Nexus Network Journal
https://doi.org/10.1007/s00004-020-00490-4

NEXUS NETWORK JOURNAL
Architecture and Mathematics

RESEARCH

# Fractal Patterns as Fitness Criteria in Genetic Algorithms Applied as a Design Tool in Architecture

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**Abstract**
This paper explores the generative use of a genetic algorithm incorporating a computer-based fractal dimension tool termed "DBVgen". Fractals offer a quantitative and qualitative relation between nature, the built environment and computational mechanics and in this paper are explored as a bridge between these realms. The primary objective was to develop and employ a sophisticated analytic tool within a creative context using fractal dimension and the Vollendorf Method. This tool was then tested on a complex case study project and the results discussed. The design process developed for this research showed that the insertion of the DBVgen tool into a traditional schematic design phase was capable of creating unique and compelling compositions and aided in developing high level architectural solutions with respect to various parametric controls and designer feedback. A valuable aspect of this exploration was in positioning the DBVgen tool up front to aid in the creative process and better leverage downstream outcomes.

**Keywords** Genetic algorithm · Fractal mathematics · Fractal theory · Cybernetics · DBVgen · Fractal dimension · Vollendorf method

## Introduction

This paper investigates how fractal patterns and tools can inform a schematic design process both in terms of generative formal solutions as well as a metric for assessing the complexity of outcomes. This investigation developed a cybernetic design process incorporating a computer-based tool termed "DBVgen" within a closed loop designer/algorithm back and forth (Driscoll 2019). The DBVgen tool incorporated a genetic algorithm that used fractal dimension (FD) as the primary fitness criterion. The proof-of-concept case study consisted of two primary stages modelled after a traditional design charette. This paper follows the same structure as the charette,

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Published online: 27 May 2020

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describing first the design of the process and algorithm and then the results of the stages and examples of the final presentation renderings. FD is a computationally inexpensive coarse-grained tool used for measuring the characteristic complexity of graphic objects (Mitchell 2009: 103–109). One limitation of this study is in the oversimplification of graphic information using FD as well as its implementation using box-counting dimension (BCD) with only five iterations of box sizes. This limitation is considered acceptable for this initial exploration and represents an aspect of research that may be broadened in the next generation of DBVgen.

## Background

This section provides a background on the key aspects of the design process and case study for this exploration. The method employed here incorporated a genetic algorithm incorporating fractal geometry as a fitness criterion. Figure 1 shows an initial hypothetical sketch of the idea showing a solid mass on the left with further development and self-similar cascading detail moving to the right. The model on the left has very little detail whereas, moving right, there is increasing detail at three discrete scales. These models are generated by a genetic algorithm with respect to some simple rules (Vollendorf method) with FD used to determine fitness.

### Genetic Algorithms

Conceptually, genetic algorithms are computer-based abstractions of biological evolution, replacing chromosomes with bit strings and using the operators—crossover, mutation and inversion—to "evolve" populations based metaphorically on sexual reproduction. In a genetic algorithm, populations evolve over time relative to an objective function, also termed a "fitness criterion". Genetic algorithms are as numerous as the problems they attempt to solve (Mitchell 1998) and in this sense do

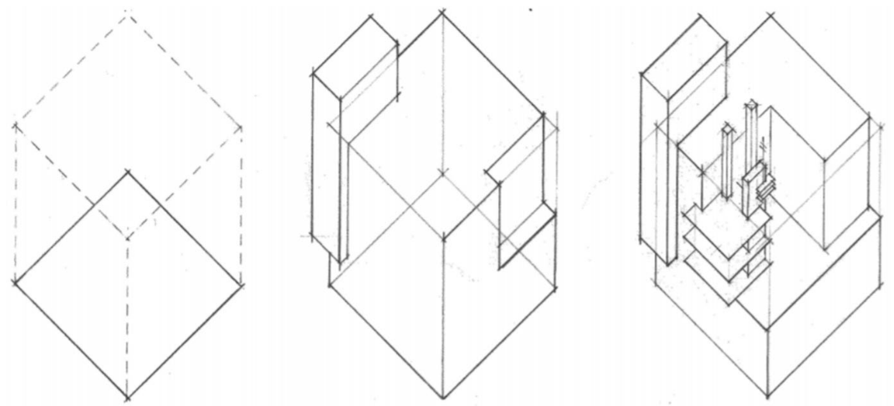

**Fig. 1** Depiction of parametric model showing three possible generations of genetic algorithm outputs representing increasing characteristic complexity. Image: author

not represent a universal search algorithm but rather a heuristic approach that can be tailored for specific applications. Genetic algorithms have been widely used not only for discriminative data analysis but also as generative models.

Genetic algorithms are becoming commercially available for practitioners. One example is the Galapagos plugin for Grasshopper, which is used as a visual programming aid for architects within the building information modeling (BIM) software Rhino. Plug-ins such as Galapagos offer non-savvy practitioners opportunities to experiment with algorithmic design tools. Galapagos has been researched as a tool to optimize spatial adjacencies for complex building programs (Boon et al. 2015). This project optimizes a three-dimensional layout for fifty programmatic spaces, essentially creating a bubble diagram that an architect may then design from schematically. Galapagos has been used for daylighting and shading studies in architecture (González and Fiorito 2015) as well as to find novel solutions to structural problems (Danhaive 2015). More relative to this present paper, Galapagos has also been used to generate new fractal forms for urban environments using cellular automata (Devetaković 2015).

## Fractals and Architecture

Like genetic algorithms, fractals have an association with nature. Benoit Mandelbrot famously applied fractals to the measurement of the coastline of Great Britain. As one zooms in on Britain's very jagged coastline a self-similar jagged structure is visible at all scales. The geometry of the coast is scale invariant in this sense. As the length of the coastline is measured with increasingly smaller instruments the measure grows longer approaching infinity (Mandelbrot 1967). This phenomenon was first studied by Lewis Fry Richardson who realized that when measuring the border between France and Spain there was no converging measurement but rather the length of the boundary was relative to the precision of the measuring device used. Richardson plotted length measures at the resolution of the corresponding metric and noticed a linear relation when plotted logarithmically (Richardson 1922). The contemporary physicist Geoffrey West who has applied fractal geometry to the analysis of biological and urban scaling refers to the convoluted or ever-folding nature of fractal geometry as well as FD, the scalar metric used to characterize fractal geometry:

> Crinkliness, later to become known as fractality, is quantified by how steep the slopes of the corresponding straight lines are on Richardson's logarithmic plots: the steeper the slope the more crinkly the curve. The slopes are just the exponents of the power laws relating length to resolution… (West 2017: 139).

Fractal geometry in architecture is not strictly scale-free but repeats at a finite number of scales and is more eccentric and freeform than the rigorous fractal geometry demonstrated in mathematics. Fractals in architecture often transform or develop in different ways and as per a designer's individual approach, or as architects like to say, a designer's "hand". A more nuanced definition of fractals in architecture begins to emerge where a fractal is not necessarily limited to a self-similar *shape* only but more a self-similar *motif* or *theme* or, in the most abstract sense perhaps, a self-similar *idea*. Dawes and Ostwald explore this notion when describing the role of invariant patterns in Christopher Alexander's work: "the creator's perspective represents a global view of the language that is consistent with Alexander's conceptualization of design as a scale-based cascade of decisions" (Dawes and Ostwald 2020: 12).

## Contemporary Approaches

Fractal-based approaches within generative design processes have been used to both analyze and create urban environments and individual buildings. Özgür Ediz and Gülen Çağdaş as well as Gürbüz et al. have investigated the use of FD as a quantifiable measure to analyze urban conditions and use (along with other fractal measures such as lacunarity) to create new urban environments and architecture that match the characteristic complexity of existing urban fabric. This approach preserves attributes of the original neighborhoods while extending the fabric into new development (Ediz and Çağdaş 2007, 2009; Gürbüz et al. 2010). Esra Gürbüz, Gülen Çağdaş, and Sema Alaçam write, "The aim of the research is not only generating new form alternatives but also considering the continuity of traditional architectural and urban patterns which faces deterioration" (Gürbüz et al. 2010: 841).

Fractal geometry in architecture and FD in architecture represent active fields of research in design and hold much promise for the future (Ostwald and Vaughan 2016). With computational tools now at our disposal it is possible for designers to analyze and generate fractal architecture with an intuitive 'hand' as well as using mathematical approaches such as FD, which is the focus of this present study.

## Fractal Dimension

FD has been widely used as a tool for assessing the complexity of an object in far flung fields such as geology and hydrology, biology and botany. Generally, FD is considered an important quantitative tool in assessing characteristic complexity (Mitchell 2009: 103–109). Mathematicians and physicists have made significant progress in developing analytic approaches related to fractals after Mandelbrot's pioneering work in the 1970s and 1980s. How cities scale is an active field of research in complexity theory including aspects of cities that are within the purview of architects and urban planners. Scale-free power laws correlate many attributes of cities. Consequently, researchers have used FD to assess them (Batty and Longley 1994; Batty 2007; Bettencourt et al. 2007; Bettencourt 2013; Encarnacào 2012; Abundo et al. 2013; West 2017). Similar tools are also being used increasingly in the analysis of the characteristic complexity of architecture (Bovill 1996; Harris 2007, 2012; Joye 2007, 2011; Ostwald 2001; Ostwald and Vaughan 2016; Vaughan and Ostwald 2018).

## Box-Counting Dimension

FD can be approximated heuristically using box-counting dimension (BCD) and is useful for irregular objects such as rivers and trees or, in this study, for orthogonal compositions that are not strictly repeating. BCD is often used to measure fractals that are not defined with pure geometry but rather consist of idiosyncratic shapes such as those found in nature and in complex, hard-to-characterize forms such as architecture or cities. BCD is determined by first overlaying a grid on an image and counting how many lattice sites or 'boxes' are necessary to completely cover the shape and the procedure repeated. Additional grids at ever decreasing or increasing scales are overlaid recursively on the shape. The coordinates of the log of number of boxes ($N\varepsilon$) and the of log of their scaling ratio ($1/\varepsilon$) are recorded in a scatter plot. The scatter plot is a graph with *log* $1/\varepsilon$ along the x-axis and *log* $N\varepsilon$ along the y-axis. From the scatter plot a sum of least squares linear regression is modeled (see Fig. 3 below). The slope of the best fit line is the FD of the object and should approximate the Hausdorff dimension. In Eq. (1), $N$ is the number of boxes at some scale $\varepsilon$ with $D$ the BCD.

$$D_0 = \lim_{\varepsilon \to \infty} \frac{\log N(\varepsilon)}{\log \frac{1}{\varepsilon}} \tag{1}$$

## Method

This section briefly describes the design exercise developed by architect and educator Dean Bryant Vollendorf repurposed in this study as the rule set for the DBVgen tool. The Vollendorf Method is a series of short exercises consisting initially of three lines on a page with regard to certain rules as follows:

1. the picture plane is rectangular;
2. lines must be parallel or at right angles to each other and parallel to one edge of the paper;
3. lines must go from edge to edge or stop at another line.

From an initial three-line composition, more lines are added which establish compositional elements. Vollendorf describes the sequence of exercises (Fig. 2):

> Exercise one: 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. If the line is placed at the center, you merely have cut the plane in half. If the line is too close to the edge, it will look like an accident. If something else is needed to complete or satisfy the plane, the line is in the wrong place. Exercise two: A second line is added parallel to the opposite edge. This gets farther into the word composition, at the same time introduces center of interest. Exercise

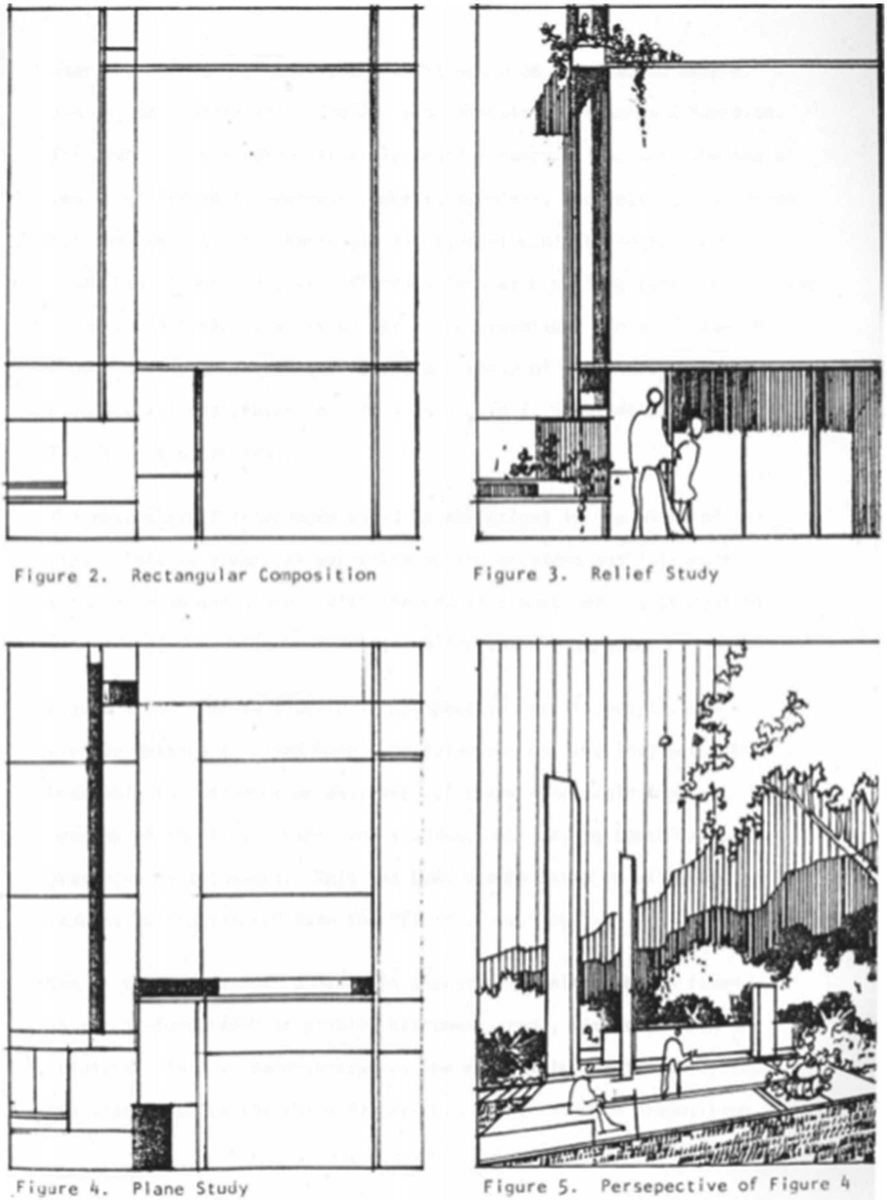


**Fig. 2** Diagram from Vollendorf's thesis representing the three lines on a page exercise and "bas relief thinking". Image: (Vollendorf 1975: 9)

three: A third line is introduced that goes from line to edge and is to reinforce the concept of resultant space. These problems are defined as "of the plane", the problems are dedicated to the two dimensional through bas relief thinking (Vollendorf 1975: 8–11).

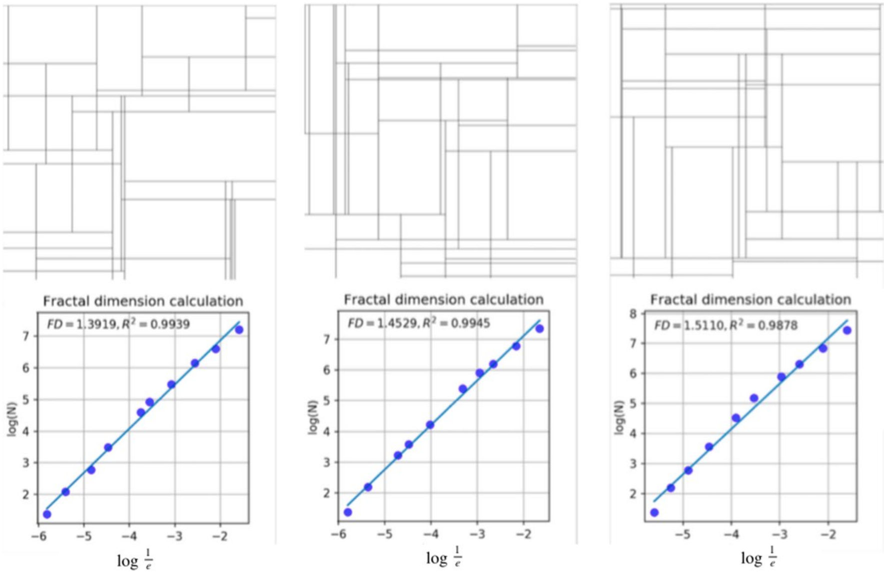


**Fig. 3** 2D compositions above and box counting dimension plots below. Images: author

## Design Process

This section describes the design process morphology developed for this present study and its application as a proof-of-concept for the case study project. For Stage 1 the design problem was relatively simple and consisted of a hypothetical park pavilion. For stage 2 the design problem was an actual urban mixed-use development project along Green Street in downtown Ithaca, NY, as defined in a request for proposals issued by the City of Ithaca in 2018. This project had a complex program and constituted an adequate problem for demonstrating the DBVgen tool in a complex real-world case study project.

The design process consists of two levels of development within a closed loop. Level one inserts a computer-based design tool (DBVgen) into the schematic phase of a traditional design process. Level two comprises a tuning phase where a human designer modified the output of the algorithm to fit the program for the project. The output of level one becomes the input for level two and vice versa with the intention that the steps repeat until the process converges on an acceptable design. The design and analysis aspects are interwoven, as will become more clear in the following sections.

The DBVgen tool developed for this study used a modified genetic algorithm inserted into the schematic phase of a traditional design process. Both the genetic algorithm and box-counting models were based on the author's work with Melanie Mitchell for the Santa Fe Institute's Complexity Explorer MOOC (complexityexplorer.org). The computer languages Python and Ruby were used within a Sketchup solid modeling environment with a simple interface allowing the designer to set parameter values as well as adjust the model in 3D and re-use it for additional runs relative to the design process. Multiple individuals could also be selected by the designer to breed for subsequent generations.

Initial compositions were randomly created with the encoded Vollendorf Method rule set. For the majority of runs 30 lines were used to create random orthogonal compositions. 3D massing models were created from elements of the 2D composition based on a parameterized number of masses formed by extruding rectangles created by the line compositions relative to an adjustable Z coordinate. Both the number of masses and the Z coordinate were modified based on the different conditions of the site and program. The initial massing model required different parametric settings that differed from subsequent details and textures.

All parameters in this exploration were set by the designer and subject to adjustment based on the results of the design process. Some parameters that the designer could control included canvas size, population size, target BCD and number of generations. For the majority of runs a population of 100 was used and the number of generations was ten. The genetic algorithm used tournament selection to determine the exemplars for a given generation based on an individual's proximity to the target BCD.

Exemplar designs were chosen from individuals forming a population within a given generation. The main parameters include the number of generations, the mutation rate and whether new lines are added or deleted. Exemplar designs were selected for crossover with other individual exemplars, mutation and cloning. The objective function chose exemplars that were closest to the target FD. Designs were measured for FD using BCD. The target FD for the Stage 1 was the maximum 2 as a starting off point for the investigation. Later in the design process the target FD was adjusted relative to site and context as well as design vocabulary as discussed in the "Results" section below (stage 2).

The box-counting procedure was as follows. The size of initial boxes, scaling factor and number of iterations were parametrized. Due to the computational expense of large populations and multiple generations, five iterations of box sizes were used for a given run beginning at .02 units and increasing in size logarithmically. The model was validated using a comparison to the Koch curve and was accurate to within .03804 when compared to the FD of a Koch curve, equal to 1.26186.

For stage 1 the designer's modifications were not input back into the algorithm, meaning a feedback loop was not instantiated. In this sense the process is described as linear.

In the case study project for stage 2 tuned designs were allowed to be input back into the algorithm for a number of back and forth iterations between level one and level two of the design process. When this occurs, the process incorporates feedback and represents a closed loop system.

## Results

### Stage 1

Stage 1 focused on the development of the design process and the development of the DBVgen tool as discussed above. The problem was a simple park pavilion with basic architectural elements such as: scale, space, form and context. The program was intentionally oversimplified to highlight the design process as clearly as possible.

Figure 3 shows a sample of basic line compositions generated randomly with respect to adjustable parameters such as the number of vertical and horizontal lines and a range for how many times lines cross. As discussed above, FD was determined using BCD with the linear regression model shown in the graphs immediately below each composition.

Figure 4 shows the most stripped down output of the DBVgen tool. The line compositions across the top represent the individual that best responds to the fitness criteria. The fitness criterion is an objective function that is being maximized or minimized. In this study, a target FD of 2 was used as a starting point for the investigation. The target FD parameter was more relevant for the case study project where a relationship between different levels of the building's scale was desired as well as a relationship to the FD of adjacent buildings. Over successive generations the FD is seen to approach the target.

Figure 5 is a sample of the DBVgen tool run for five generations. Exemplar compositions for each generation are shown along the upper most row of the image at top but now with a number of rectangles extruded as masses. Masses are allowed to overlap, and any number of masses may be set in the corresponding parameter. The next set of images below show the masses extruded to a random height within a threshold. The graphs at the bottom display the exemplar BCD for each run and the mean over successive generations. The BCD measures only the 2D compositions. This vignette image shown in Fig. 5 is a more or less arbitrary example culled from any number of genetic algorithm runs. An important leverage point offered by algorithmic design is the sheer number of potential variants a designer may peruse and be inspired by. For this example, the BCD for exemplars range from 1.624 to 1.646.

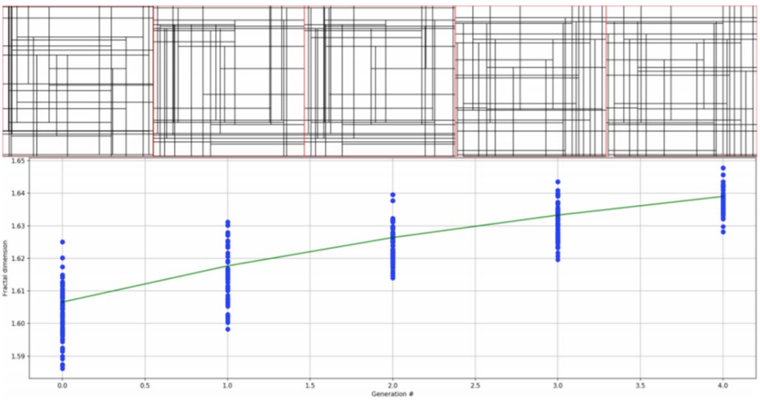


**Fig. 4** Output of DBVgen. Truncated timeline showing five models progressing in order of iteration from left to right and increasing in BCD. Image: author

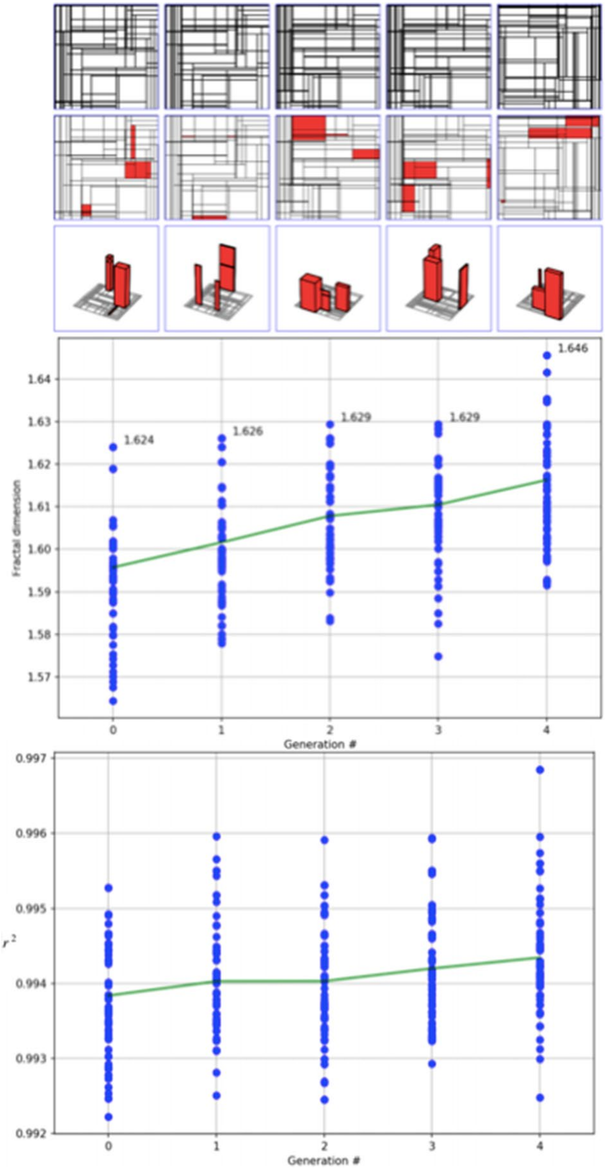


**Fig. 5** Output of DBVgen tool. Graphs show the FD and $r^2$ for all individuals in each generation aligned vertically with the exemplar's FD noted and the mean shown in green. Image: author

Figures 6 and 7 represent how the output of the design process was fit in a fast and loose way to the park pavilion for stage 1. For this phase there was a minimum of fitting performed. The output of the algorithm was simply rotated and placed within a made-up context, giving it scale and establishing the output as potentially built architecture. Site elements, such as a sculptural nude, plantings and sun

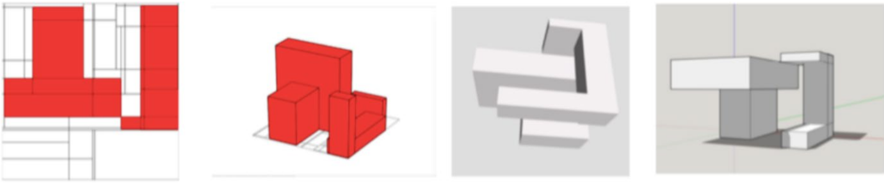

**Fig. 6** Progression of outputs to solid modeling environment. Image: author

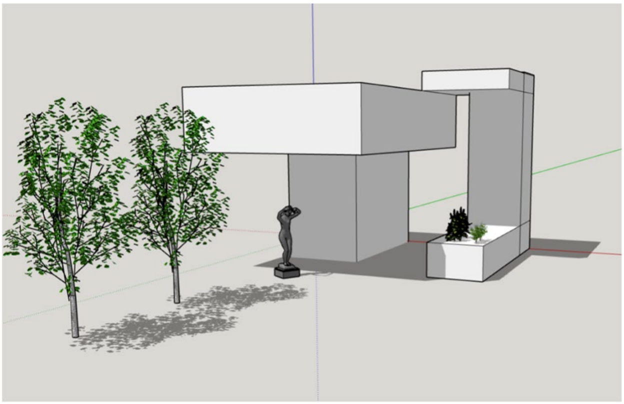

**Fig. 7** Pavilion design as demonstration project for Stage 1. Image: author

shadows, are placed in the design to provide scale. Basic components of architecture are introduced including a sense of enclosure and a relationship to context imagined as a crude landscape.

## Stage 2

For stage 2, compositions were developed in the same way as described for stage 1. However, significantly more fitting was done with the program for the complex case study project in mind. The design process focused on three distinct scale ranges termed micro, mezzo and macro.

### Micro

Figures 8 and 9 depict the initial composition for stage 2, which was generated by DBVgen and selected to be the organizing element for the project. This composition was conceptualized as a fractal generator for the entire complex. This composition was a compromise between a modestly high BCD of 1.477 and a simple geometric composition that could be easily translated into a masonry block and potentially cast in concrete. The BCD was close to the adjacent Herald Square building to the north which had a BCD of 1.516. The composition triggered an idea for the building

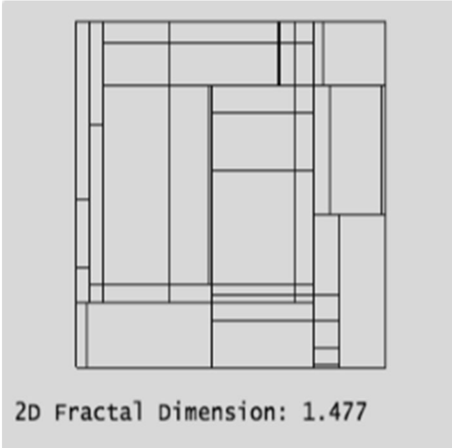


**Fig. 8** Selected initial composition. Image: author

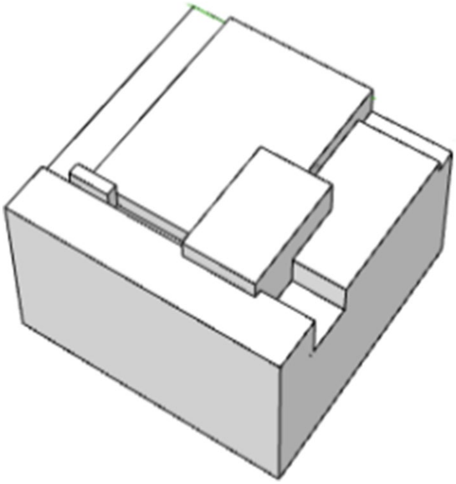

**Fig. 9** Extruding and fitting of composition to define a module used as a motif for the project. Image: author

in combination with many hours studying the programmatic requirements and the complex site conditions. Figures 8, 9 and 11 show how the initial composition was used as the generator for the project. The 3D block that constitutes the main element at the micro level had a BCD of 1.267 after fitting (Fig. 12) which was less successful at maintaining a consistent BVD with the other levels of the building or the site's immediate architectural context. This was a result of simplifying the block in order to create a realistic masonry unit that could be cast in formwork without too many nooks and crannies (Fig. 9).

## Mezzo

Figure 10 shows the application of the DBVgen tool at the mezzo level. This was considered to be more at the human scale and at the scale of architectonic systems such as structural systems (columns, beams, mid-scale massing), fenestration systems, and envelope.

Combinations of elements were used to create spaces, rooms, outdoor gathering loci, etc. DBVgen compositions were used at the mezzo level in relation to specific areas of the building. The compositions were then overlapped on the relevant area

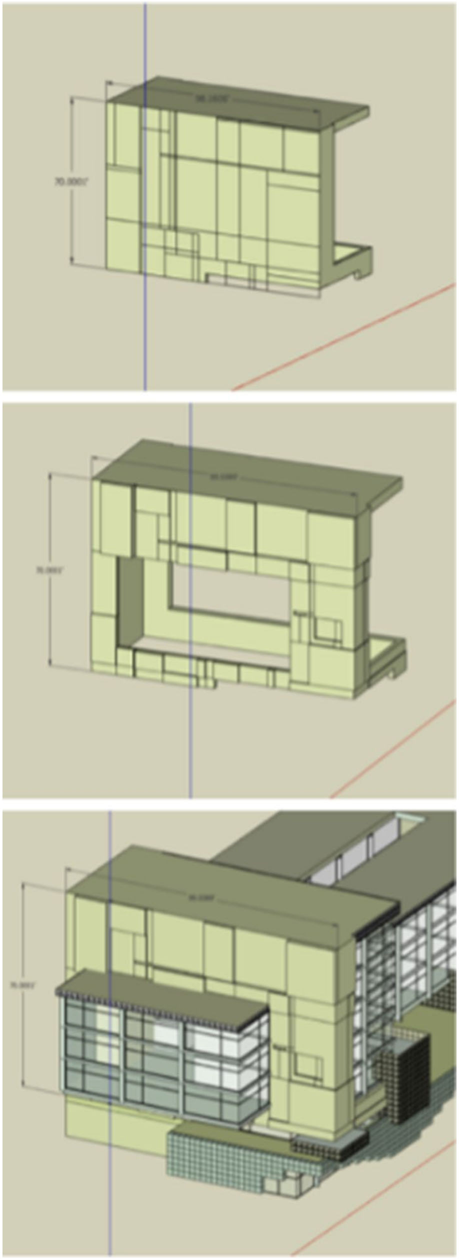

**Fig. 10** Mezzo level process sample. Image: author

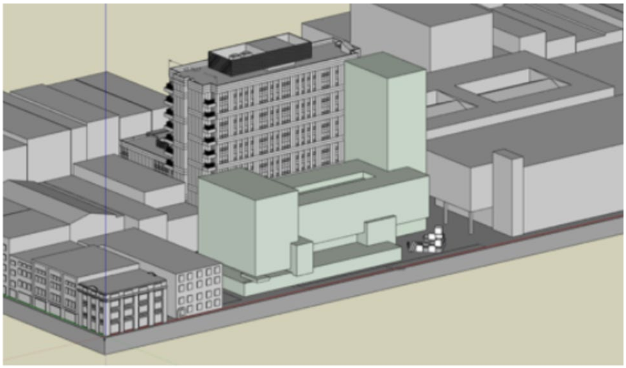

**Fig. 11** Massing model as reflection of motif. Image: author

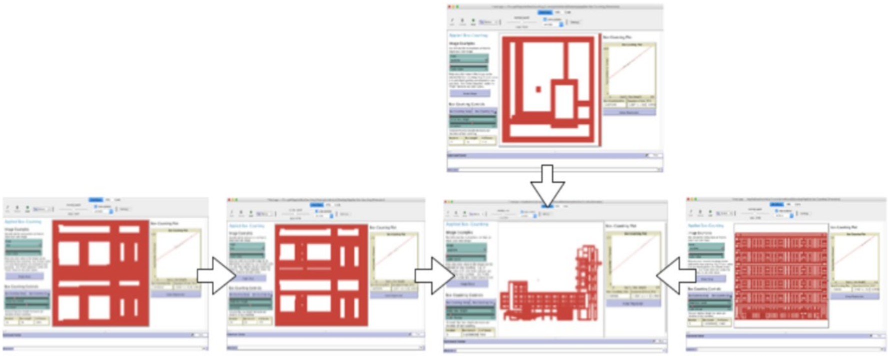

**Fig. 12** BCD of major design elements. Micro level is shown above. Mezzo level is shown in the two images on the left. The macro level is the middle right image and the far right image depicts the adjacent building, Harold Square. Image: author

like a mask and incorporated into the overall building design (Fig. 10). The design now starts to incorporate the three levels of detail as an ensemble composition. The general idea guiding design choices at this level was that the complexity of the detail would increase downward so that the building would appear to pixilate as it approached the street. Initial BCD at the window bay was 1.437. The mullion configuration was redesigned, and the BCD increased to 1.477, which was still lower than the macro level but within an acceptable range (Figs. 11, 12).

## Macro

The macro level was considered as the level of the overall building and its connection to the larger city block plan. Figure 11 shows the massing model for the macro level. It is based directly on the micro masonry block shown in Fig. 9. Figures 13 and 14 are a few of the presentation drawings for the final presentation and juried critique. The intention of the design was to see the self-similar element as a theme


**Fig. 13** Presentation perspective looking west. Rendering by Karl Andrew and Razin Khan


**Fig. 14** Presentation perspective looking east. Rendering by Karl Andrew and Razin Khan

running through the building from the smallest component to the largest. The overall plan of the building began with the micro module as a motif and reflects the motif throughout the design decisions inherent in its form. It was intended that the fractal theme should be more than surface treatment and integrated into the space plan and general layout. Figure 12 shows a vignette of the BCD of the final schematic design at the three levels of scale as well as the Harold Square building immediately to the north of the building's site. The overall building is shown in south elevation which had a BCD of 1.589. Although slightly above the Harold's Square's south elevation of 1.516, this was close enough to create a relationship between the two buildings at this scale in terms of a similar level of characteristic complexity.

## Conclusion

The relevance of this work to the scientific and design community is primarily in amalgamating and applying genetic algorithms and fractal patterns in a context of real-world architecture. The aim was two-fold: to develop the software architecture DBVgen, that is, a computer-based tool implementing FD as a fitness criterion for a genetic algorithm using the Vollendorf method, and to implement the DBVgen tool in a proof-of-concept case study project. The latter was a serious proposal for a building. The DBVgen tool was flexible enough to include functionalities that were project-specific, such as matching BCD of adjacent buildings and specific dimensions of building components.

A significant conclusion of this study was that FD alone is not a sufficient metric for generating designs or establishing a connection to program, site, context or natural features but can significantly enhance the design process when incorporated within a larger context of systems thinking and cybernetic design. The study showed conclusively that FD implemented with BCD in the DBVgen tool and incorporated into a larger design system including the creative process of the designer was successful.

### Challenges

Challenges in terms of incorporating the DBVgen tool into a creative context were primarily in the ease of use and scalability of the system. At this prototype stage, however, this limitation is considered acceptable.

### Next steps

A 3D FD implementation of the DBVgen tool was beyond the scope of this study and represents a next step. Other functionalities that were not explored are the ability to incorporate within the algorithm more unique details of the program and context, such as circulation patterns, room adjacencies, natural features and so on.

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