Fractals as basis for design and critique

In partial fulfillment of Doctor of Philosophy

JOHN DRISCOLL
STUDIO johncdriscoll.com

Dissertation Committee

Wayne Wakeland, chair
Systems Science, Portland State University

Joe Fusion
Systems Science, Portland State University

Annemarie Jacques
School of Architecture, Portland State University

John Jacques
Professor Emeritus Clemson University

Antonie Jetter, Graduate Office representative
Engineering and Technology Management, Portland State University

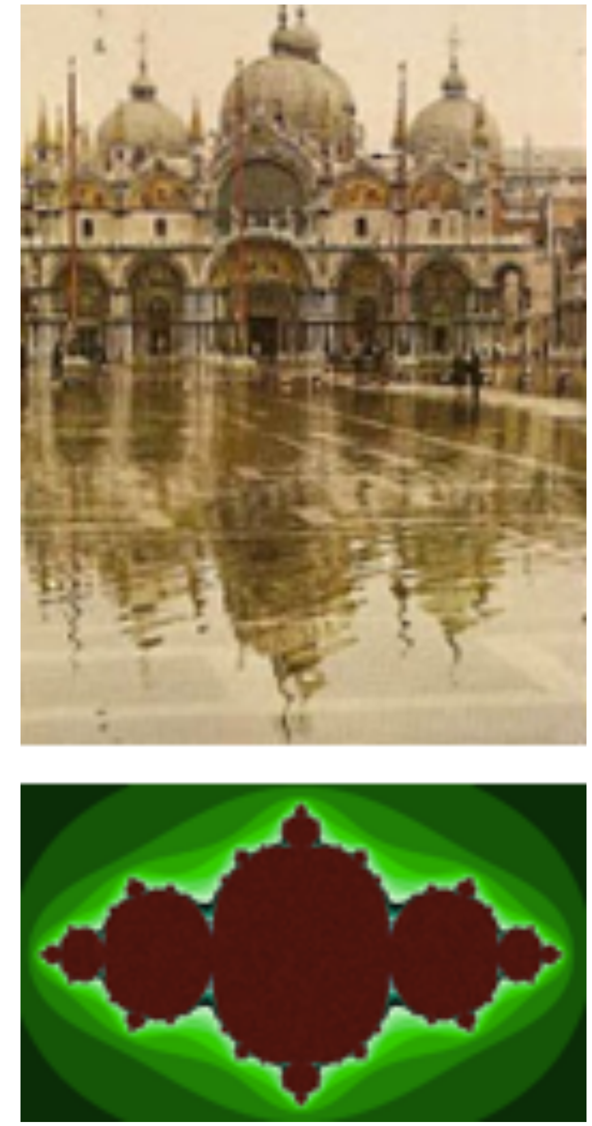


FIG 1. Above: San Marcos Church in Venice reflected. Below: San Marcos Julia fractal, J(-3/4, 0).

CONTENTS (paper)

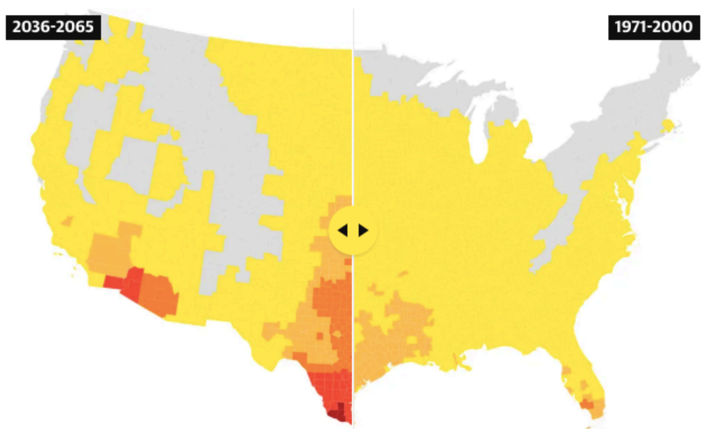
CONTENTS (slides)

MOTIVATION

"Why have cities not, long since, been identified, understood and treated as problems of organized complexity?
(Jacobs, 1961)

Climate crisis: extremely hot days could double in US, study shows

Amid widespread US heatwave, experts predict dangerous extremes in summer temperatures will only get worse

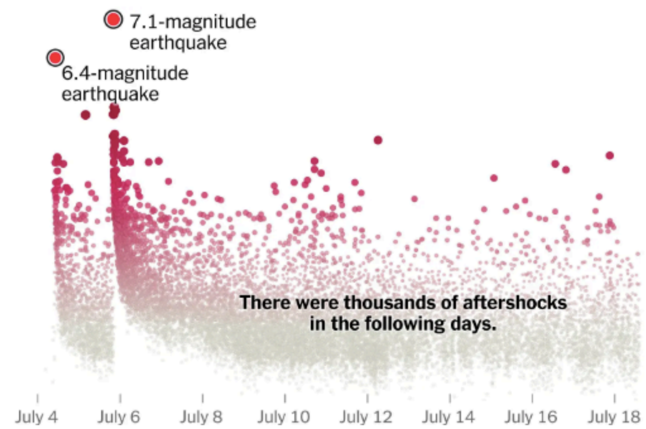


Without further action to reduce global heat-trapping pollution, parts of Florida and Texas could feel like 100F or hotter for over four months out of the year.

How Two Big Earthquakes Triggered 16,000 More in Southern California

- Two powerful earthquakes this month were part of a swarm of thousands of others that continue to hit the area every few minutes.
- Each aftershock has a tiny chance of being severe, leaving scientists concerned that the activity could trigger strong earthquakes in nearby faults.

1h ago



Heat Waves in the Age of Climate Change: Longer and Deadlier

- Two-thirds of the United States is expected to bake under what could be record high temperatures heading into the weekend.
- The average number of heat waves in 50 major American cities has tripled since the 1960s.

1h ago

Raquel Morales in the Bronx on Thursday. Temperatures in the city are forecasted to reach 100 degrees over the weekend. Desiree Rios for The New York Times

Dr. Feigenbaum beside a waterfall near the Cornell campus in upstate New York in 1984. He applied his expertise in mathematical physics to other areas as well, like mapmaking. Diego Goldberg

In 1979, a French scientist, Albert J. Libchaber, observed the same cascade of period doublings in the temperature fluctuations in the center of a convecting fluid. Dr. Feigenbaum's theory of the transition from order to chaos now described phenomena in the real world.

- 51% of the world population is living in urban areas and this comprises only 3% of the world's surface (World Population Data Sheet, 2012).
- Buildings alone account for 39% of CO_2 emissions in the United States. This is larger than any other sector (U.S. Green Building Council, 2019).
- Some research into the science of cities has shown that densely populated urban environments are generally more efficient the larger they become (West, 2017, Bettencourt, 2013).

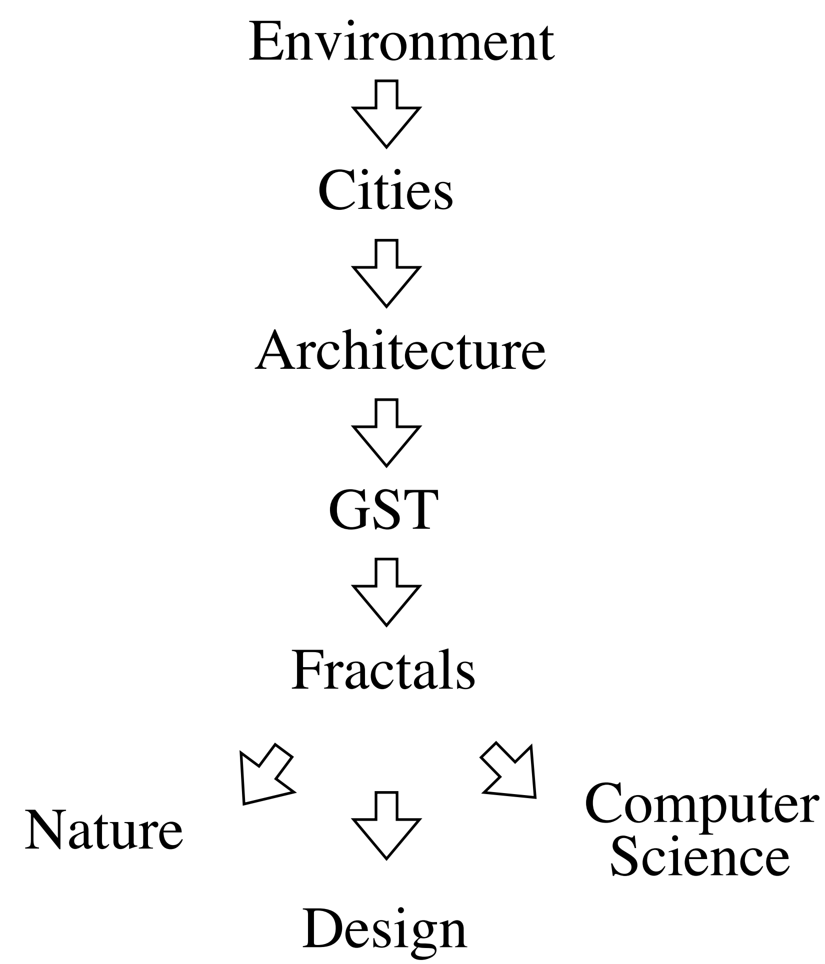
INTRODUCTION

- The design industry is responding to the complex systems represented by architecture and urban planning by increasingly incorporating the power of computer technology into the design process.

- This is a **paradigm shift**, and requires that designers rise to the challenge of both embracing modern technologies to perform increasingly sophisticated tasks without compromising their objective to create **meaningful architecture**.

- We present an algorithmic design process that incorporates **fractal theory** and methods.

- Fractals are a bridge between nature, design and computer science.



RESEARCH QUESTIONS

General motivation

- Can fractal theory and methods be used to create more efficient buildings and cities?
- Can fractal theory and methods reach across diverse domains such as architecture, the natural environment and computer science?
- Can these domains be integrated towards a more wholistic/holistic design process?

Questions addressed by this dissertation

- How might a designer from an architecture perspective internalize computer based tools towards a more integrated approach?
- Can fractal dimension (FD) be used to generate novel design solutions to complex architectural problems?
- Might fractal theory be re-framed as a critical method for analyzing architecture in more significant ways then how it is currently being used?

Generative and algorithmic design in architecture:

Emergence:

Hemberg, Martin, et al. "Genr8: Architects' experience with an emergent design tool." *The Art of Artificial Evolution*. Springer, Berlin, Heidelberg, (2008). 167-188.

Weinstock, Michael. "The architecture of emergence: the evolution of form in nature and civilization." (2010).

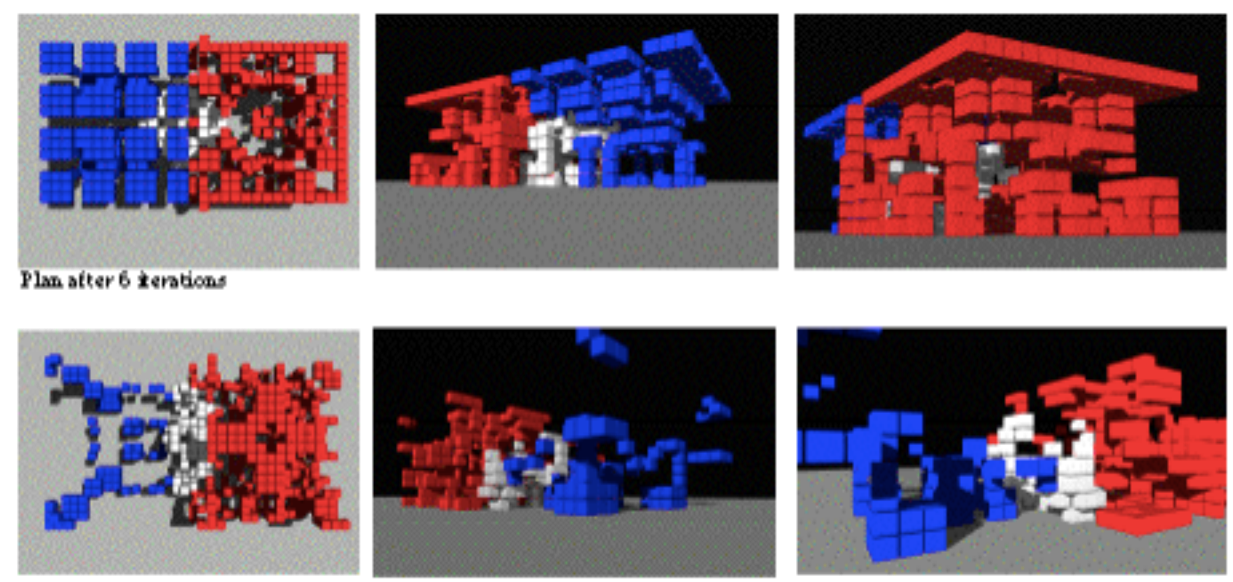
Agent based models (swarm intelligence):

Batty, Michael. "Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals." *The MIT press*, (2007).

Cellular automata

Coates, Paul, et al. "The use of Cellular Automata to explore bottom up architectonic rules." (1996).

Herr, Christiane M., and Thomas Kvan. "Using cellular automata to generate high-density building form." *Computer aided architectural design futures 2005*. Springer, Dordrecht, 2005. 249-258.



Plan after 8 iterations

FIG 3.

Genetic algorithms:

Coates, Paul, and Dimities elaelaborated. "Genetic programming and spatial morphogenesis." (1999).

Fractals: next slide.

BACKGROUND

Analysis incorporating fractal theory

Kiani, Zohreh, and Peyman Amiriparyan. "The Structural and Spatial Analyzing of Fractal Geometry in Organizing of Iranian Traditional Architecture." *Procedia-Social and Behavioral Sciences* 216 (2016): 766-777.

Ediz, Özgür, and Michael J. Ostwald. "The Süleymaniye Mosque: a computational fractal analysis of visual complexity and layering in Sinan's masterwork." *Arq: Architectural Research Quarterly* 16.2 (2012): 171-182.

Encarnação, Sara, et al. "Fractal cartography of urban areas." *Scientific reports* 2 (2012): 527.

Joye, Yannick., "A review of the presence and use of fractal geometry in architectural design." *Environment and Planning B: Planning and Design* 38.5 (2011).

Ostwald, Michael J., and Josephine Vaughan. "Determining the fractal dimension of the architecture of Eileen Gray." *ANZAScA 2008* (2008): 9-16.

Bovill, Carl, "Fractal geometry in architecture and design." Springer (1996).

Batty, M. & Longley, 'Fractal cities: a geometry of form and function' Academic Press, (1994).

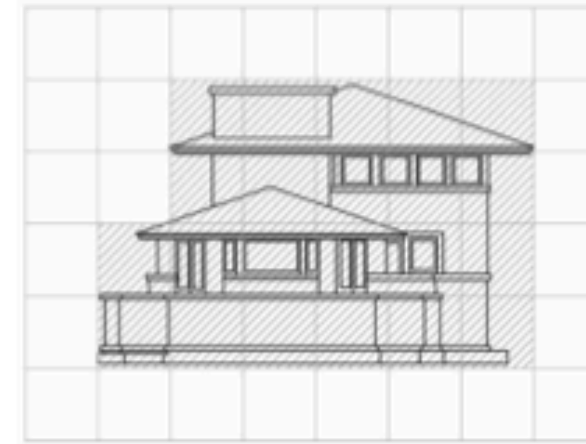


Fig. 1. Starting grid placed over the east elevation of the Tomek house showing box-counting

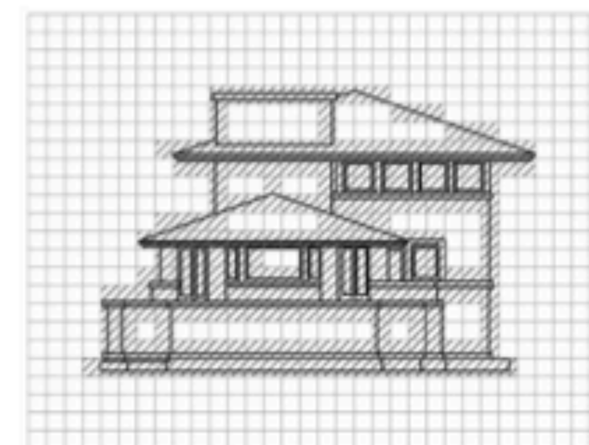


Fig. 2. Third stage grid placed over the east elevation of the Tomek house showing box-counting

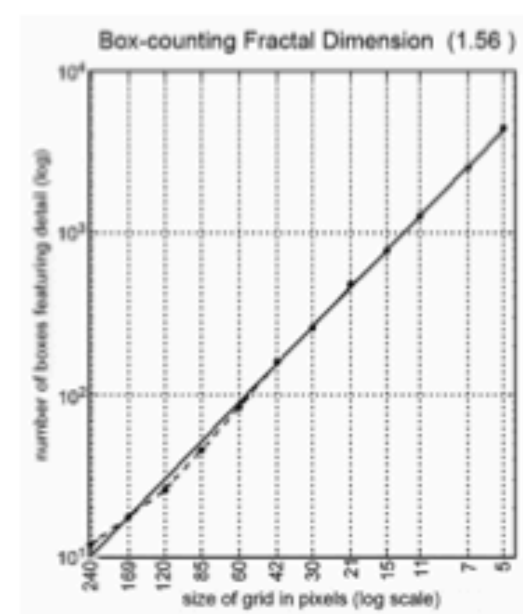


Fig. 3. Log-log diagram of the comparison between the number of boxes counted in a grid

FIG 4.

BACKGROUND

Fractal algorithms: Knowledge on which this work is building.

Rian, Iasef Md, Mario Sassone, and Shuichi Asayama. "From fractal geometry to architecture: Designing a grid-shell-like structure using the Takagi–Landsberg surface." *Computer-Aided Design* 98 (2018): 40-53.

Rian, Iasef Md, and Shuichi Asayama. "Computational Design of a nature-inspired architectural structure using the concepts of self-similar and random fractals." Automation in Construction (2016).

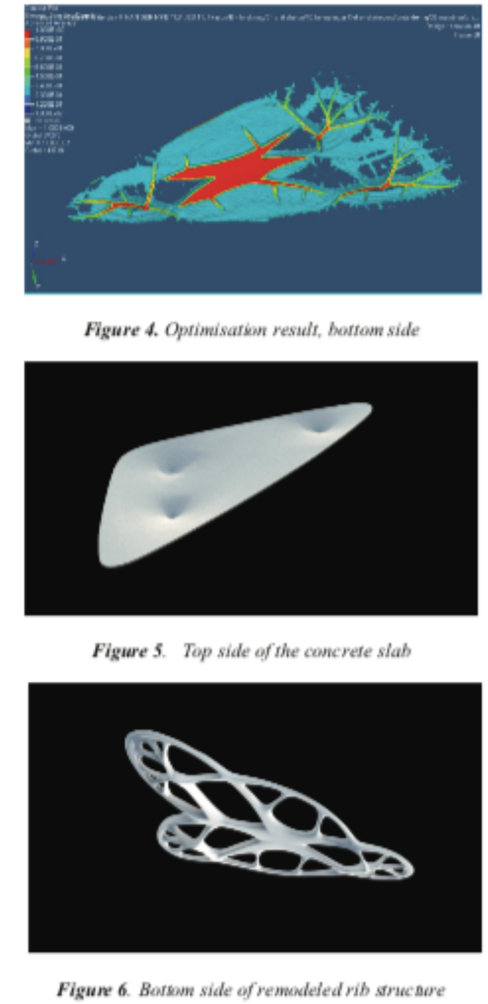


FIG 5.1.

Dombernowsky, Per, and Asbjørn Søndergaard. "Design, analysis and realization of topology optimized concrete structures." Journal of the International Association for Shell and Spatial Structures 53.4 (2012): 209-216.

Gürbüz, Esra, Gülen **Çağdaş**, and Sema Alaçam. "A Generative Design Model for Gaziantep’s Traditional Pattern." *Proceedings of the 28th Conference on Education of Computer Aided Architectural Design in Europe*. (2010).

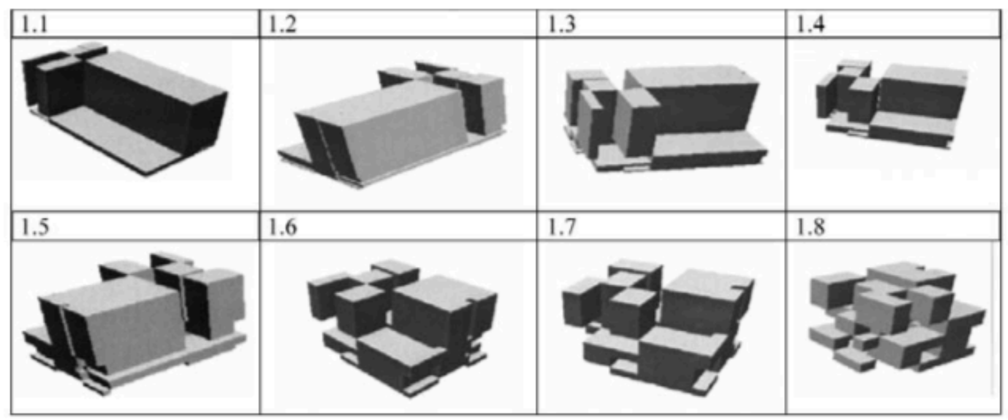


Table 3. Block design based on fractal dimension

FIG 5.2.

Ediz, Özgür, and Gülen Çağdaş. "A COMPUTATIONAL ARCHITECTURAL DESIGN MODEL BASED ON FRACTALS." *open house international* 32.2 (2007).

Fractals and genetic algorithms

Coates, Paul, Terence Broughton, and Helen Jackson. "Exploring three-dimensional design worlds using lindenmayer systems and genetic programming." *Evolutionary design by computers* (1999): 323-341.

FIG 6.

BACKGROUND

Fractals in historic architecture:

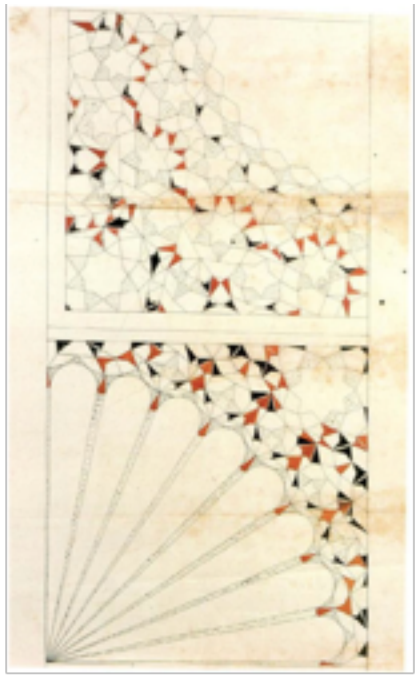


Fig. 2.3.1.4 15th century Topkapi Scroll showing a quarter section of a dome in plan that is further subdivided into miniature muqarnas (Wikipedia Commons).

Fig. 2.3.1.5. Detail of Red Mosque in Safed, Israel, 1276. (Wikipedia Commons).

Fig. 2.3.1.2. Kandariya Mahadev Temple, Madhya Pradesh – Photograph by RM Nunes. (https://www.dataisnature.com/?p=2138).

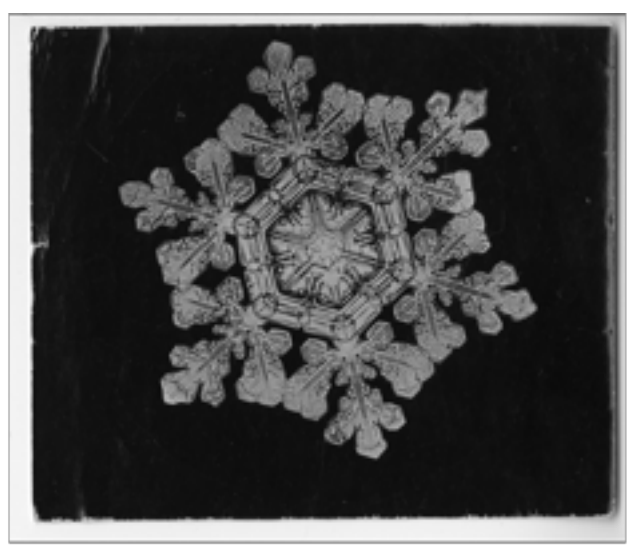


Fig. 2.3.1.3. A "Dendrite Star" photomicrographed by Bentley, W., Smithsonian Institute, (1890).

FIG 7.

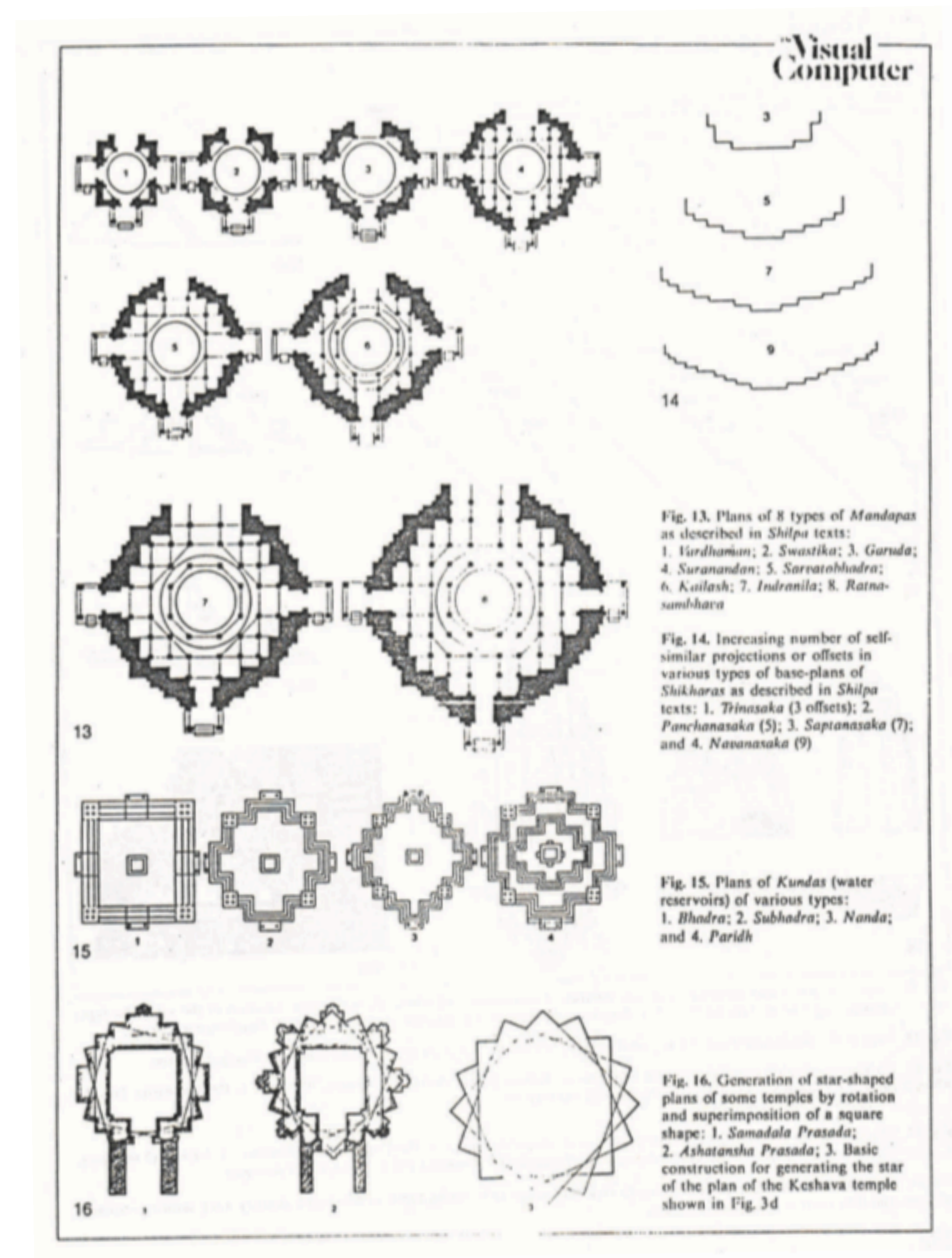


FIG 8.

IDEA

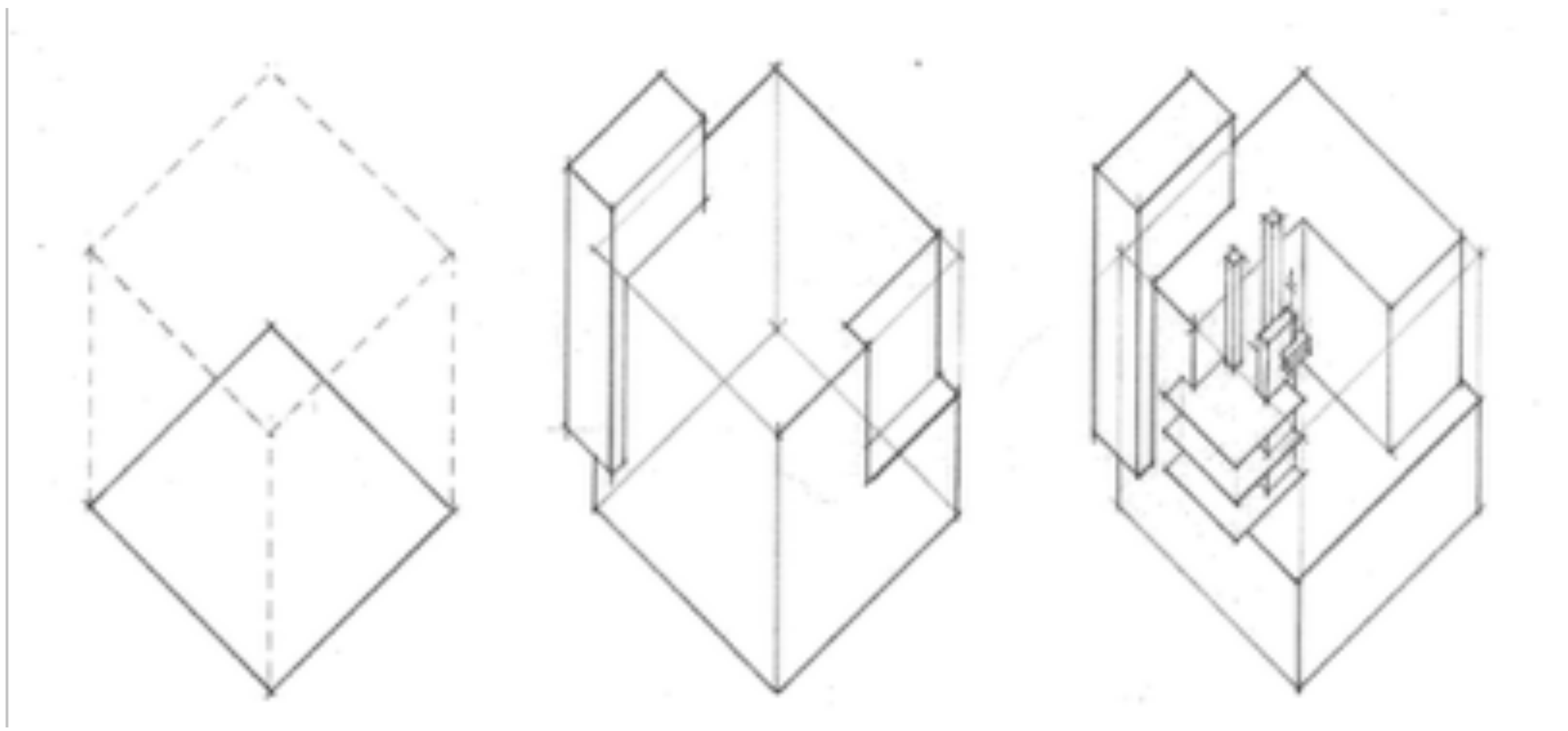
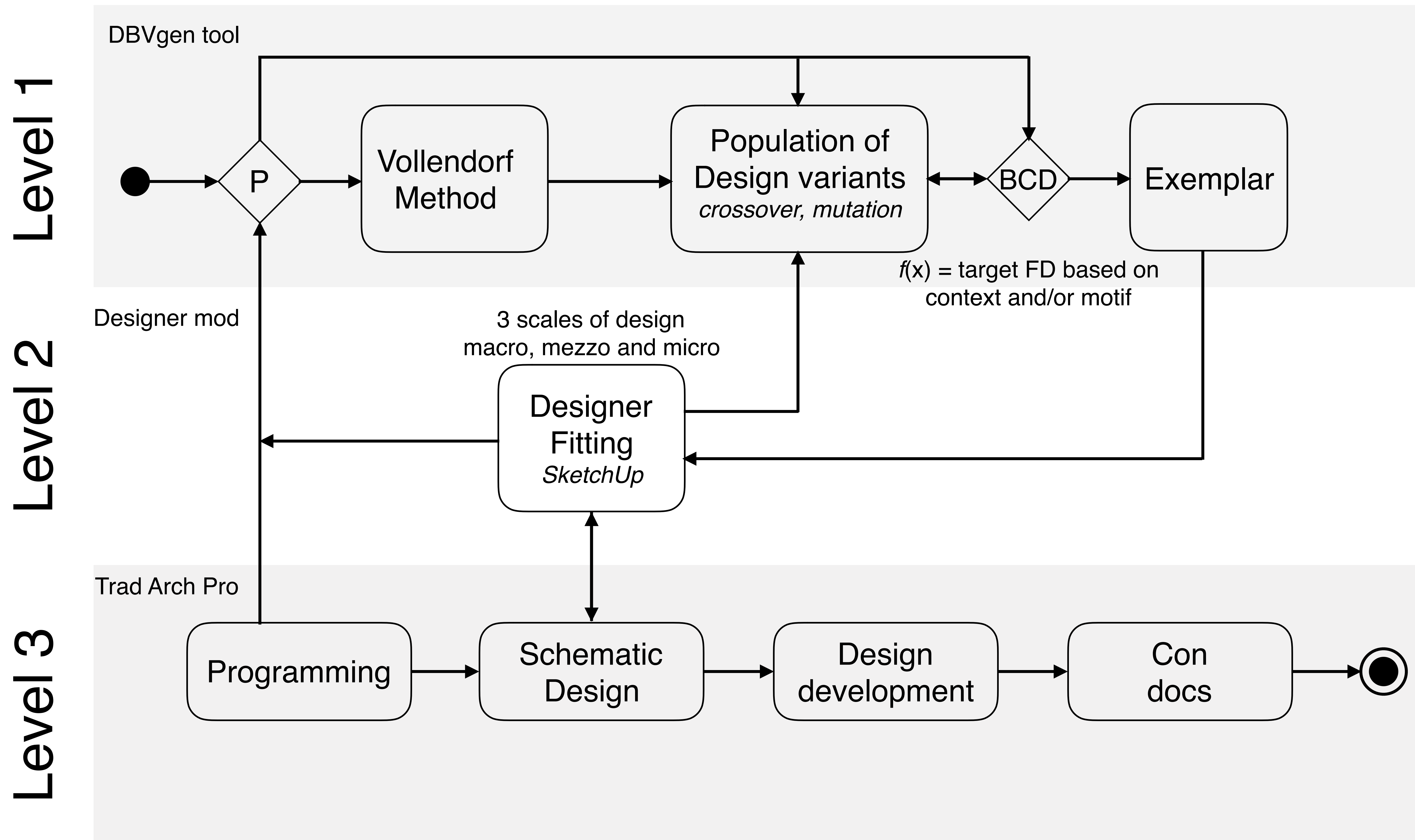


FIG 9.

DESIGN PROCESS DIAGRAM



Key		
start	transition	End
program design parameters	Box-counting dim.	Phase

Vollendorf Method / rules for generating compositions.

- With one line create a design, the line must be parallel to the edge in one direction, and go from edge to edge in the other.
- A second line is added parallel to the opposite edge.
- A third line is introduced that goes from line to edge.
- More lines are added either horizontal or vertical going from edge to edge or stopping at another line.

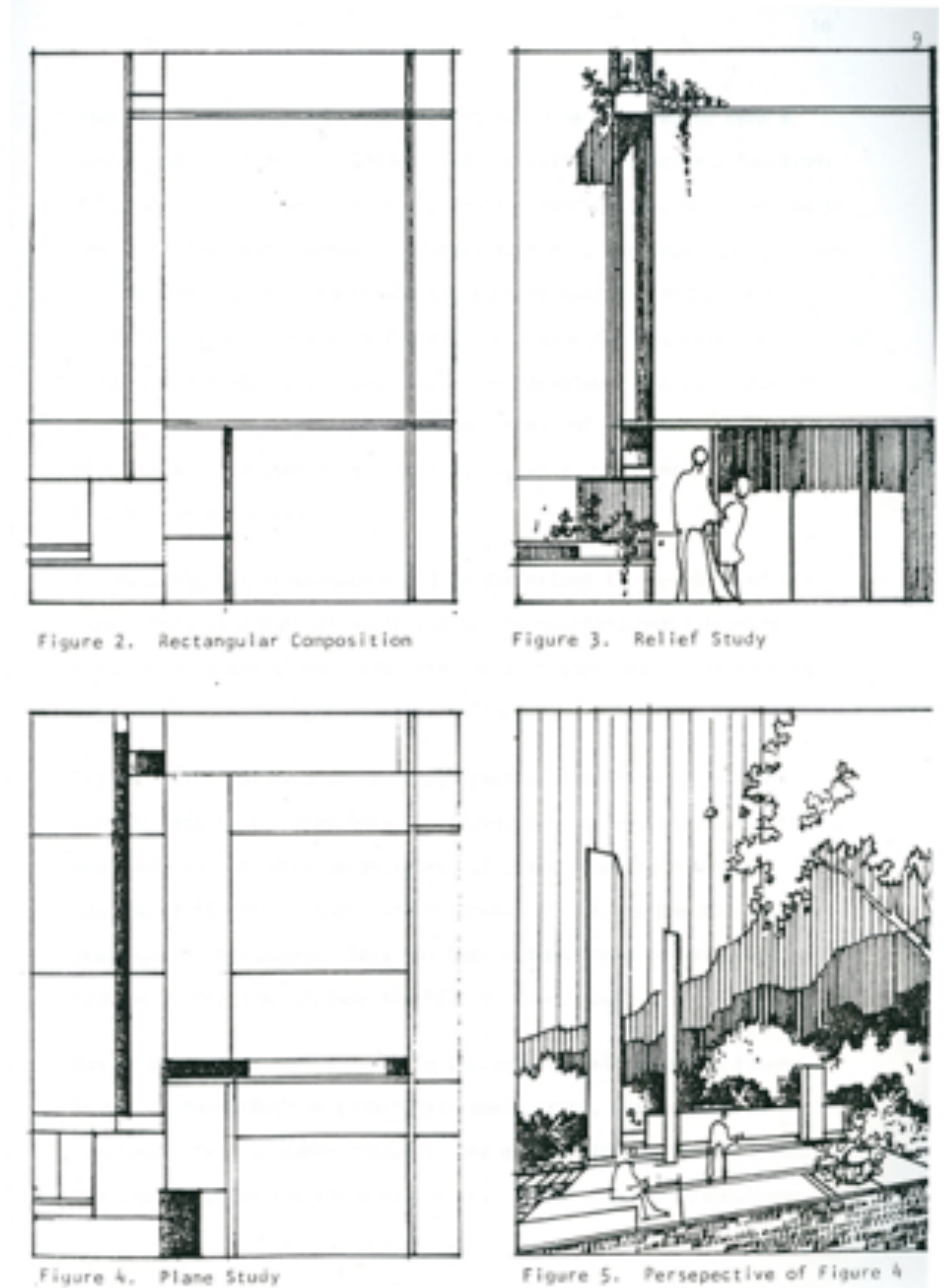


Fig. 15. Diagram from DBV's thesis representing the 3 lines on a page exercise (Vollendorf, 1975) (used by permission).

Genetic algorithm (GA)

A genetic algorithm was used to search for compositions closest to a target FD.

1. Fitness $f(x)$ = target FD using BCD
2. tournament selection (with replacement) to determine parents
3. 2 parent cross-over (recombination) as well as cloning of elites
4. random mutation
5. add to population, go to step 2

METHOD

Fractal dimension (FD) and Box-counting dimension (BCD)

- Fractal dimension is used to analyze the multi-scale self-similarity of buildings. We use a box-counting algorithm to determine the FD.

$$D_0 = \lim_{\epsilon \to 0} \frac{\log N(\epsilon)}{\log \frac{1}{\epsilon}}$$

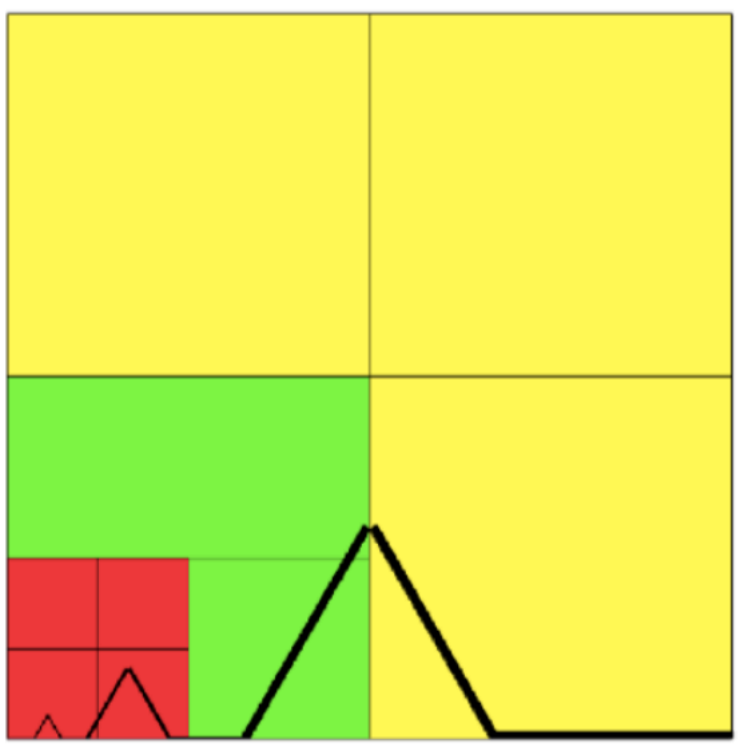


FIG 16. Partially iterated Koch curve and BCD conceptual diagram.

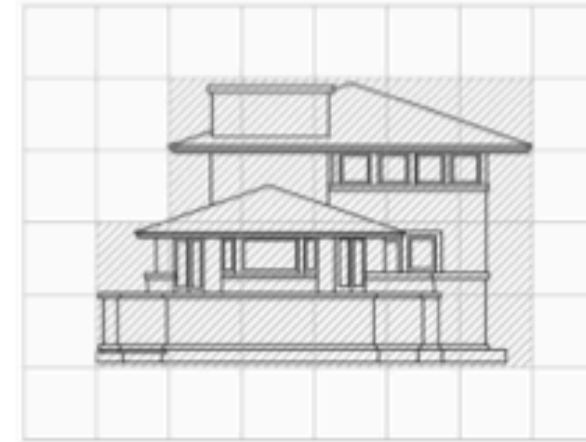


Fig. 1. Starting grid placed over the east elevation of the Tomek house showing box-counting

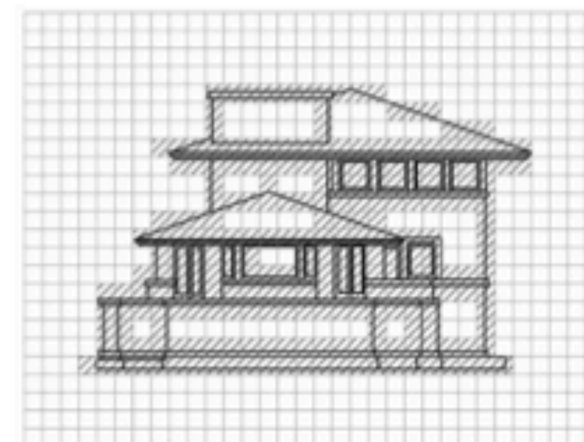


Fig. 2. Third stage grid placed over the east elevation of the Tomek house showing box-counting

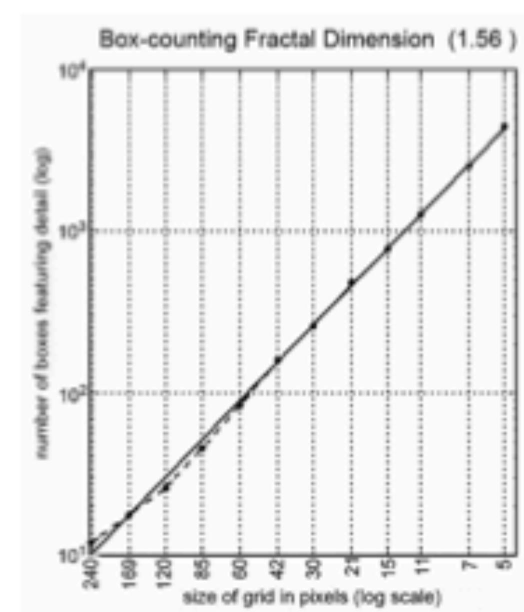


Fig. 3. Log-log diagram of the comparison between the number of boxes counted in a grid

FIG 17. Fractal analysis of FLLW's Tomek House (Otswald, Vaughn, 2008).

Juried critique:

- **Jurors**: 9 professional architects. Various backgrounds

- non-local and asynchronous

- **Presentations**: 2 juried pin-ups and 1 final

    Dropbox (background material)

    Drawings, algorithm outputs

    written description of process and project

    website: johncdriscoll.com

    videos

FIG 18.

- **Feedback**: response to questionnaire and interview style dialogue

    email

    phone conversation (1 juror)

    in-person interview (2 jurors)

PIN-UP #1

Parameters –> design variants –> FD –> exemplar

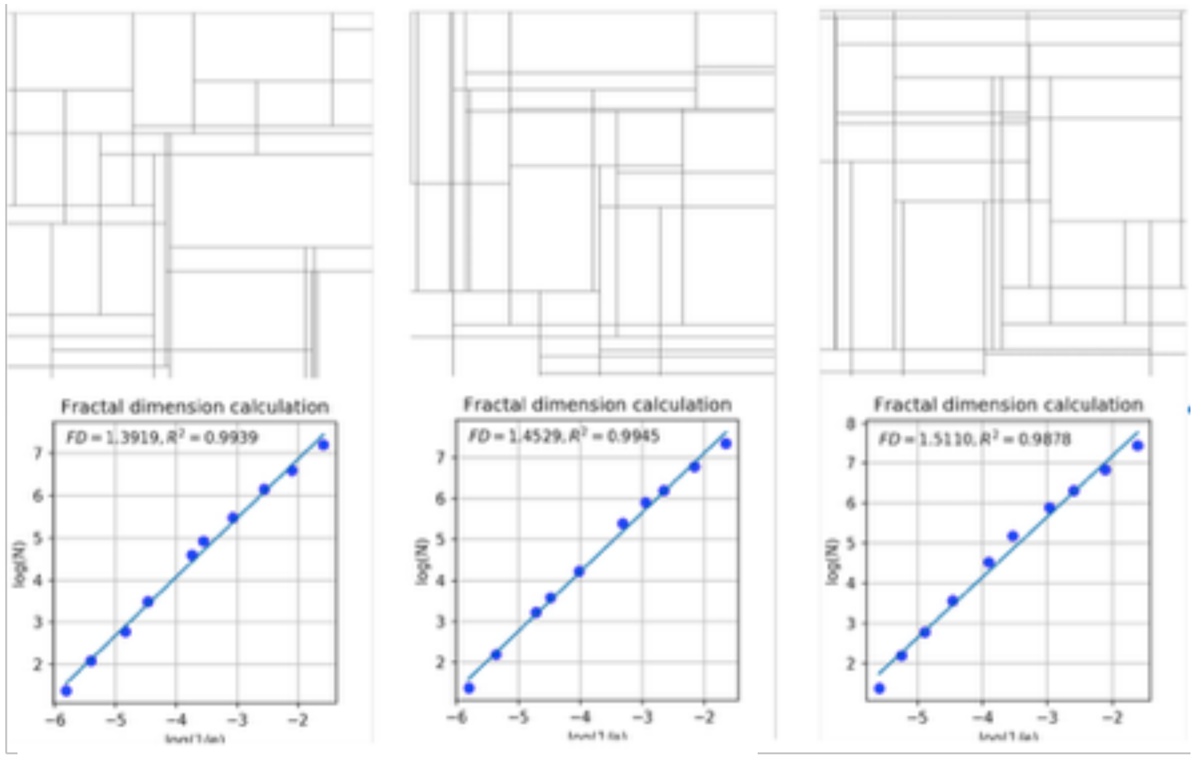


FIG 19. 2D compositions and BCD.

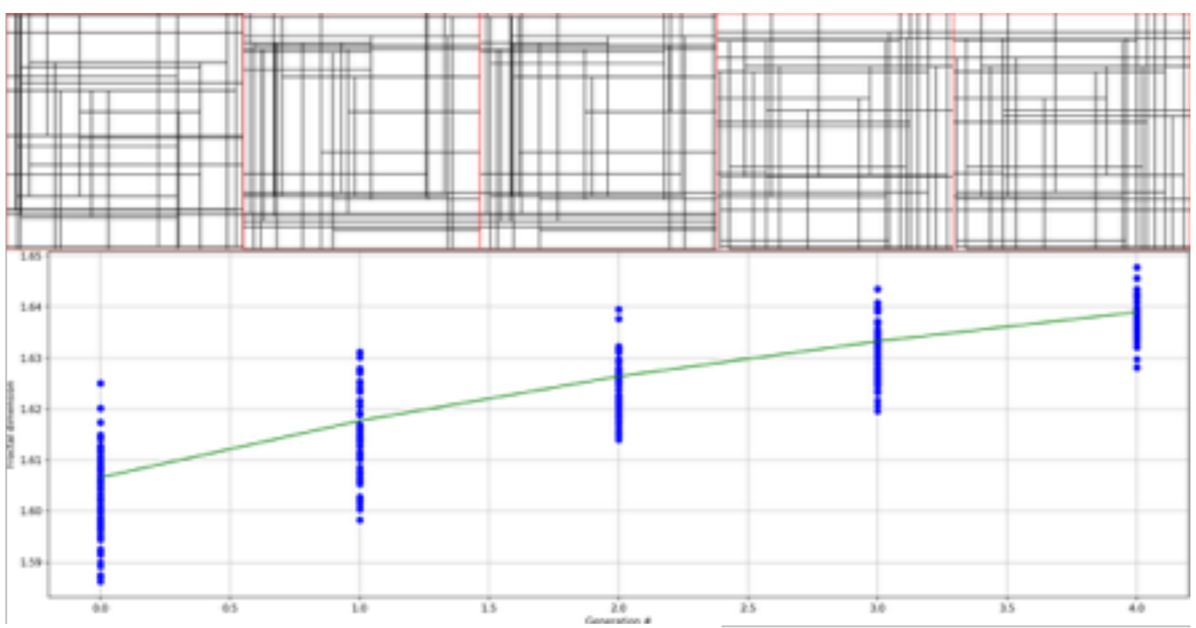


FIG 20. 2D compositions timeline.

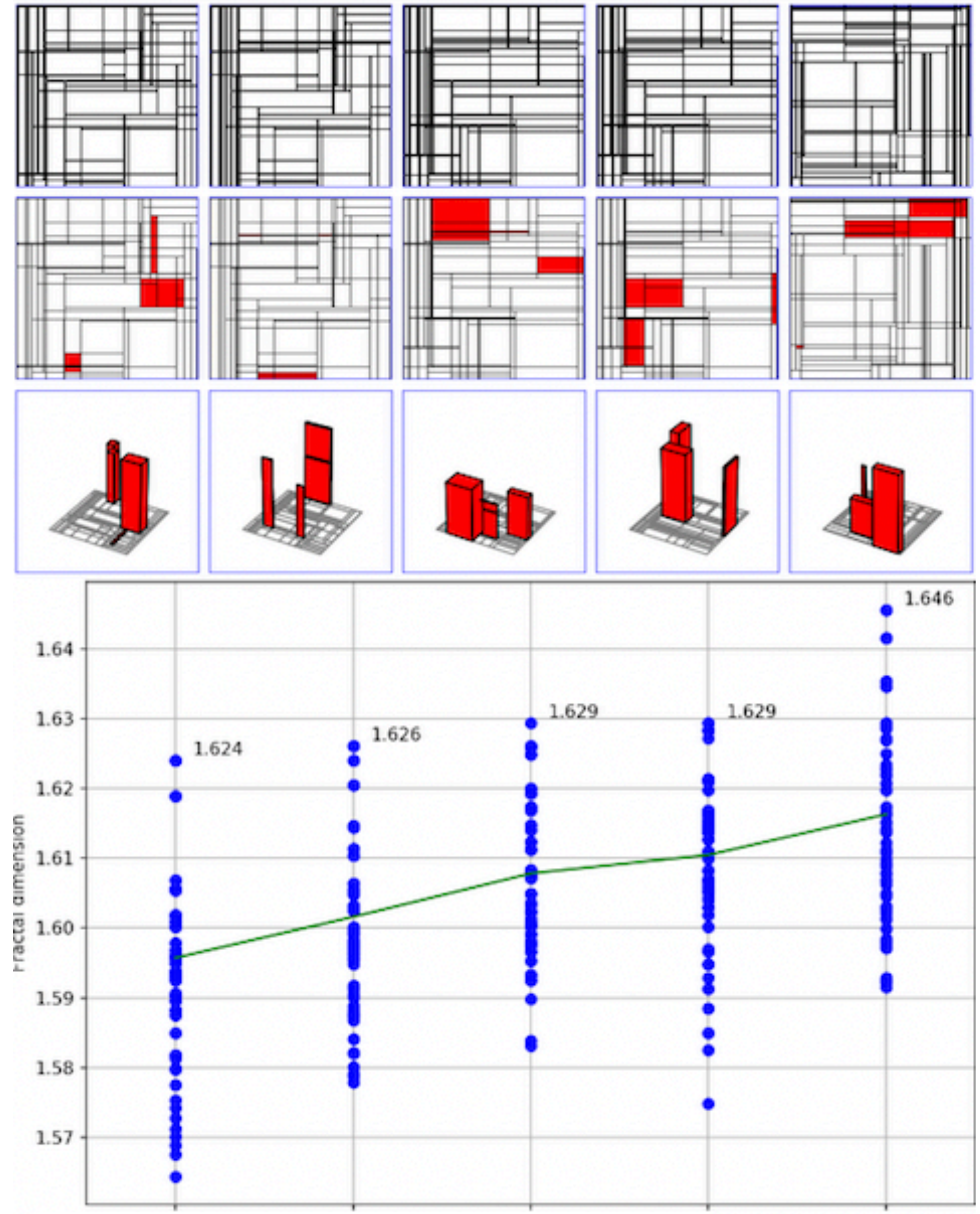


FIG 21. 2D & 3D compositions timeline.

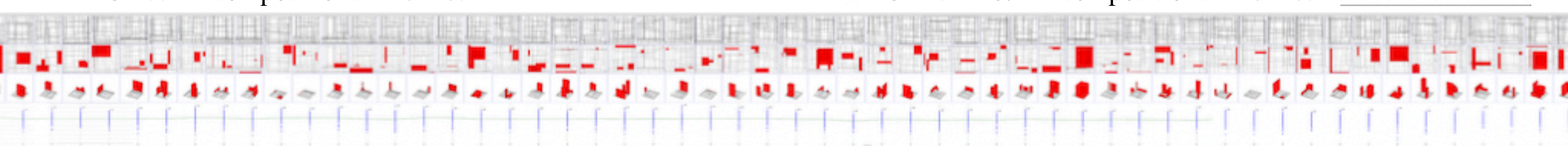


FIG 22. 2D & 3D compositions timeline.

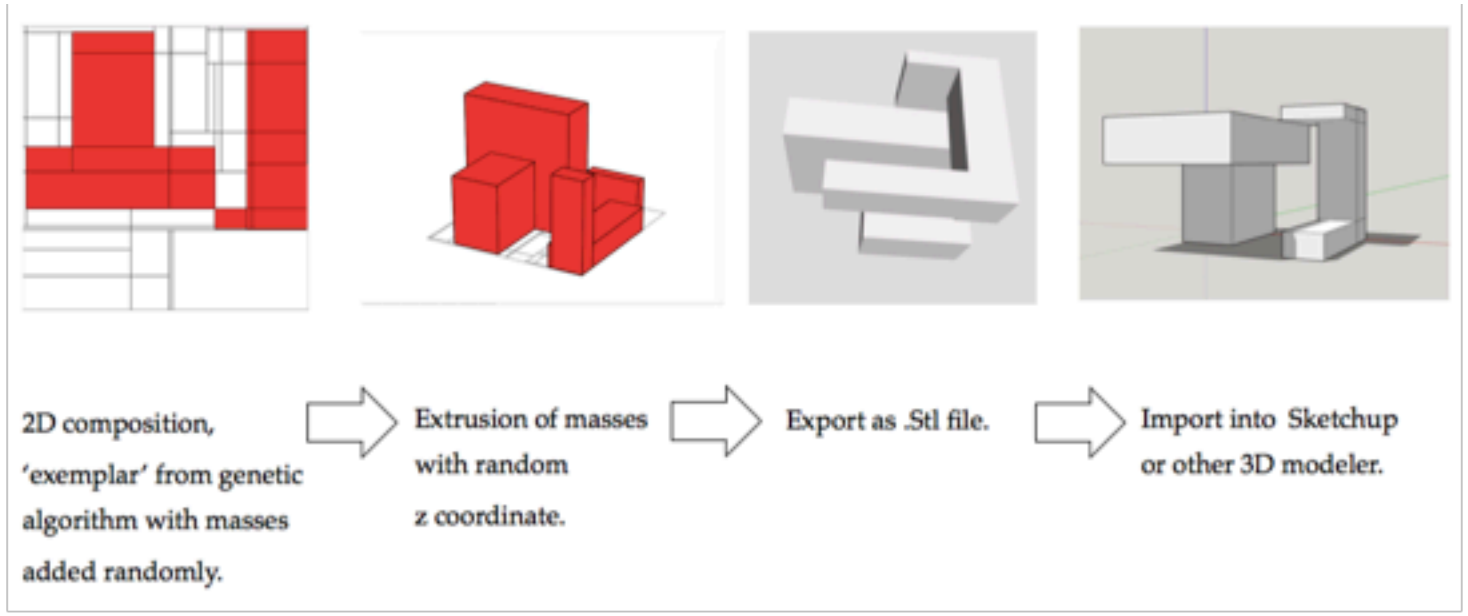


FIG 23. Progression of outputs to modeling environment.

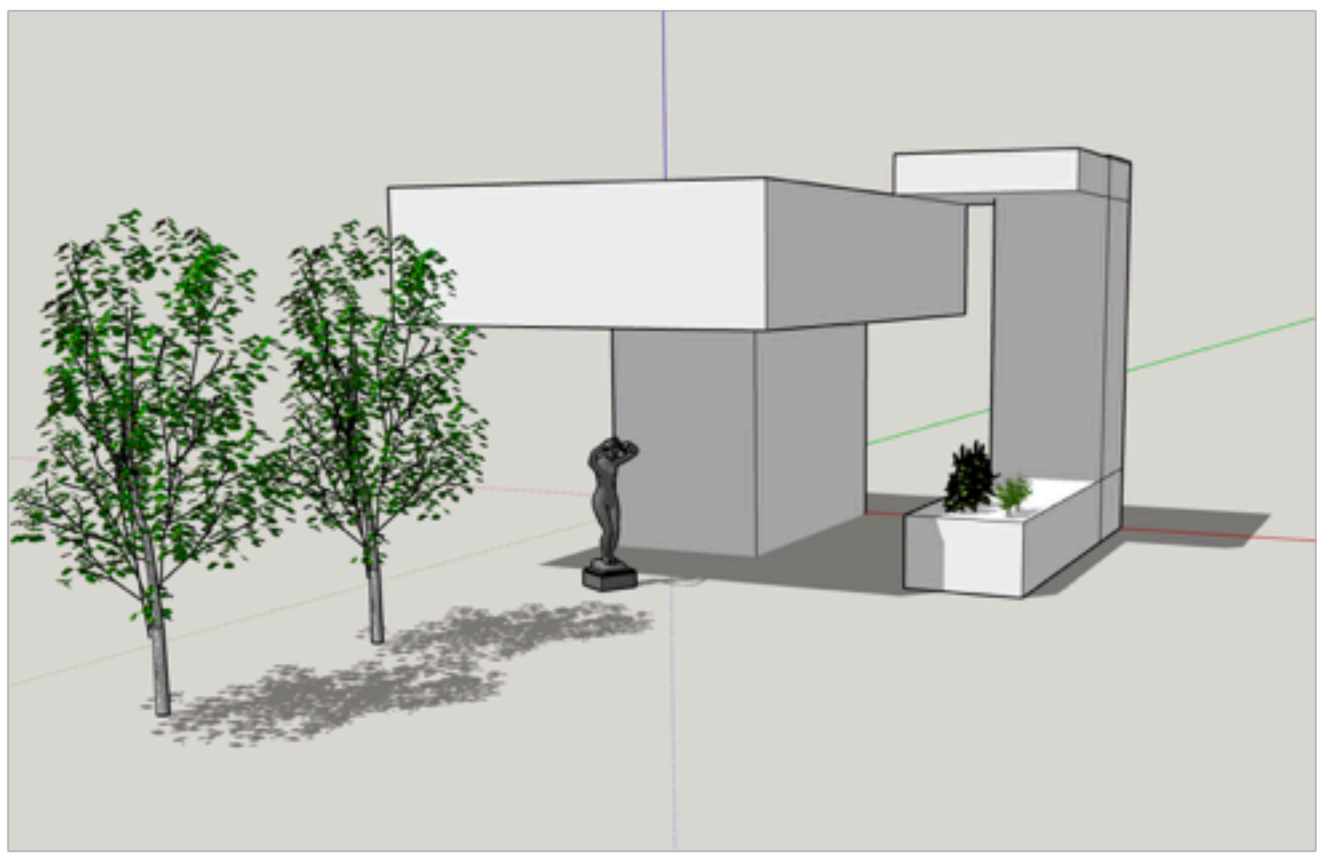
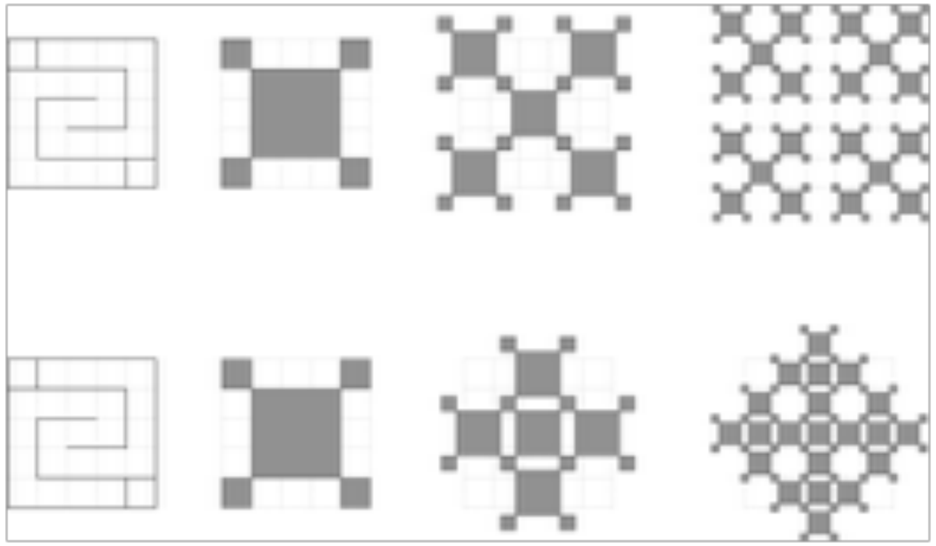


FIG 24. Pavilion project as proof of concept.

PRECEDENT ANALYSIS

Fractals as critical tool in the work of FLLW



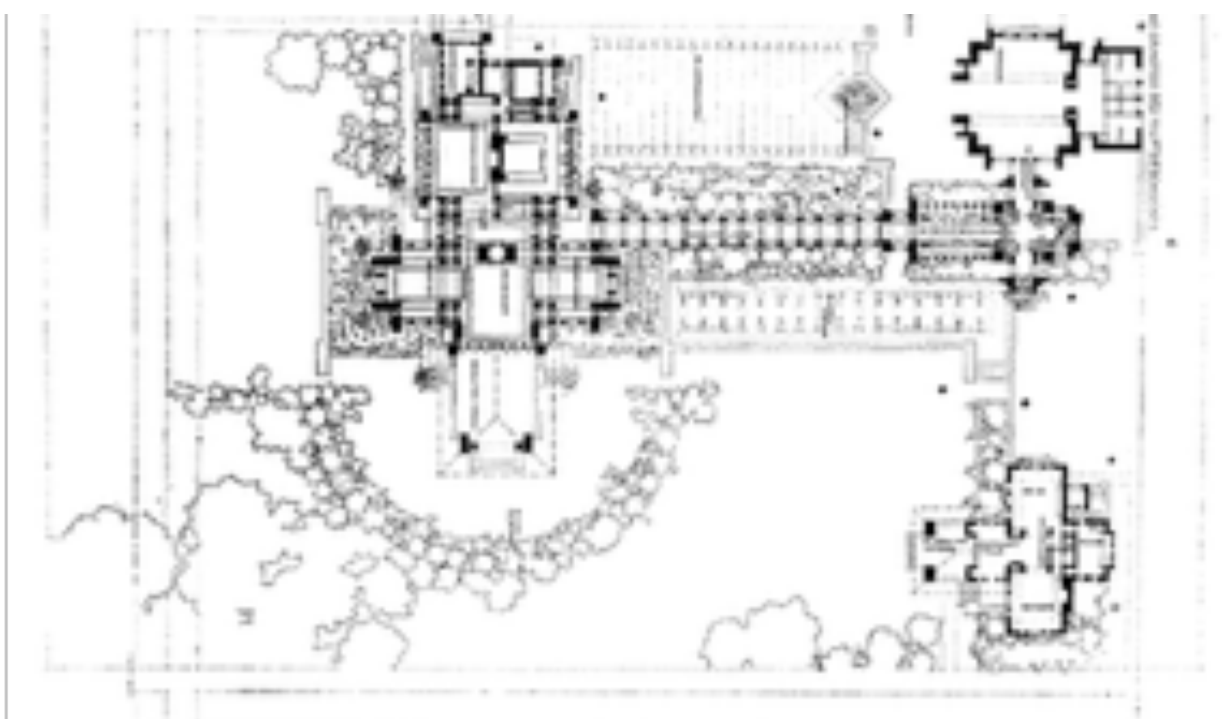


FIG 25. Hypothetical fractal algorithms in FLLW's Martin House.

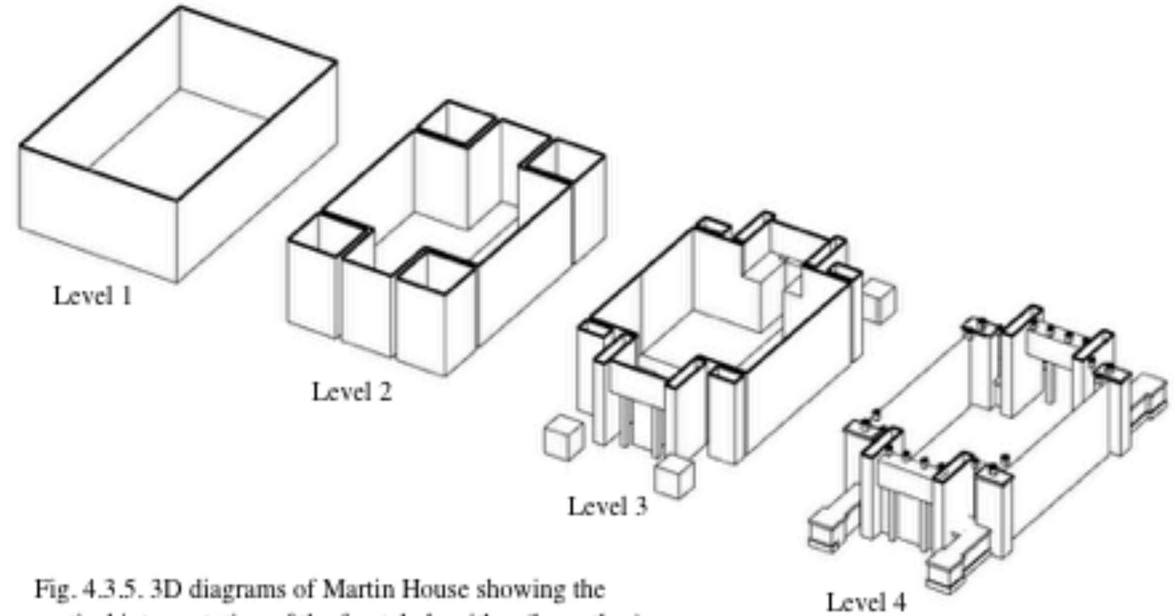


Fig. 4.3.5. 3D diagrams of Martin House showing the vertical interpretation of the fractal algorithm (by author).

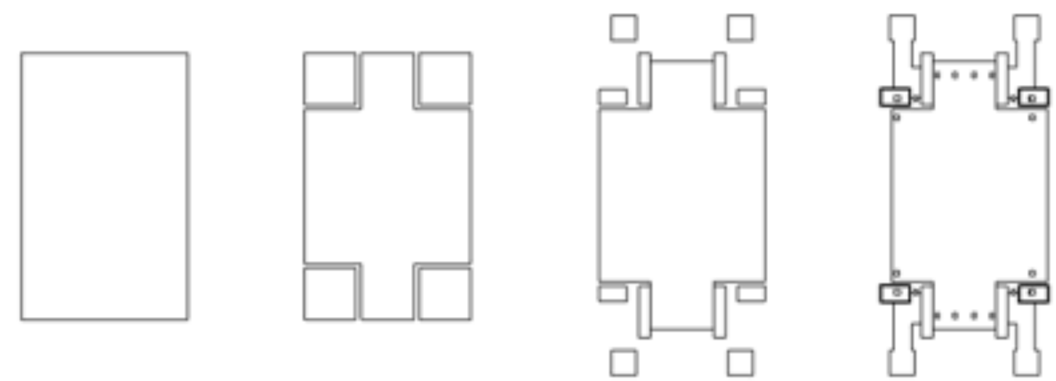


Fig. 4.3.6. 2D interpretation of Martin house as a simple iterative idea (by author).

FIG 26. Hypothetical fractal algorithms in FLLW's Martin House.

PRECEDENT ANALYSIS

Dean Bryant Vollendorf: Search to Saguaro

Fig. 4.4.3. Exterior perspective view of Saguaro. Dean Bryant Vollendorf architect, 1995.

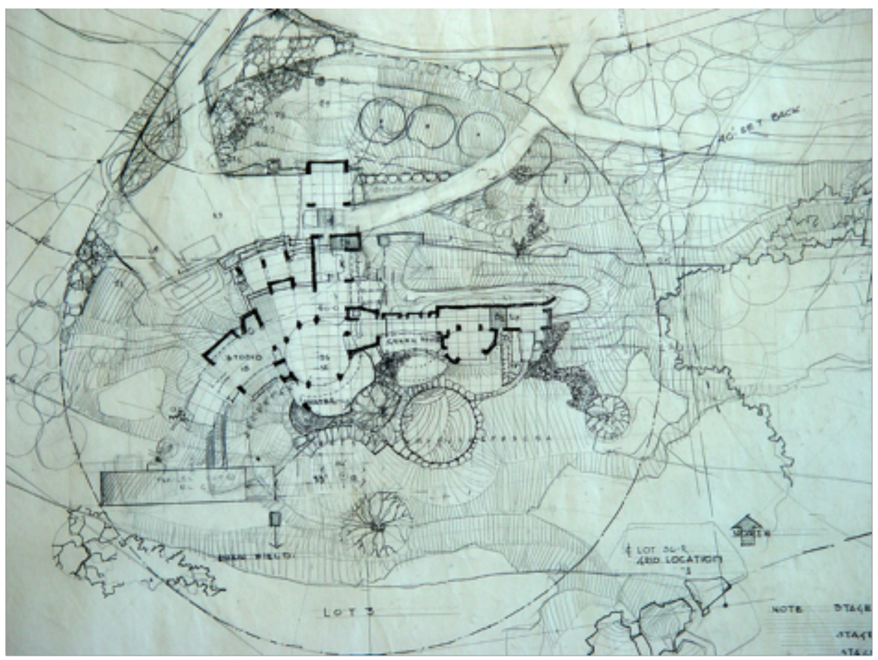


Fig. 4.4.1. Plan view of Search. Dean Bryant Vollendorf architect, 1976.

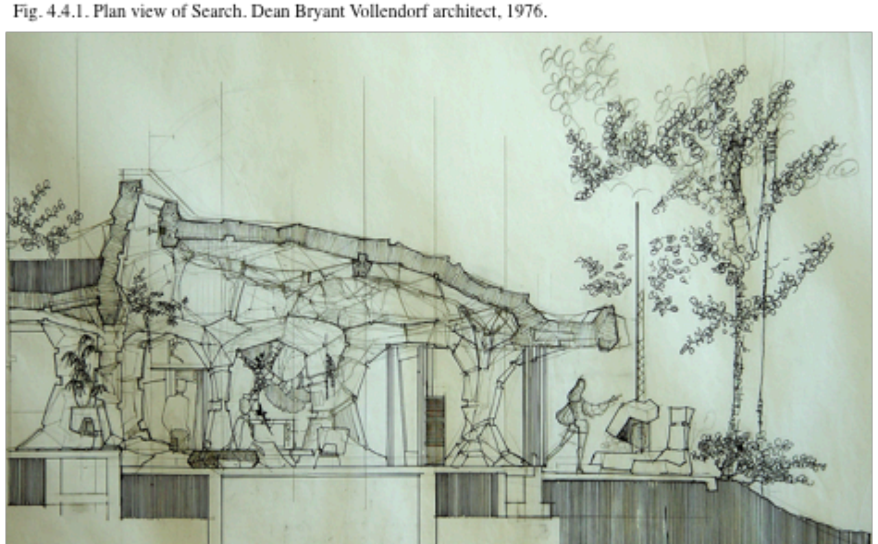


FIG 27. Dean Bryant Vollendorf, Saguaro above and Search below.

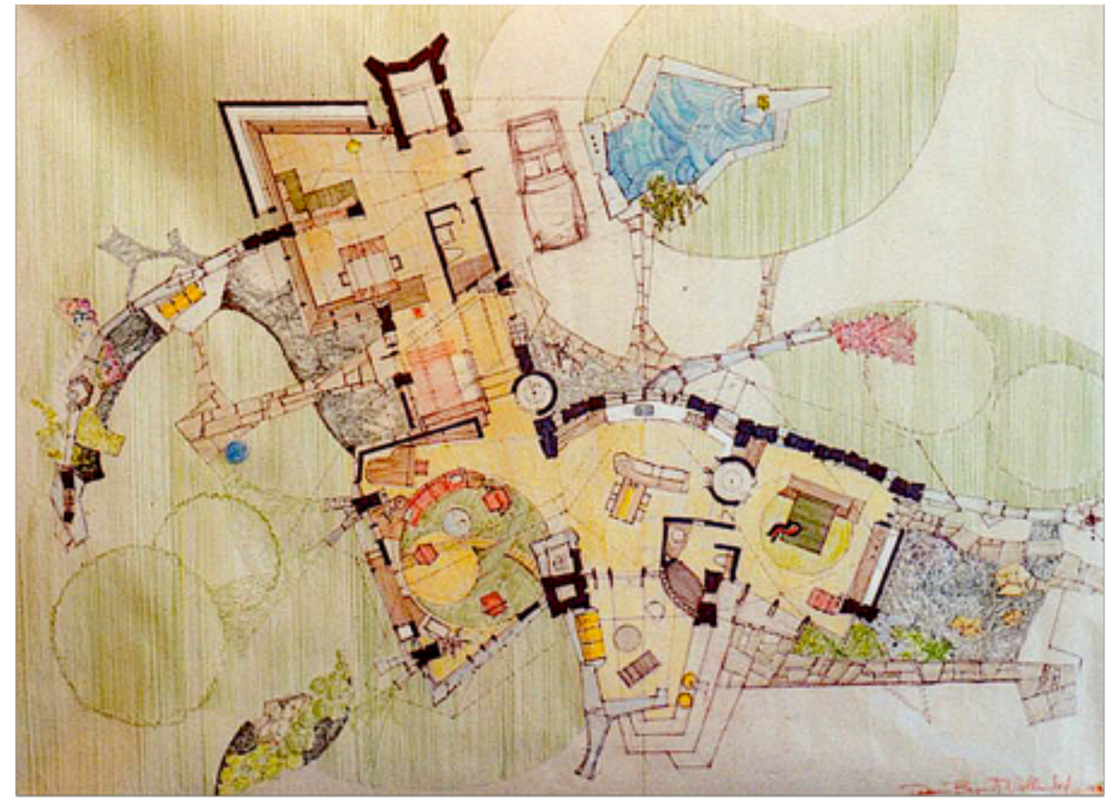


Figure 4.4.4. Saguaro plan view. Dean Bryant Vollendorf architect, 1995.

FIG 28. Dean Bryant Vollendorf, Saguaro.

PIN-UP #2

MICRO, MEZZO, MACRO

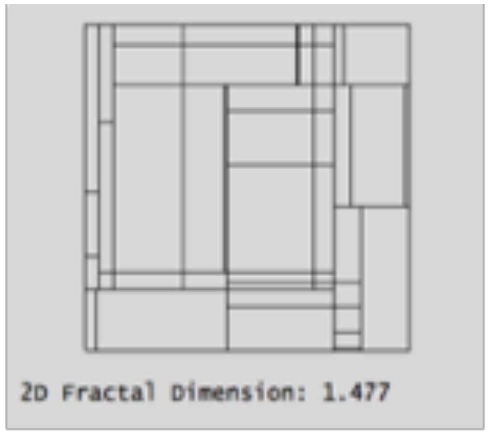


FIG 29. Selected initial composition.

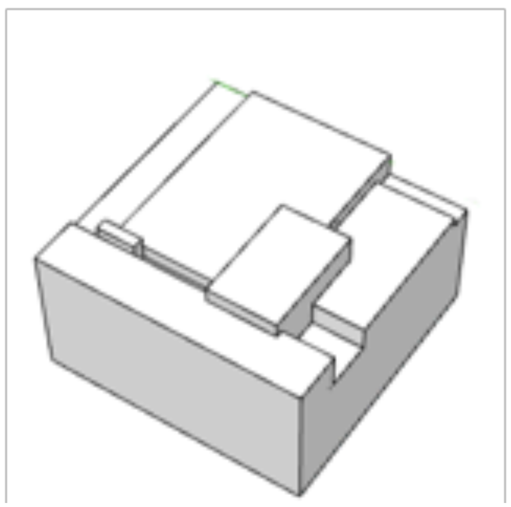


FIG 30. Extruding and fitting by designer used as motif for project.

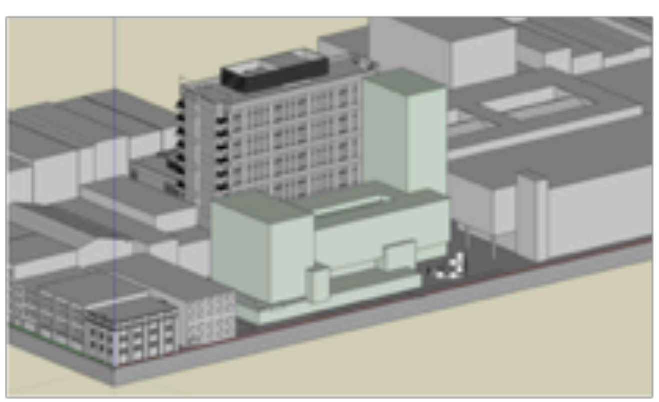


FIG 31. Massing model as iteration of motif.

FIG 32. 3D prints of
Top: Micro.
Middle: Mezzo
Bottom: Macro

- **Micro, Unit block:** This could be a masonry unit. Potentially each block could be different.
- **Mezzo, architectonic level:** Combination of elements to create space, rooms. outdoor gathering space.
- **Macro, parti:** The fractal attribute should be more than surface treatment but part of the space plan of the general layout.

PIN-UP #2

M I C R O

PIN-UP #2

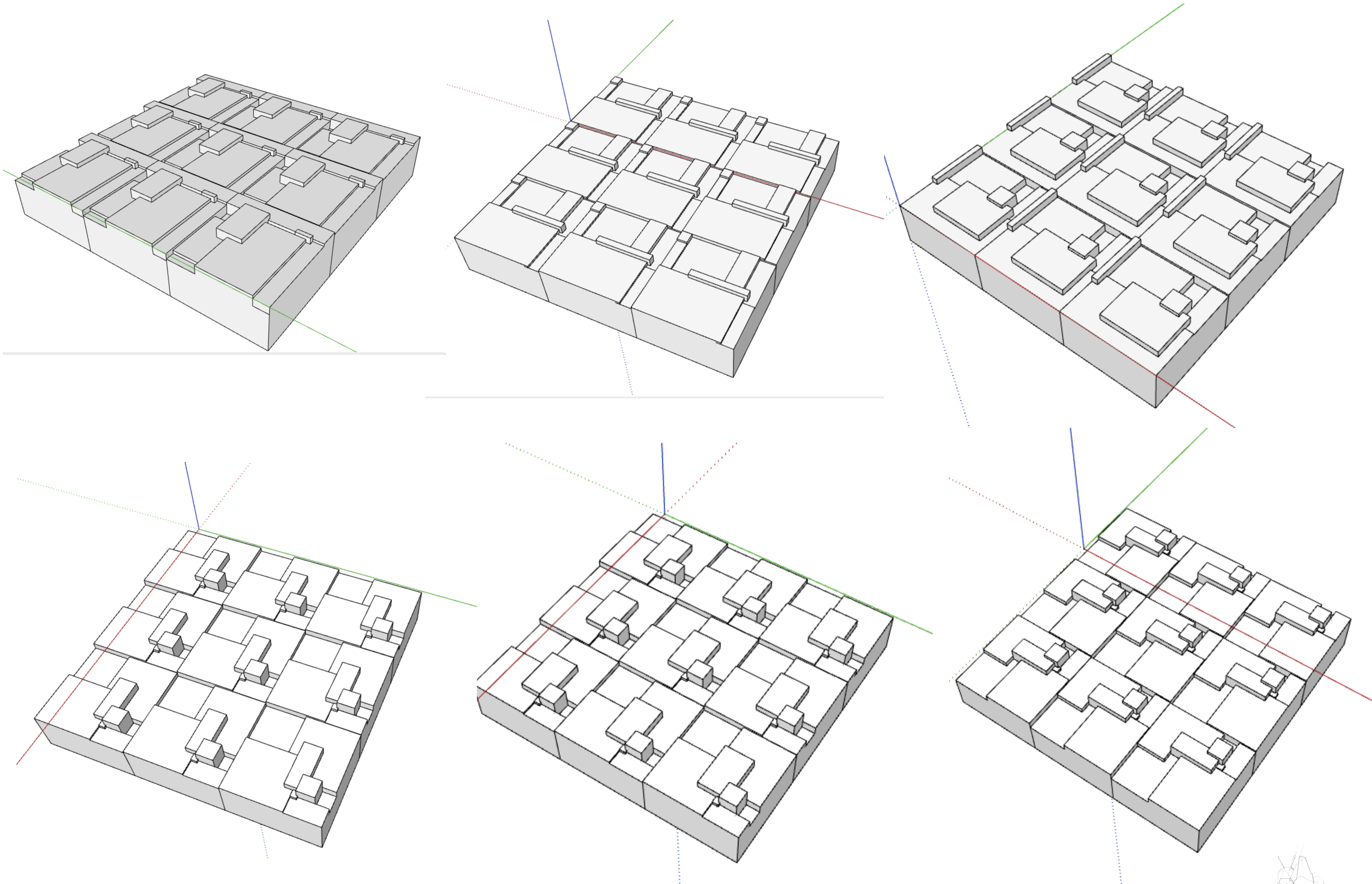


FIG 33.

PIN-UP #2

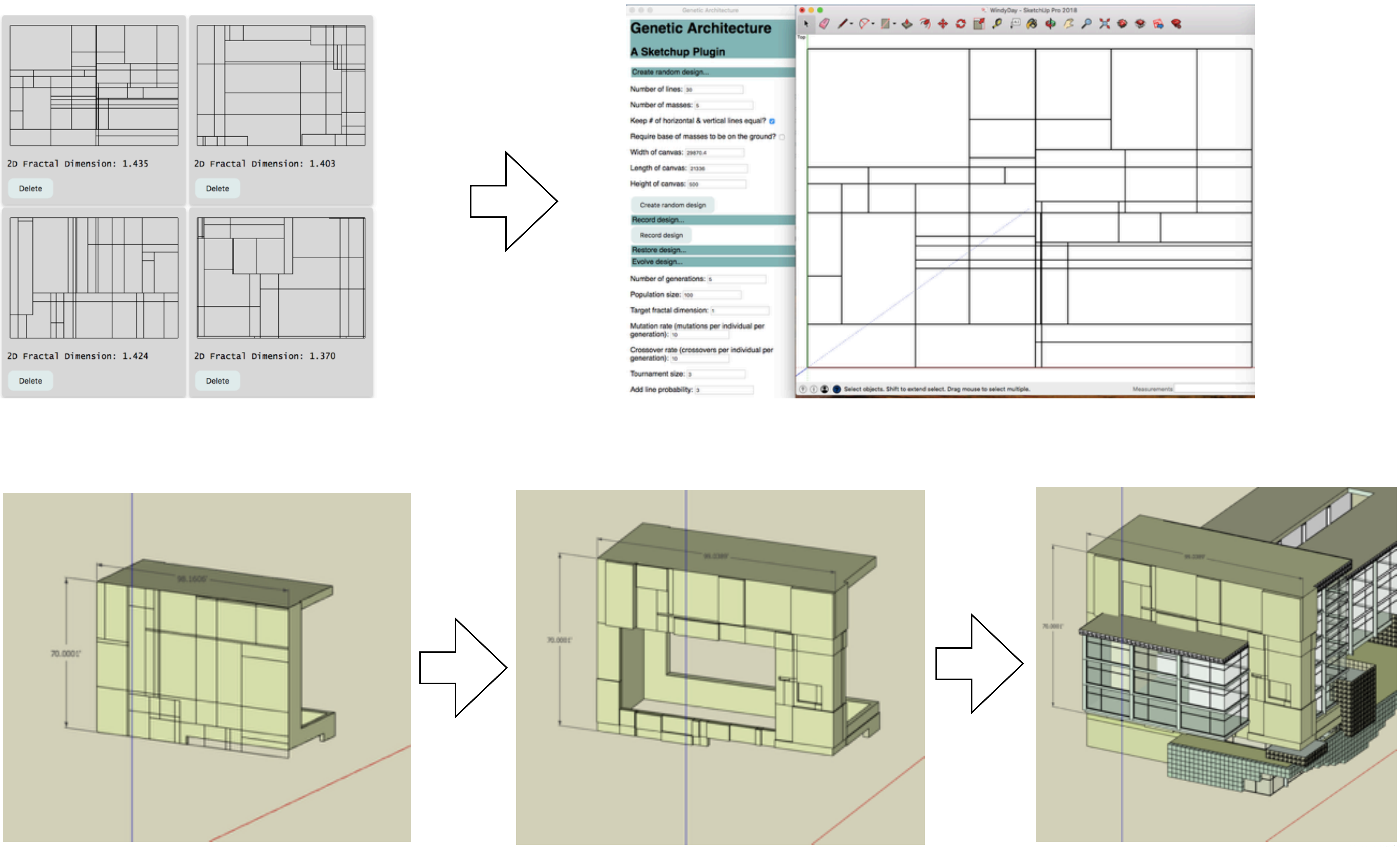


FIG 34. Parameters –> design variants –> FD –> exemplar –> fitting. FD = 1.435.

PIN-UP #2
M A C R O

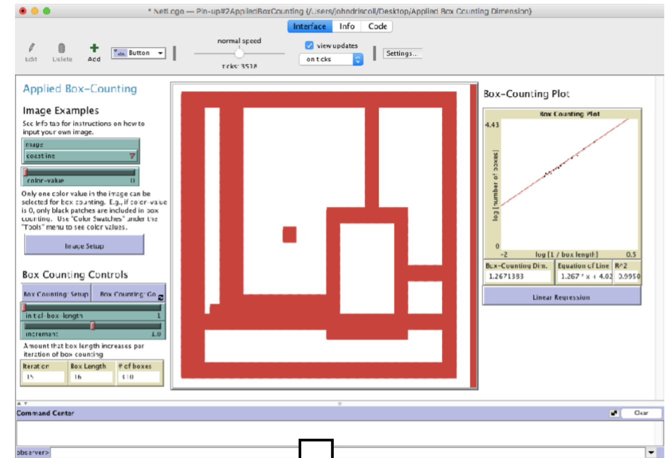
PIN-UP #2

FIG 35.

FIG 36.

PIN-UP #2

Level 1. Micro. FD = 1.267

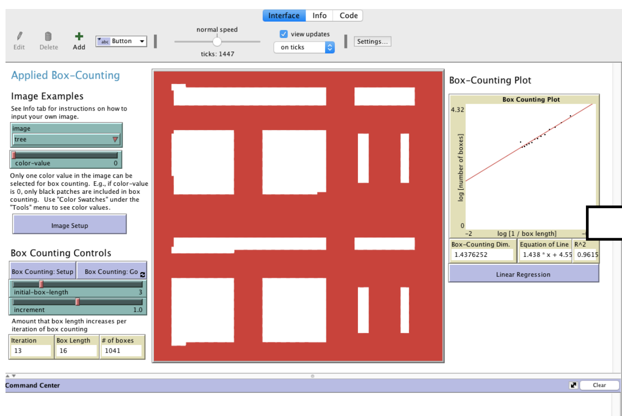


Micro

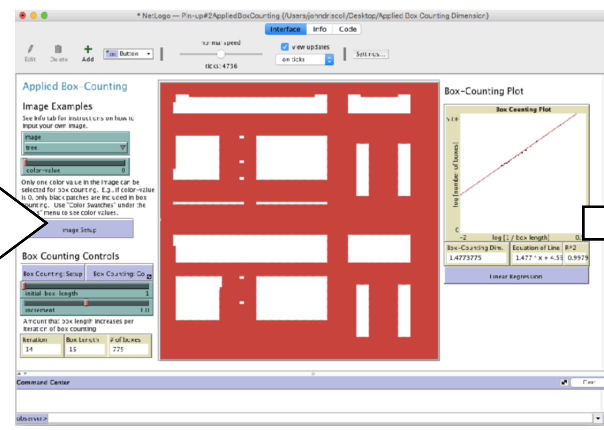
Masonry block micro level FD of 1.267. Result of simplifying the block during the fitting stage.

Context

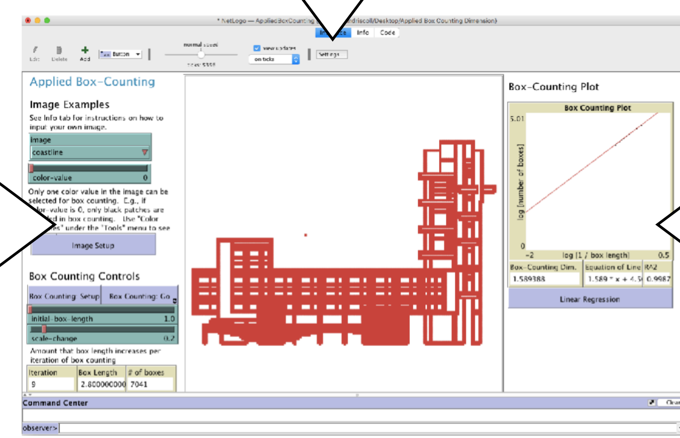
Relationship between the two buildings at this scale in terms of a similar level of *detail*.



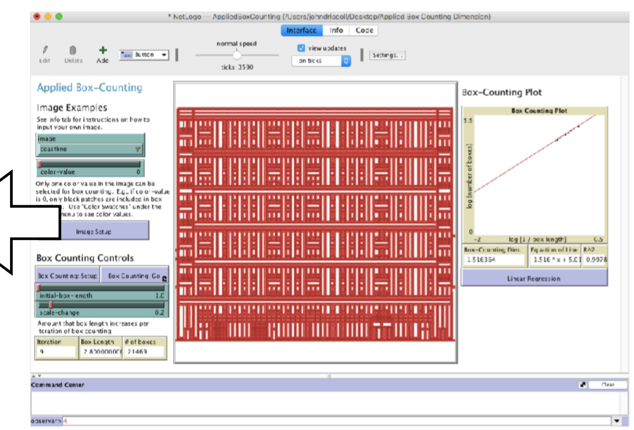
Level 2. Mezzo. FD = 1.437



Level 2. Mezzo. FD = 1.477



Level 3. Macro. FD = 1.589



Context. Harold Square. FD = 1.516

Mezzo

Initial FD at the window bay was 1.437. The mullion configuration was redesigned and increased the FD to 1.477.

Macro

Overall building was measured in south elevation and had a FD of 1.589. Slightly above the Harold's Square's south elevation of 1.516.

Level / context	Level 1	Level 2	Level 3	Harold Square
BCD	1.267	1.477	1.589	1.516

Table 1: showing FD at 3 levels of scale.

FIG 36.

FIG 37.

FIG 38.

FINAL PRESENTATION

PIN-UP #3

FIG 39.

LITTLE COMMONS

GREEN STREET ITHACA, NY

EXTERIOR PERSPECTIVES

6.21.19

JOHN DRISCOLL STUDIO johncdriscoll.com

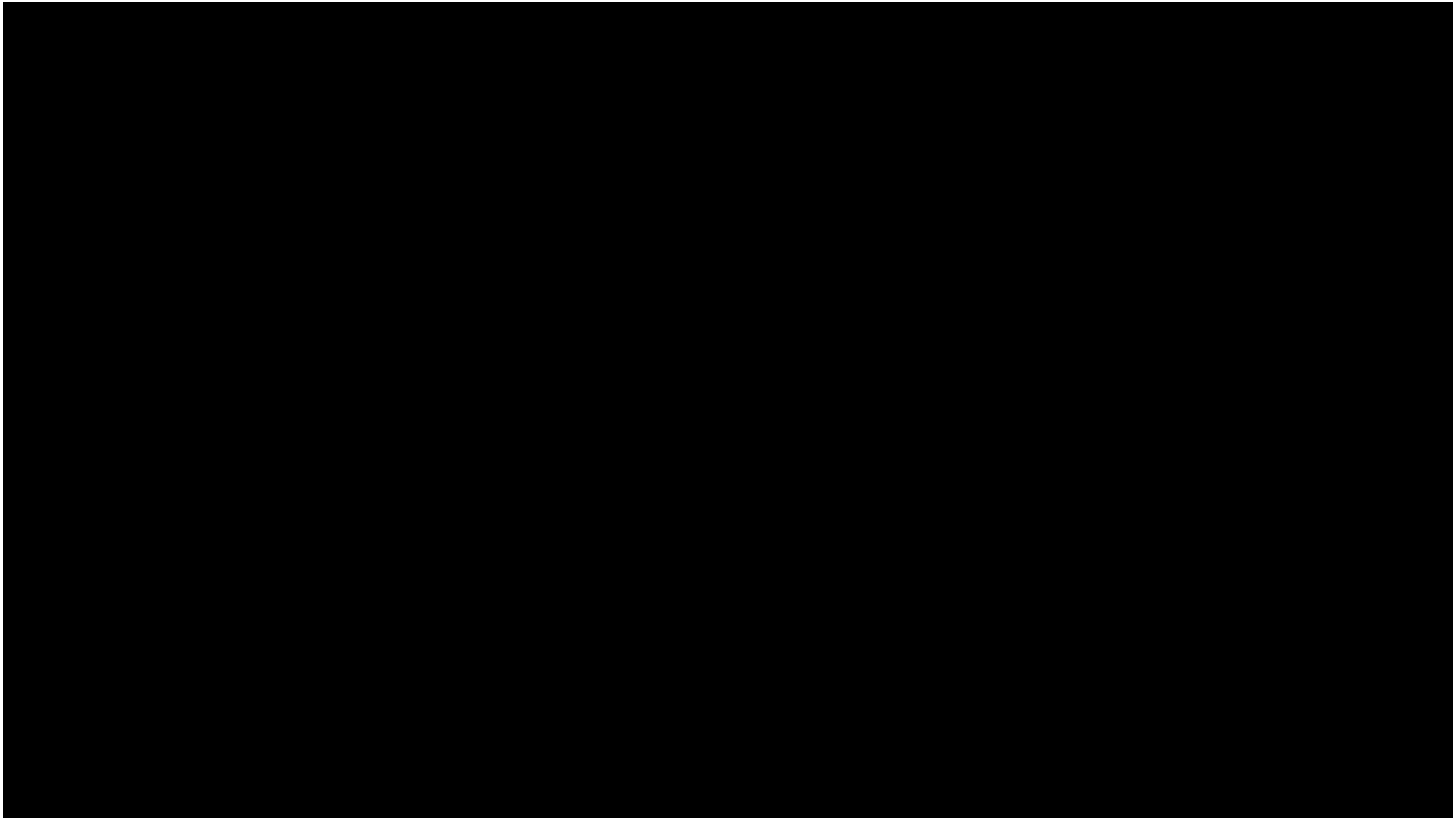


FIG 40.

RESULTS of CRITIQUE

Juror's responses chunked into 10 general categoryies

	Research question	JWS	DM	SR	JF	GH	KM	KK	BH	TM	Total
1	Level 1 produced compelling designs	-1			-1	1	1	-1		-1	-2
2	Level 2 produced compelling designs	-1				-1	-1	-1			-4
3	Level 3 produced compelling designs				1	1	1	1	1		5
4	Usefulness of tool to you	-1				1			1	1	2
5	Fractals generally relate to your personal design approach	1	1						1	1	4
6	Fractals have merit generally in architecture design	1	1		1					1	4
7	Designer's role is essential	1			1	1	1	1	1		6
8	Tool must be project specific and unique to project criteria				1	1		1	1	1	5
9	Universal quantitative tool is valuable							-1		1	0
10	AI is generally a favorable development in architecture	-1				-1		-1		1	-2

Table 2**:** Jurors' feedback.

Level 1: less successful: 3 of 5 jurors said relationship between FD and how it was informing the larger design to be inconclusive.

Level 2: not successful: 4 of 4 jurors indicated a disconnect between the output of the algorithm and its use in the creative process.

Level 3: successful: 5 of 5 jurors found the larger design process compelling.

Project specific: 6 of 6 felt strongly that the ability for the architect to work with the algorithm in relation to a specific and unique project was most important.

SUMMARY of FINDINGS

- Cybernetic design process.

Proof of concept for human/machine experiment using FD as form generation for real-world complex architectural project.

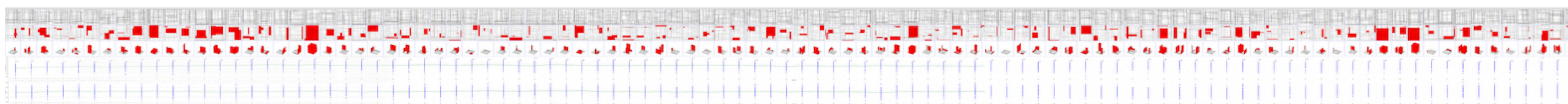


FIG 22. 2D & 3D compositions timeline.

- DBVgen tool, implementation and critique.

Vollendorf method useful in establishing coherent methodology at different levels of design process.

generative algorithm
human designer

FD as generative tool

good design –> higher FD
higher FD ~~–>~~ good design

- Integrated organizing principle (OP)

Degree of integration of the details within an overarching OP that is quantifiable using FD.
Coordinated level of detail at 3 scales and relation to context.

Level / context	Level 1	Level 2	Level 3	Harold Square
BCD	1.267	1.477	1.589	1.516

Table 1: showing FD at 3 levels of scale.

DISCUSSION

- Fractal algorithmic design.

  More nuanced appreciation of fractals in architecture.

  designs having multi-scale and multi-functional representations of some unifying organizing principle as the result of an iterative process.

- Fractals and efficiency:

  Employing a geometric strategy that can approximate other shapes has a certain pragmatic efficiency that fractals afford in an architectural context.

  The efficiency of branching structures might also account for their use in building infrastructure such as plumbing and wiring and ductwork as well as vehicular transport networks, e.g., highways, byways, tri-ways etc.

  Cities are theorized to result in part from the space filling property of fractals, similar to DLA (Batty, 1994). Fractal geometry related to biological uptake and distribution systems characterized by 3D space filling trees composed of one dimensional elements essentially (West, 2017).

- Fractal thinking:

  The word "organic" implies a hierarchical organizational structure from the whole unified organism to sub-systems such as the circulatory system to cells to organelles within the cells, etc. Fractal ideation may involve a similar hierarchical chunking of ideas like Russian dolls.

  $\{[(y_i), (y_i)], [(y_i), (y_i)]\} \rightarrow [(x_i,x_i),(x_i,x_i),(x_i,x_i),(x_i,x_i),] \rightarrow [(x_i),(x_i),(x_i),(x_i),(x_i),(x_i),(x_i),(x_i)]$,
  where x_i is some single digit natural number and y_i is a corresponding 2 digit number.

CONCLUSION

- Design process considered as an "exact and scientific metaphysics.

  General: *Meaning* creating design system.

  Specific: Trans-disciplinary fractal theory applied to architecture towards a solution to a complex urban problem.

- The tool *DBVgen* using Vollendorf method to create compositions and FD as fitness criterion was an important first for a fractal based generative design system.

  More elements need to be added to the model to generate fractal forms.

  Model needs to be highly customizable for unique projects.

- Research agenda offered to analyze fractal processes in architectural precedent.

  More work needs to be done to develop a method for studying fractals in architecture as put forward in this dissertation.

FUTURE OPPORTUNITIES

- Tool (DBVgen) development

    More development of fractal dimension as generative tool

        More Quantified analysis of methods including high vs low FD.

        3D implementation of FD (cube-counting dimension).

    More complex fitness function?

        Lacunarity. Multi-fractals. L-system implementation. Cellular automata implementation.

    Additional designers/architects to experiment with tool

- RFP presentation

- Construction

    Concrete block casting

    Automated construction research towards eventual implementation?

- Research agenda: Fractal algorithms and FLLW, Organic architecture, other styles.

    FLLW

    Publication of DBV's work

    Other architects and architecture?

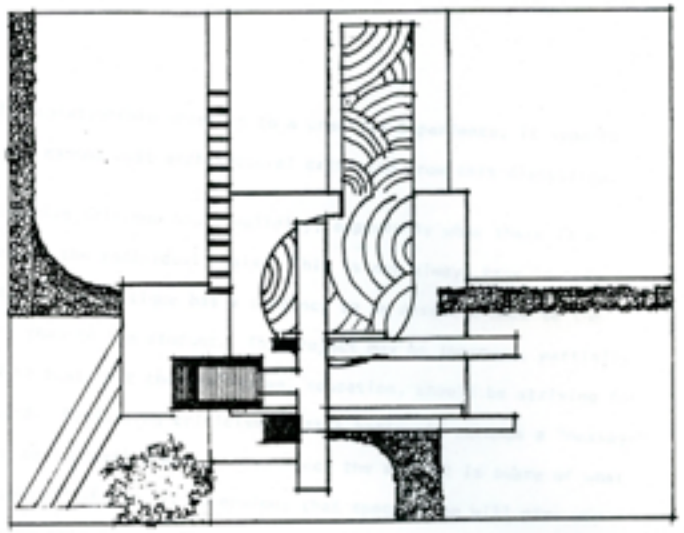


Figure 8. Composition with Counterpoint Landscape for a Memorial to Paul Wittgenstein

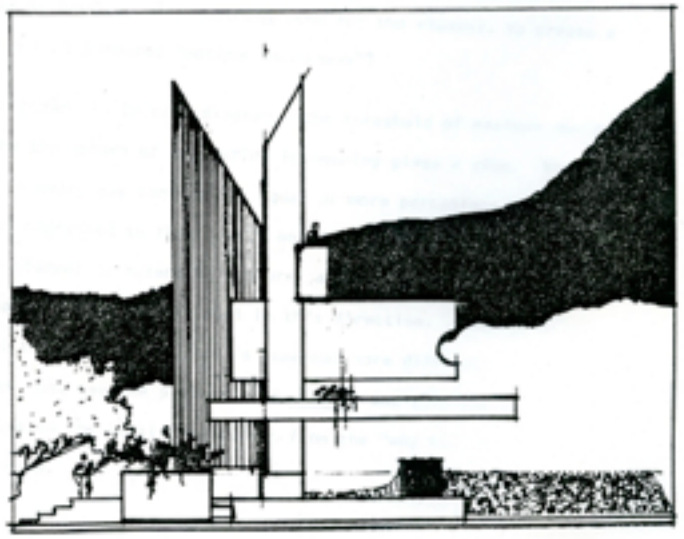


Figure 9. Elevation of Composition

Thank You