Title: **Using AI to Simulate Urban Vertical Growth**

Authors: Rafael Ivan Pazos Perez, Founder, Ivan Pazos Architect
Adrian Carballal, PhD, Associate Professor, Department of Information and Communications Technologies, Faculty of Computer Science, Universidad de A Coruña
Juan R Rabuñal, PhD, Director, Centre of Technological Innovation in Construction and Civil Engineering (CITEEC), Universidad de A Coruña
María D García-Vidaurrázaga, PhD, Adjunct Professor, Department of Construction Technology, University College of Technical Architecture, Universidad de A Coruña
Omar A Mures, Centre of Technological Innovation in Construction and Civil Engineering (CITEEC), Universidad de A Coruña

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Using AI to Simulate Urban Vertical Growth

Authors

Rafael Ivan Pazos Perez, PhD , Founder
Ivan Pazos Architect
2-2-28-602 Minami-Azabu, Minato-Ku
Tokyo 106-0047 Japan
t: +81 070 4079 5623
e: ip@ivanpazos.com
ivanpazos.com

Rafael Ivan Pazos Perez holds a PhD in Computer Science from Universidad de A Coruña, Spain, a Master's degree in Architecture from Columbia University, USA, and a Bachelor's degree in Architecture from Universidad de A Coruña. He leads his own architecture practice; previously he gained professional experience with Peter Eisenman and Skidmore Owings & Merrill, both in New York; and at Nihon Sekkei in Tokyo. He is a licensed architect in the State of New York and in Spain. He has taught architecture at Korea University and Hanyang University in Seoul.

Adrian Carballal, PhD, Associate Professor, Department of Information and Communications Technologies, Faculty of Computer Science

Juan R. Rabuñal, PhD, Director, Centre of Technological Innovation in Construction and Civil Engineering (CITEEC)

María D. García-Vidaurrázaga, PhD, Adjunct Professor, Department of Construction Technology, University College of Technical Architecture

Omar A. Mures, Centre of Technological Innovation in Construction and Civil Engineering (CITEEC)

Universidad de A Coruña
La Maestranza, s/n
A Coruña, E-15001 Spain
t: +34 981 16 70 00
e: secretaria@six.udc.es
udc.es

Abstract

This research explores the use of artificial intelligence to simulate how cities will grow vertically. By learning how cities have evolved in the recent past, genetic algorithms can successfully simulate vertical urban growth. The research was applied to buildings 130 meters and taller in the Minato Ward of Tokyo in 2015. An evolutionary computer model was built from a standard genetic algorithm, using historical and economic data, which then simulated future growth for the 2016 to 2019 period. The results obtained matched the area of study's real vertical growth for the study period, with a 85.7% accuracy for the number of buildings, 73.7% for their average heights, and 96.3% for the likelihood of new construction projects happening within a mapped area. By learning how a city evolved in the past, the model replicated the future vertical growth of a city center.

Keywords: Vertical Growth, Genetic Algorithms, Evolutionary Computation, Minato Ward, Tokyo, Skyscrapers

Introduction

Artificial intelligence and machine learning processes have been successfully used in the past to predict how cities will expand over territory. Most of the algorithms used for such purposes were cellular automata models, originally designed to simulate biological growth. This research, however, offers two novel approaches. The first is that it focuses on how densely populated metropolitan centers grow, not horizontally, but vertically. The second is the use of evolutionary computation, specifically genetic algorithms, which are not commonly used for the simulation of urban growth.

> “Economic stimulus packages by the Japanese government tend to result in an increase of high-rise construction, which materially manifests itself after three years. This produces a clear wave-like pattern.”

Evolutionary Computation

In the early 1950s, Allan Turing (1952) used the term "morphogenesis" to refer to the growth of flowers, and showed mathematically how a complex organism could assemble itself without any master planner. He was particularly concerned about recurring morphological patterns in the growth of living organisms. Further computational studies developed the first cellular automata computer models to be successfully used for the prediction of urban growth. Genetic algorithms were originally developed by Holland (1975 & 1998), as he began to study the logical processes involved in adaptation. Holland was inspired by the studies of cellular automata by Burks (1960) and neural networks by Selfridge (1958), particularly in exploring how simple rules could lead to complex behavior. The concept was further developed by Koza (1989 & 1992), into what he called "genetic programming", which consisted of breeding computer codes. The algorithms were not originally intended to simulate any biological systems, as their name might suggest, but rather used the logic of genetics, adaptation, evolution and natural selection as a way of finding the most appropriate solutions to a problem.

Currently, evolutionary computation and artificial neuronal networks are the two branches of machine learning yielding better results, and which have proven to be the most successful. Both disciplines are widely used to solve or simulate various kinds of complex systems, and are inspired by biological processes, but not intended to simulate nature.

This research uses economic and historical data about Tokyo high-rises as a starting point for genetic algorithms, to learn how to simulate a system and find solutions to a problem from the data given to them. Once all the data is gathered and organized, the information is fed into the algorithm, so that it can identify recurring patterns and relations in the data, through which it can later make its own simulations.

One aspect that has led to confusion in the media regarding this research is the difference between prediction and simulation. The evolutionary computation process proposed here doesn't predict vertical urban growth, but instead simulates likely scenarios thereof. It can simulate very accurately how the city could grow vertically, such as which zones in the urban areas are more likely to host new high-rises, the approximate number of high-rises, and the height patterns that are likely to occur. However, it is unable to accurately predict the exact location, size and height of the new developments, as self-organizing systems respond not only to logical, but also to random patterns.

Urban Growth: Tokyo's Minato Ward

Many authors, from pioneering studies by Weaver (1958) in the natural sciences to Jacobs (1961), have compared urban growth to biological growth. More recently, authors such as Johnson (2001) and Al-Sayed and Turner (2012) have pointed out how urban growth resembles the growth of biological organisms, and how city growth is governed by a combination of evolutionary and self-organizing processes.

The original research work started in 2015 and was published in 2017 by the *Journal of Urban Planning and Development*. The aim was to use artificial intelligence (AI) to aid planners, policy makers and urban designers in predicting how self-organization processes might produce vertical city growth and, therefore, to be able to react accordingly. For this purpose, a computer model was developed that could estimate the most likely location, height, and number of new skyscrapers that would be built in a determined area of a major city. The research focused on Tokyo and one of its central wards: Minato (see Figure 1). The team fed data to a standard genetic algorithm regarding the historical development of Tokyo, largely based on previous research published by the team in the *Journal of Asian Architecture and Building Engineering* (Pazos, 2014).

Figure 1. Partial view of the Minato Ward skyline in 2015.

The algorithm proposed could have also been applied to any other large and densely populated metropolitan area with a significant number of high-rise buildings. In order to apply the proposed genetic algorithm to a larger area, or to another city, it is first necessary to gather extensive data regarding past development. Tokyo was chosen for several reasons. Tokyo is the "sixth-tallest" city in the world, based on number of tall buildings of at least 150 meters' height (326) (CTBUH Skyscraper Center, 2019). Another reason was that Tokyo high-rise growth is not largely planned or regulated by the government or master-plans (with a few recent exceptions), but instead mostly follows a self-organizing process based on individual decision making, which is ideal for the use of artificial intelligence (AI). Genetic algorithms can identify complex relations and recurrent patterns in a set of data. The reason why Minato Ward was chosen specifically, was that as of 2015, it housed 28.7% of all of Tokyo's buildings over 130 meters, including the three tallest buildings within the city (CTBUH Skyscraper Center, 2017).

For the purposes of this research, the team only focused on buildings over 130 meters in height. According to the "CTBUH Height Criteria," there is no absolute definition of what constitutes a "tall building". What really defines a tall building is its height relative to its environment as well as the slenderness of the building—a building that significantly "sticks out" in relation to its surroundings. For the case of Minato Ward, the height of 130 meters is a clear benchmark for a building to be easily noticed (see Figure 2). A 3D model of the ward was used for documenting the buildings, and to generate data and diagrams to be used later in the evolutionary model.

Two different data sets and types of processes were used. The first was graphic, using a series of probabilistic parameter maps with construction and morphological data, to probabilistically determine locations that would likely support new high-rise buildings. The second was numeric, which simply combined economic and construction data.

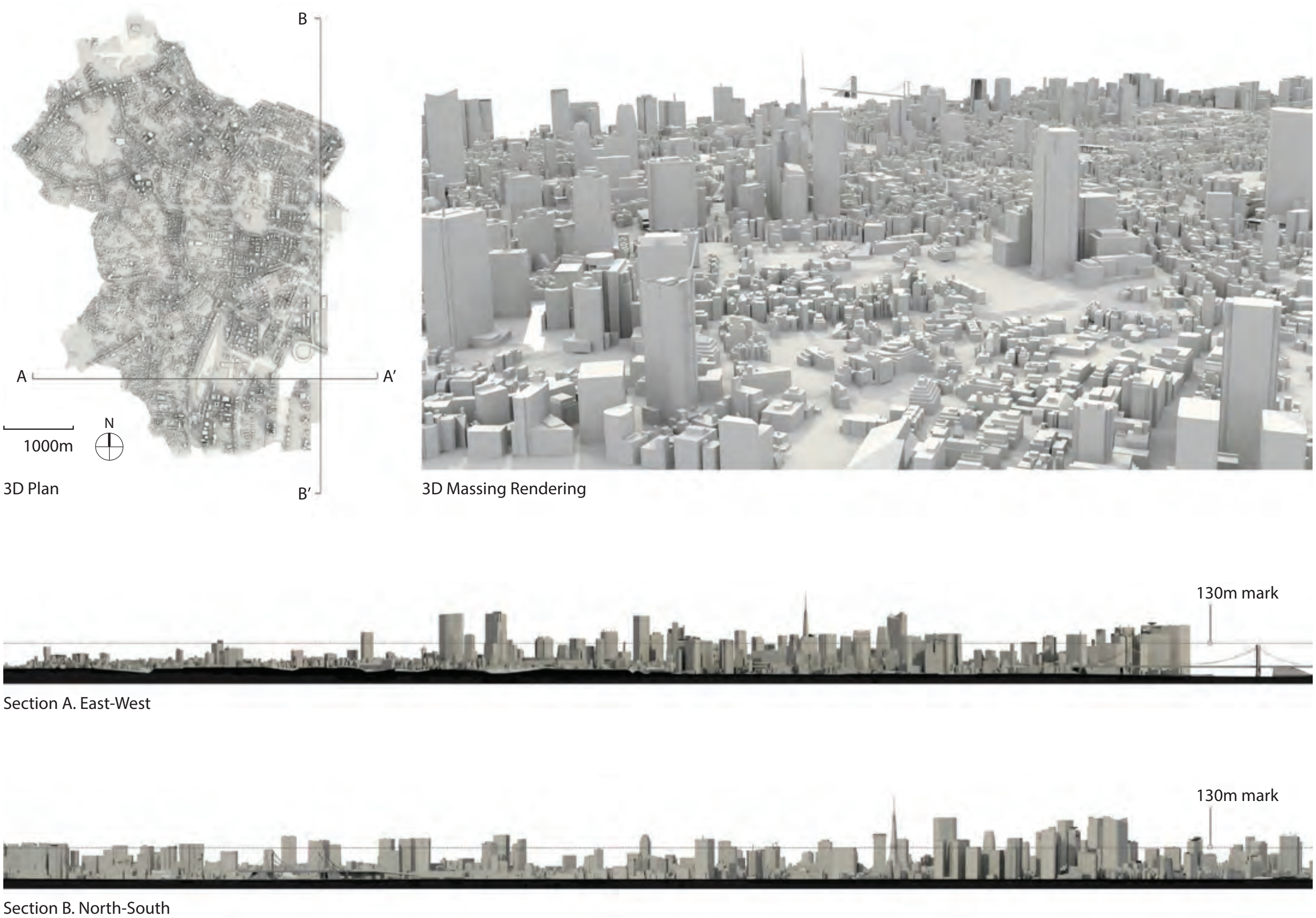

Figure 2. Minato Ward skyline renderings from a base photogrammetric 3D image (Google Earth 2015), post-edited and rendered.

Parameter Probabilistic Mapping

A series of grayscale probabilistic maps were developed, based on existing data. The final product is the result of overlapping the four individual gradient maps in Figure 3.

- Public vs private land (Figure 3A)
- Existing master plans (Figure 3B)
- Vertical density (Figure 3C)
- Public transportation density (Figure 3D)

This final gradient map (see Figure 4) was used later, as the base for the evolutionary mapping model.

Economic and Construction Parameters

Sets of economic data were used in combination with construction data for the evolutionary computation process. More specifically, the data concerned the number of high-rise buildings built per year, their height, areas, and their relation to the overall economic conditions of each year. Tokyo's low economic growth typically has resulted in an increase of high-rise developments, in part due to lower land prices, the introduction of economic stimulus, and less-restrictive building regulations as the government attempts to boost productivity across the economy (see Figure 5). In Tokyo, high-rise construction has been more of a tool to boost economic development than a result of economic growth itself (Pazos 2014). Since 1960, a total of 51 buildings over 130 meters were completed in Minato Ward, with 31% of them having been built during the year 2003 alone, mainly because height limitations were eased in the year 2000 by the Urban Regeneration Act (the typical high-rise building takes an average of three years to build in Tokyo).

Thus, it can be assumed that economic stimulus packages by the Japanese government tend to result in an increase of high-rise construction, which materially manifests itself after three years. This produces a clear wave-like pattern, through which the evolutionary model contrasts economic and construction data to generate its simulations.

Figure 3. Probabilistic diagram mapping, correlating conditions to likelihood of high-rise construction.

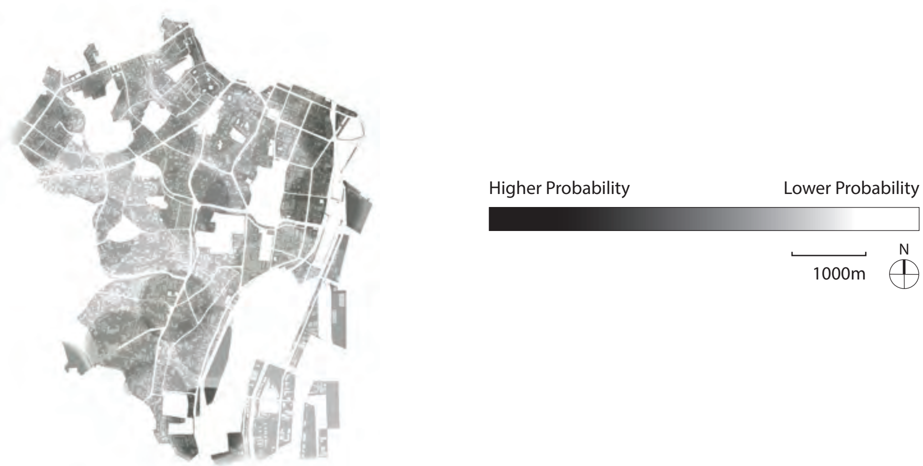

Figure 4. Probability of High-Rise Development, Minato Ward, Tokyo, 2016-2019 allocation diagram produced from overlapping all the diagrams in Figure 3. The darker gray areas show a higher probability of future high-rise developments.

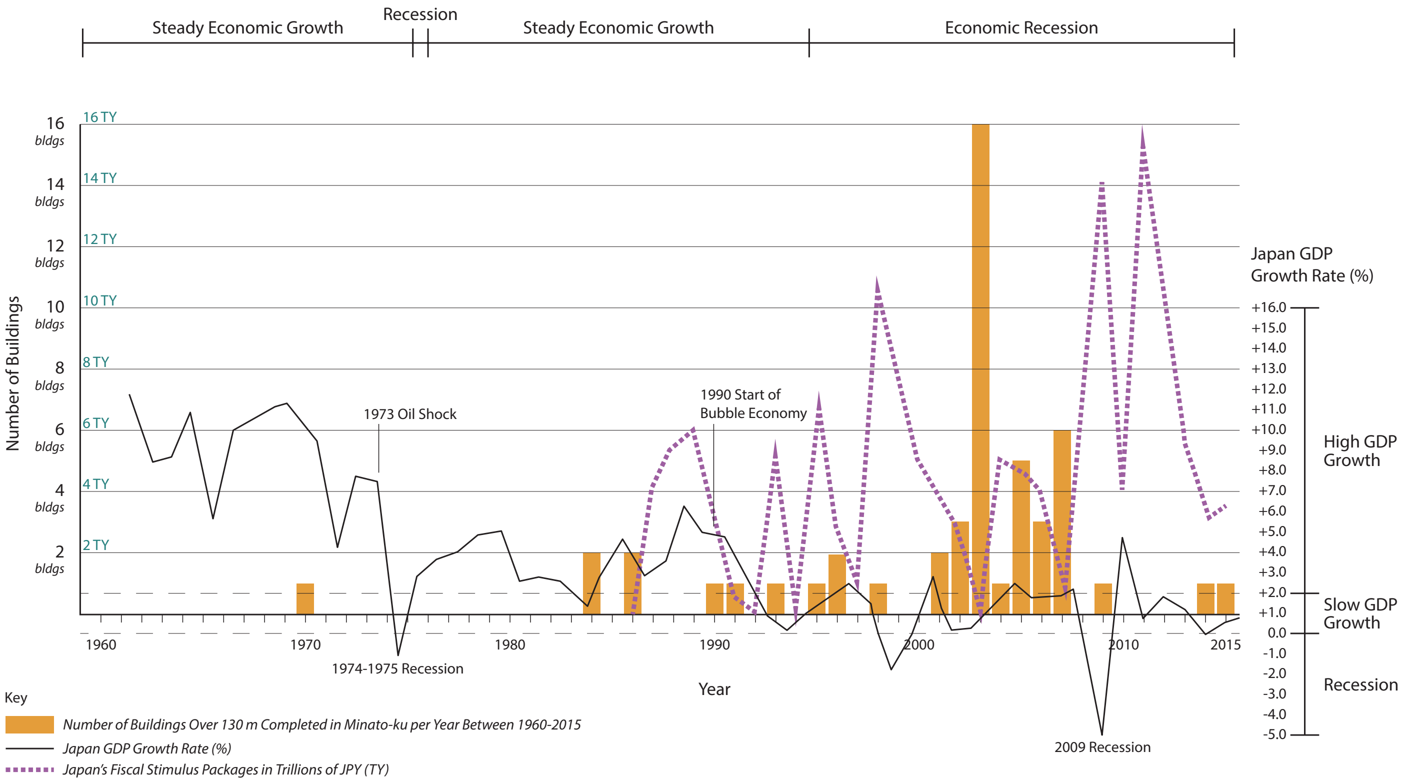

Figure 5. Number of buildings 130 meters and higher built per year in Minato Ward from 1960 to 2015, combined with Japan's Gross Domestic Product (GDP) growth rates and economic stimulus packages.

Evolutionary Computer Model: Vertical Growth Algorithm

The probabilistic gradient map and the economic parameters (see Figures 4 and 5) were combined to generate a computer evolutionary model to simulate the construction of buildings over 130 meters in the Minato ward of Tokyo for the period of 2016-2019. The gradient plan (as seen in Figure 3) was used as a base for the genetic algorithm process. First, the computer model learned how to generate the gradient map plan, using data from the 2015 conditions. It could then later predict its evolution by generating a new gradient map for the next four years.

Economic data from the World Bank (2016), containing 184 economic indicators, was also input into the evolutionary algorithm for the years 1991-2015. This is the period following the bursting of the Japanese economic bubble, and is when most high-rise construction took place in Tokyo. Based on simulations using this data, the algorithm can then generate new simulations representing future development. Construction data taken from the Emporis Building Directory (2017) and the CTBUH Skyscraper Center (2017) were also input into the algorithm.

The essential work of the algorithm is to identify and learn patterns from the data, and then create its own routines based on data for future economic predictions. In essence, it is auto-generating its own simulations, regarding high-rise construction for the years to come. This hybrid genetic algorithm (Mathias et al. 1994) calculated the best possible combinations of selections and transformations for all the input features (see Table 1).

Once both predictive models were determined, the gradient probabilistic plan was used (as seen in Figure 4) for the generation of a stochastic roulette wheel,

Operators	Add, subtract, sin, cos, tan, asin, acos, atan, log, exp, sqrt, and inverse
Initialization	Ramped Half-and-half
Fitness Function	R-Squared Correlation
Recombination Strategy	1-point Crossover
Mutation Strategy	Leave-flipping
Mutation Rate (pm)	0.05
Crossover Rate	0.90
Selection Strategy	Proportional Roulette Wheel
Replacement Strategy	Invert-fitness

Table 1. Technical specifications of the algorithm proposed.

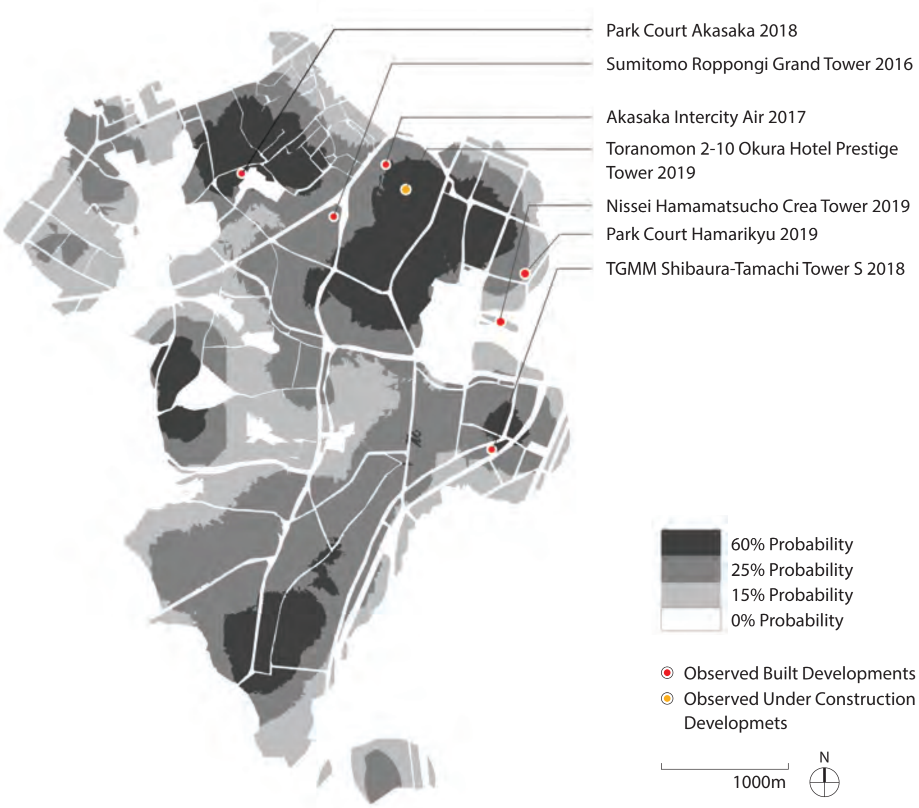

Figure 6. Genetic algorithm predictions on a probabilistic grayscale. The darker gray shows the higher probability.

“As field observations were repeated every year, by 2017 it was evident that the algorithm predictions were far more accurate than the field observations.”

based in stochastic universal sampling (Baker 1987). A total of 100 independent simulations have been made according to the 2015 map by estimating the possible locations of the buildings in Minato Ward over the 2016-2019 interval. The number of buildings and their height were determined using both predictive models. A probabilistic map was then generated, where the darker grayscale tone represents a higher likelihood of a new building over 130 meters to be developed (see Figure 6).

Results and Evaluation

In December of 2015, the algorithm was tested to simulate the vertical growth of Minato Ward in Tokyo for the period of 2016-2019. Simultaneously, as an independent process, the team gathered data regarding the ongoing high-rise construction in the ward and repeated the process every year to make its own predictions regarding the evolution of the skyline. The researchers' first impression was that the algorithm was wrong, which seemed to be a correct assumption, given that both sets of data initially seemed to be very different. As field observations were repeated every year, by 2017 it was evident that the algorithm predictions were far more accurate than the field observations.

Table 2 shows the data gathered through the latest observations made in April 2019, and is contrasted with the initial data obtained from the computer model back in 2015. The table compares the two sets of data and shows the differences in the right column.

The team's observations in early 2019 identified the following buildings already completed over the 2016-2019 period: Sumitomo Roppongi Grand Tower (231 meters, 2016), Akasaka Intercity AIR (205 meters, 2017), Park Court Akasaka Hinokicho The Tower (170 meters, 2018), Nissei Hamamatsucho Crea Tower (156 meters, 2018), TGMM Shibaura (169 meters, 2019) and the Park Court Hamarikyu The Tower (140 meters, 2019).

There are also some buildings still under construction and scheduled to be completed by September 2019, such as the Okura Tokyo Prestige Tower (189 meters, 2019). Another two buildings currently under construction, which were initially scheduled to be completed during 2019 but are running behind schedule, are the Toranomon Hills Business Tower (185 meters) and the Toranomon Hills Residential Tower (220 meters). These two buildings were shown in previous observations, however, as their official schedules have been delayed to 2020-21, they have been excluded from the list.

As of April 2019, the evolutionary algorithm has proven to be 85.7% accurate on its predictions regarding the total number of buildings over 130 meters to be built in Minato Ward for the 2016-2019 period, with a total of seven buildings completed or about to be completed, and a total of six buildings predicted by the genetic algorithm back in 2015. The results will not be definitive until the end of 2019, as construction delays are common, and there are several other tall buildings under construction as well.

Regarding the total cumulative height of the buildings of at least 130 meters for the four-year period, the data shows a total of 1,260 meters, versus the 1,464 meters predicted by the genetic algorithm, which results in an accuracy level of 86%. This gives it a similar success rate as the prediction of the total number of buildings.

On the other hand, the average height observed was 180 meters, as opposed to the 244.1 meters' average height predicted by the algorithm, yielding results of only 73.7% accuracy, or a difference of 64.1 meters. This result was probably less accurate than the others, due to the fact that 300 meters was set as the maximum height for the genetic algorithm process, despite the fact that currently the tallest building in the ward is only 255 meters. A correction on the initial parameters of the computer model would probably have produced better results. As machine learning generates knowledge from the data it uses, wrong or inaccurate data will produce incorrect results.

The algorithm had an error of plus or minus one building per year as an average, which suggests that, even if the algorithm was very precise in predicting the overall number of buildings for the four-year period, it was not accurate in predicting the exact time of construction completions, typically deviating from reality by a few months. Those deviations are acceptable in the overall reading, as one year offsets the differences for the next one.

The six red dots on the Minato Ward map (as seen in Figure 6) show the six buildings already completed by April 2019. The orange dot shows the buildings currently under construction and scheduled to be completed by September 2019. Regarding the location of the buildings, the algorithm predicted areas with higher and lower probability of allocating the new developments. The results provided by the genetic algorithm were the following:

- 60% of buildings will be allocated to the dark-gray areas (three to four buildings).
- 25% of buildings will be allocated to the medium-gray areas (one to two buildings).
- 15% of buildings will be allocated to the light-gray areas (or one building).
- 0% of the buildings will be allocated to the white areas.

The current data observed is convergent with the computer model predictions, and the team's current observations are the following:

- 57%, or four buildings, are located in dark-gray areas
- 28.7%, or two buildings, in the medium-gray area.
- 14.3%, or one building, in the light-gray area.
- 0 buildings in the white areas.

Conclusions

The constantly changing skyline of Tokyo has come to redefine its identity, as its high-rise structures are relatively new. The changing skyline and morphological evolution are both driven by a self-organizing and evolutionary process. This research developed an adaptive evolutionary model and was tested via genetic algorithms, which, in the end, were able to imitate the future vertical growth of Tokyo's Minato Ward.

The results yielded by the algorithm simulations mirrored real developments, as they were 85.7% accurate for the total number of buildings, 86% accurate for the accumulated heights, and 75% for the average height of all new constructions 130 meters and higher in the four-year period of the study. The allocation of new construction projects within the grayscale map was also very accurate, with maximum deviations of only 3.7% over the original predictions. It is worth noting that the sample is very small, with only seven buildings over the four-year period, meaning that the difference of one building results in a 14.3% error. For future studies, a larger area and time period would most likely produce better results in terms of evaluating the methodology.

As was mentioned in the introduction, the evolutionary computation process cannot predict what is going to happen, but it can generate a system that simulates reality with a high degree of accuracy, while providing another way of thinking about how to organize height and spatial data (see Figure 7).

	Observed Real Developments			Algorithm-Predicted Developments			Difference (Observed-Predicted)		
Year	Number of Buildings	Total Accumulated Height (m)	Average Height (m)	Number of Buildings	Total Accumulated Height (m)	Average Height (m)	Number of Buildings	Total Accumulated Height (m)	Average Height (m)
2016	1	231	231	0	0	0	+1	+231	-231
2017	1	205	205	2	407.4	203.7	-1	-202.4	1.3
2018	2	326	163	1	220.9	220.9	+1	+105.1	-57.9
2019	3	498	166	3	836.4	278.8	0	-338.4	-112.8
Total	7	1260	180	6	1464	244.1	+1	-204	-64.1

Table 2. Observed available data for future construction in Minato Ward versus predictions by the algorithm for the years 2016 to 2019.

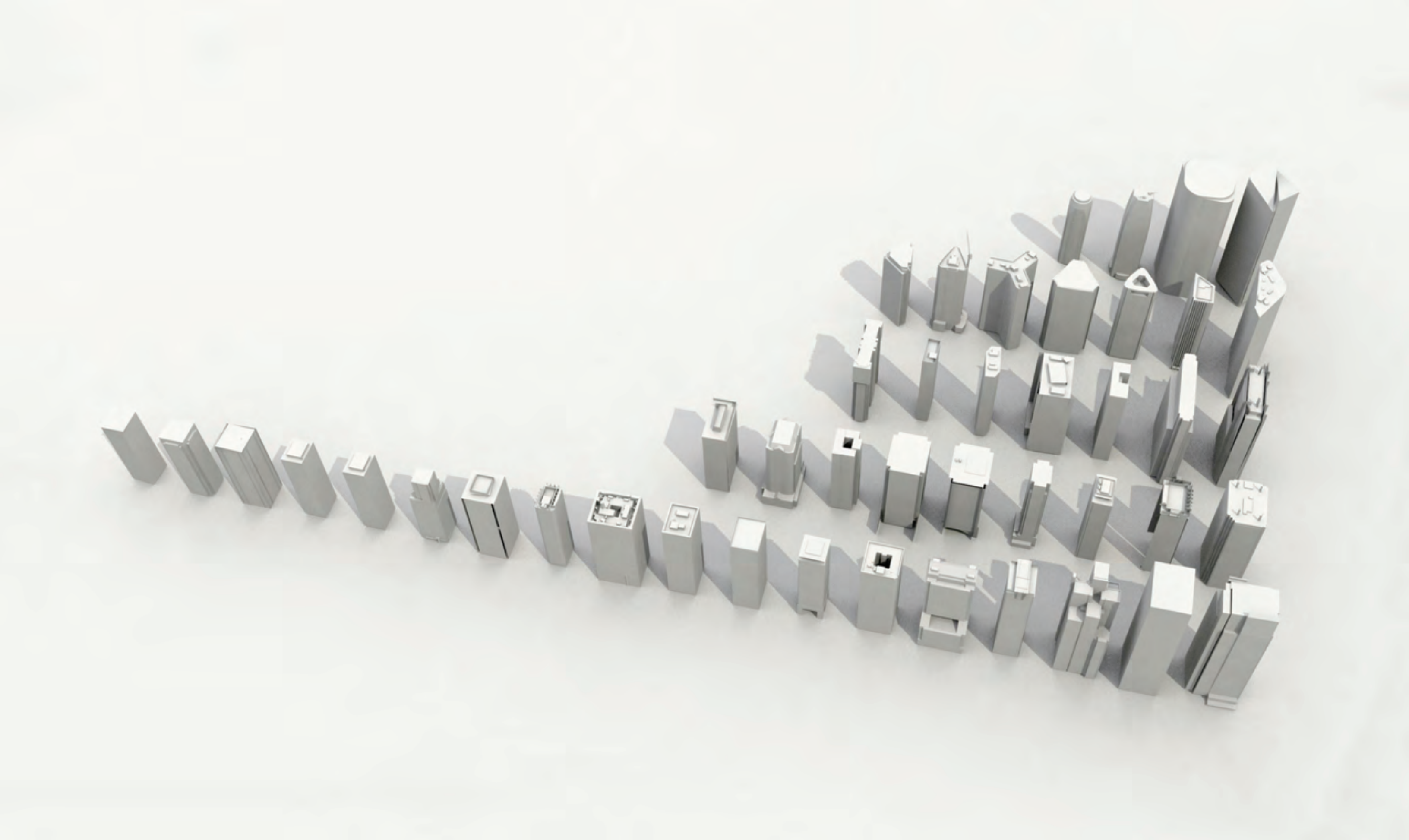

Figure 7. Minato Ward buildings over 130 meters in 2015. The buildings are organized by height and by plan type.

In this case, it learned from the given data and generated a simulation that was 73.7% to 96.3% convergent with the actual evolution of the ward's vertical growth over the four years that was established for the study. Being able to simulate how a city can grow like a self-organizing system could be useful for urban planners, designers, policy makers, and governments to make better decisions regarding the future of our cities. ■

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