I did proved some aspects, and perhaps opened the potential in other areas for architectural expression through fractal geometry.

Personal

I'd like to close out my thesis exploration and associated document with a simple personal reflection. Regardless of the appropriateness of its place in this academic document, I've earned the right to do so. After beginning work on my graduate degree in 1987 and forced to leave school for financial reasons a year and a half later, returning to finish it now twenty-four years later has been quite an experience to say the least. I don't believe it is possible that a single adjective, both positive *and* negative, could be omitted from describing my experience. Nor was any human emotion left behind along the way. However, the positives certainly outweigh the negatives and this particular journey is now complete. A huge thanks to all who were involved and supportive along the way.

Notes

[1] Most of the computer software applications specifically related to generating fractals that I discovered during the time of my exploration were limited to generating two-dimensional images, rather than three-dimensional forms or models. The few that could generate models required conversion through other software creating a rather complicated working process. I experimented with and considered using the three-dimensional modeling software application Rhino® and the associated and integrated graphical algorithm editor Grasshopper™ to generate forms. Ultimately, given the time constraints, I determined that the learning curve for these various pathways was too steep.

[2] The use of a more sophisticated modeling/design software such as Rhino® rather than the chosen SketchUp may have allowed for improved compatibility between design and analysis software.