AUTOMATIC GENERATION OF VIRTUAL CITIES BASED ON USER DEFINED ZONING DISTRICTS

A Thesis

by

KATHRYN ELIZABETH VAN MAANEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Visualization

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Approved by:

Chair of Committee,	Vinod Srinivasan
Committee Members,	Rodney Hill
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ABSTRACT

Automatic Generation of Virtual Cities

Based on User Defined Zoning Districts. (May 2012)

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Traditionally, city maps are drafted in two dimensions, on paper and using GIS technology, and specify the placement and boundaries of different zoning districts. Two dimensional maps place limitations on the designer, including, but not limited to, the inability to foresee areas which might be shaded by neighboring buildings. This thesis presents a prototype for a visualization tool to create city maps in three dimensions. Three dimensional city planning can be beneficial because it allows the designer to envision a proposed skyline and balance the positive space of the building mass and the negative space surrounding and in between buildings. This visualization tool allows the city planner to layout a city map using four different zoning districts. Once drafted, the city map is populated with three-dimensional building models representing buildings commonly found in each local zoning district. The purpose of this virtual environment is to help visualize a hypothetical city created under conditions of the proposed city map.

TABLE OF CONTENTS

CHAPTER Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

CHAPTER I

INTRODUCTION

Dong [11] defines visualization as a process that begins with mental imagery and eventually evolves into a design solution. Visualization is a way of allowing the designer to communicate ideas but it also serves as an aid while working through the design process [11]. Computer visualization is often utilized to enhance educational tools. This is particularly true for teaching natural phenomena that cannot be easily observed by the human eye. For example, the human eye cannot observe molecular structure and behavior however, computer generated images can be created to represent this phenomenon. Three-dimensional computer graphics can also aid in the visualization of proposed architecture. Computer generated models allow the architect to further study a working design and better understand spatial relationships. A more precise computer model may help accurately specify fabrication materials and methods before construction [11].

I.1. Terminology

The focus of this project is on applications of visualization in the planning and design of cities. It is important to understand the terminology common to the urban planning industry as well as the traditional planning and zoning process. My thesis assumes beginner planning knowledge and focuses on zoning implementation.

The journal model is *IEEE Transactions on Visualization and Computer Graphics.*

I.1.1. Planning

Geographical Information System(GIS) describes hardware or software which gathers, maps and analyzes data relative to location [13].

Urban planning is a process concerned with maintaining the welfare of people and creating a well functioning system of public and private transportation within a city while accounting for and preventing environmental damage ensued by mankind on itself [10].

A *master plan*, also commonly referred to as a *comprehensive plan*, is a long term community plan to help shape the pattern of growth and development in a community [10]. Some issues addressed in detail, in this plan, are growth over time, street patterns, transit, public access to community facilities, housing and land use [10]. The professionals who practice this work are commonly referred to as *city planners*. City planners tackle issues such as how to create a well functioning system of public and private transportation within the city and how to account for and minimize environmental damage resulting from human activities [10].

I.1.2. Zoning

Zoning is the division of a city or county into areas or zones which determine the land uses for property within these zones. Each specific *zone* or *zoning district* includes a set of detailed guidelines and restrictions for buildings occuring within said district. District guidelines monitor what type of buildings are approved for the delegated land use. Additional guidelines, such as height, lot coverage and property setback, exist to provide building uniformity [10]. My thesis assumes beginner planning understanding and focuses on zoning implementation.

The placement and layout of all zoning districts in an entire city is compiled in a single graphical map known as a *zoning map*. The zoning map delineates all district boundaries within the city [10]. A *zoning lot* is an individual lot or *parcel* within a given zoning district [10].

Each city writes an approved *zoning ordinance*, also commonly called a *unified development code*. This code is an ordinance enacted by the city council as a set of regulations and standards for land use and building structures within the city [10].

A *Building Setback* is an offset distance taken from a street, road, or boundary line. When building setbacks are established on a designated plot of land, no building may cross those setback lines [10].

I.1.3. Form

This thesis focuses a large amount on studying, defining and creating building form. It is important to understand the basic concept of form as it pertains to architecture. *Form* is a three-dimensional mass or volume constructed of many surfaces. Each surface has a unique shape and when configured together create form. Additional visual properties contributing to form include, size, color, texture, position and orientation [5]. Ching defines the primary solid forms as the sphere, cylinder, cone, pyramid and cube in Fig. 1.

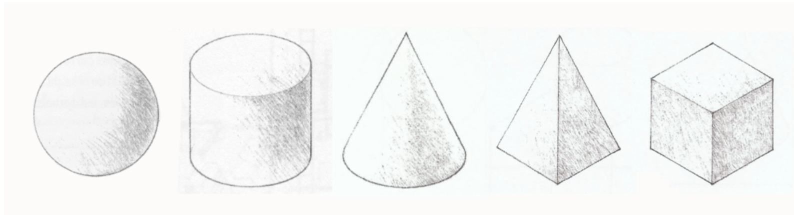

Fig. 1. Five primary solids

I.2. Background

The notion of creating zones within a city began to emerge in the 1910's. Fig. 2 photographs how skyscrapers in New York City began to densely populate the city creating narrow corridors of shadowed unused space between buildings [4]. The negative space in between towering buildings is not desirable as it is deprived of sunlight and ventilation. In 1916 New York City was the first in the nation to establish a complex zoning ordinance when it passed the Zoning Resolution of 1916 [4]. The ordinance restricted building use according to zoning district and placed limitations on the size of buildings to be built. One limitation placed by the resolution capped the maximum building mass allowed per building [4]. This law refers to the spacial area enclosed by a single building. All of the city was zoned into one of five height districts: one-times-district, one-and-one-quarter-times district, one-and-one-half-times district, two-times district, and two-and-one-half-times district[4]. The height district acts as a multiplier on the width of the street adjacent to the building[4]. For example, in a one-and-one-half-times district in which the street width is 100 feet, the facade of the building may only reach a height of 150 feet before the facade structure must be stepped inwards. In Fig. 3, Bressi[4] illustrates an orthographic section of the theory behind setback restrictions for different height districts. As these building restrictions were enforced in new skyscraper construction, resulting building structures started to resemble a tiered wedding cake. Resulting structures are documented by Bressi[4] in Fig. 4. Additionally, the Zoning Resolution of 1916 placed regulations on developing land which governed the type of building uses permitted for the entire unbuilt city[4]. Three different use categories existed: residence, business, and unrestricted[4]. The Zoning Resolution of 1916 set the ground work for future zoning practices and numerous cities soon followed their lead by establishing their own city ordinances [16].

I.3. The Zoning Process

As previously stated, each city adopts a city planning code to promote public health and safety. Some specific purposes of the City Planning Code of San Francisco[2] include:

- To guide, control and regulate future growth and development in accordance with the Master Plan of the City and County of San Francisco.

- To protect the character and stability of residential, commercial and industrial areas within the City, and to promote the orderly and beneficial development of such areas.

- To provide adequate light, air, privacy and convenience of access to property, and to secure safety from fire and other dangers.

Fig. 2. Skyscrapers in New York City built so close together formed dark and hazardous spaces in between them[4]

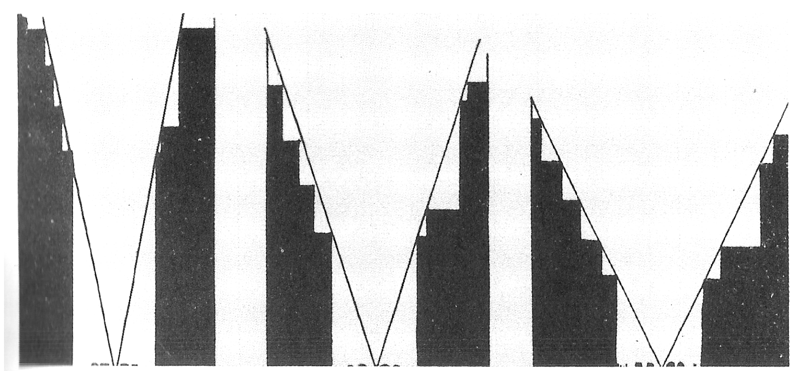

Fig. 3. The Zoning Resolution of 1916 placed tiered setback regulations on skyscrapers in New York City

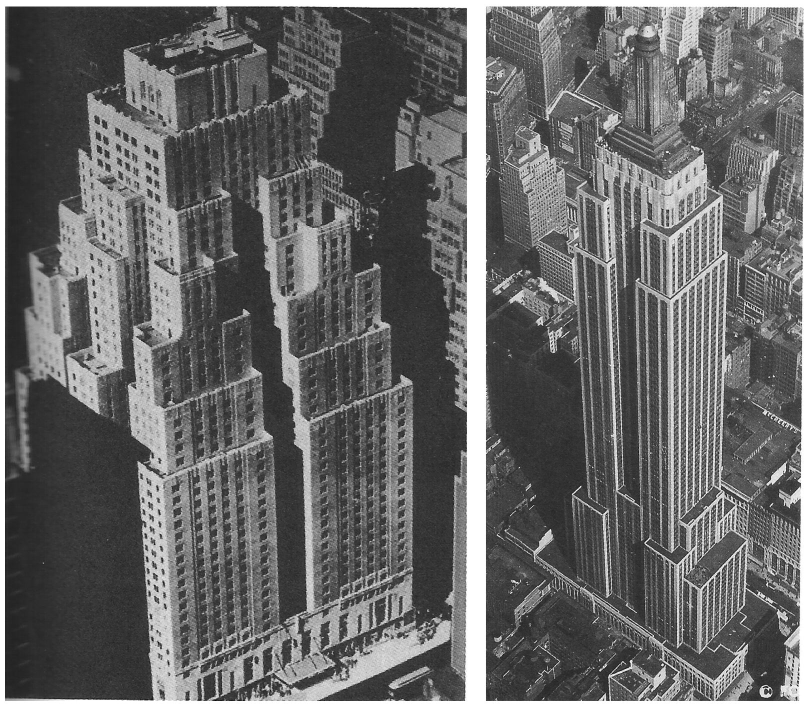

Fig. 4. (Left)Hotel New Yorker and (Right)Empire State Building. Both structures resulted from the tiered setback regulations defined in the Zoning Resolution of 1916

- To prevent overcrowding the land and undue congestion of population.

- To regulate the location of buildings and the use of buildings and land adjacent to streets and thoroughfares, in such manner as to obviate the danger to public safety caused by undue interference with existing or prospective traffic movements on such streets and thoroughfares.

I.4. Motivation

A city planner traditionally drafts placement of zoning districts on a two-dimensional zoning map. Before computer visualization systems were utilized, city planners would gather several different maps, each representing different land data, and combine the data as desired into a single map on paper by hand[9]. This process was extremely time consuming for the planner. The recent development of GIS allows planners to quickly access and analyze different sets of geographical data and information. Additionally, planners now have the ability to read and combine endless sets of data in layers and compare and contrast layers in an endless number of combinations[9]. The use of GIS data has significantly quickened the city zoning process. An example GIS planning tool provides complex two dimensional maps to city planners depicting expected growth and future land-use patterns[1]. Fig. 5 shows an example zoning map for the City of Austin created using GIS information available on the City of Austin website[6]. This zoning map demonstrates placement and scope of several different zoning districts, each represented by a different color and applied to individual plots of land on the map. Just looking at two dimensions, it is hard to visualize what a city may look like after it is developed. Additionally, the relationships between neighboring districts cannot be easily observed. Issues such as high-density and office buildings casting shadows on low density commercial buildings could possibly go unnoticed in two dimensions, but is easily seen in a three dimensional environment.

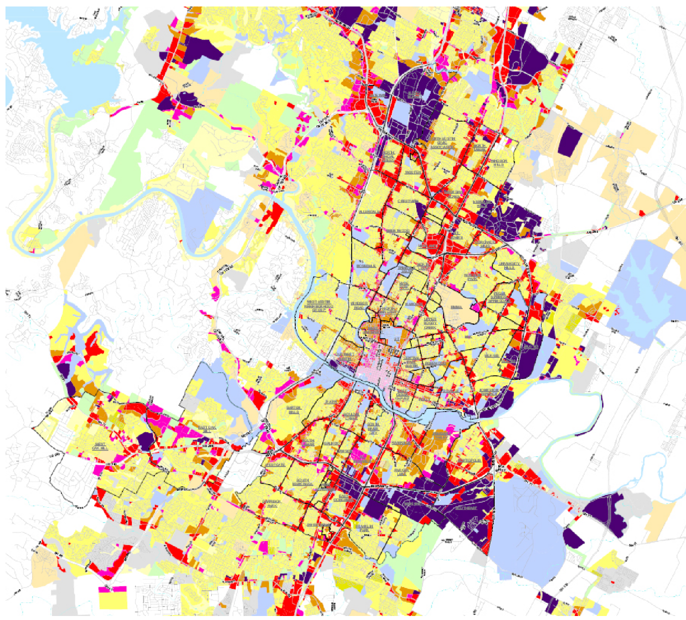

Fig. 5. Zoning Map for the City of Austin created using GIS data available on the City of Austin website in 2008.

A project manager must consult a written zoning ordinance when constructing in accordance with a city plan. Each city has an individual zoning ordinance defining districts or zones. Each district or zone represents a different usage category for buildings erected under that group [27]. The rules located in the ordinance can be incorporated into a three-dimensional design program to make the design process easier and more fluid. The implementation of delegated land use zones in a three dimensional virtual environment allows the planner to visually see the proposed working relationships within the same zones, as well as, interrelationships existing where different zones meet.

The visualization of zoning maps is useful for more than just observing relationships between zoning districts. A natural part of the design process is to try multiple design scenarios because there is never a single right answer to the problem. Roeseler [21] stresses that the process of delegating land use zones should be a flexible and variable one when designing city maps. The ability to analyze multiple design solutions quickly and with ease is desirable in a visualization tool being utilized for urban planning.

This thesis focuses on creating a visualization tool to combine some of the rules implemented in creating two-dimensional city maps with the idea of visualizing hypothetical three-dimensional representations of traditional two-dimensional city maps. The intent is to introduce a new design technique associated with city planning by increasing the level of design flexibility as well as increasing the users ability to visualize a larger variety of design solutions.

CHAPTER II

PRIOR WORK

The creation of urban city environments in a virtual world is a task that has been practiced and implemented for several years using different processes. There are existing techniques which implement processes to create digital replications of pre-existing environments. These processes often use photographic[24], satellite[23] or video[15] imagery. Additionally, there are techniques which create virtual environments which are new, unique and do not already exist in the real world. In contrast to the prior, these environments are created according to a set of rules which govern variables such as road placement, building height, and building setback.

Sometimes the virtual world demands a digital replication of an existing city environment. Kawasaki [15] proposed a method to derive a 3D city map using information gathered from real world video input. Video tracking of environments involves attaching a camera to a vehicle, perpendicular to the direction of vehicular movement, and tracking placement of existing structures while driving through the streets. Kawasakis method is a technique requiring patience, consistency and lengthy time commitments. Through the software program Google Earth, Google has been working for years to create 3D representations of existing buildings to incorporate with satelite imagery[23]. Google SketchUp is a 3D modeling package available to any user looking to contribute to Google Earth[26]. Users may submit 3D models to a building catalog called 3D Warehouse[23]. Google has standards and requirements for buildings which may be added to Google Earth and only the best are used[26].

Sun[24] discusses real world replication techniques using aerial photographs to generate transportation networks. In the aerial photographic image, roadways are easily recognized and distinguished as a separate entity. A large amount of research and development continues to occur in the direction involving reconstruction of existing cities. However, this direction of research limits the virtual designer to only what already exists in the real world.

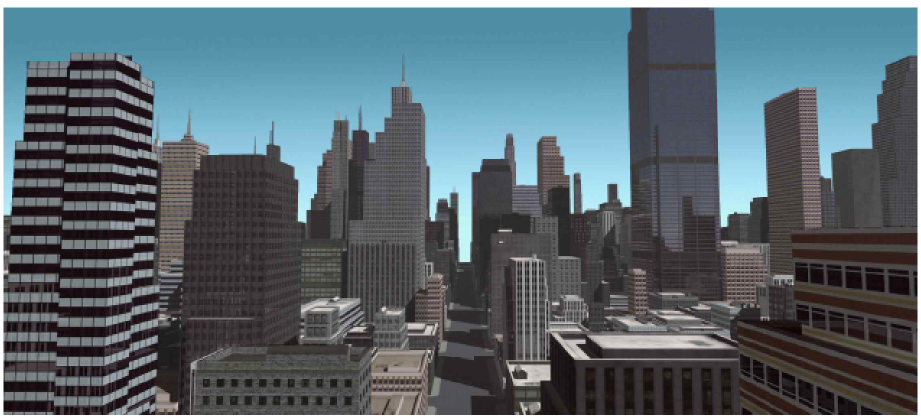

Fig. 6. Image of a virtual Manhattan from Parish's CityEngine

A creative world of endless possibilities exists when designing techniques to generate arbitrary city structures, which do not replicate real world environments. L-systems, known also as Lindenmayer systems, were founded by Aristid Lindenmayer for use in biological development, but have been adapted for use in computer graphics[20]. These L-systems utilize a repetitive recursive function, which consistently replaces portions of a simple basic object with various differing parts, according to rules established by the programmer. Parish [19], wrote and implemented a program he named CityEngine and integrated the use of L-systems with rules based on data gathered from studying the city plans of Tokyo, France, London and New York. The focus of Parishs CityEngine is to procedurally generate transportation networks, subdivide land into parcels and create unique building structures of arbitrary environments from scratch[19]. The subdivision step which divides the map into individual land parcels, of varying size, reflects population density information which is input from the user. Additionally, the selection of building type for each parcel is also governed by GIS information supplied by the user and each building is procedurally generated according to rules specific to each building type[19]. Fig. 6 displays an image created by Parish[19] using CityEngine of a virtual Manhattan.

If we take a close look at the underlying infrastructure of a city, we will see that it is made up of many different land usage subcategories. Zoning ordinances are present when designing most city plans to broadly separate the land into use categories. Unlike the other design techniques, Watson [25] created a program called NetLogo to procedurally define land usage utilizing four subcategories, residential, business, industrial and road. The user must supply the terrain information and the program automatically subdivides the terrain into a grid of many smaller rectangles called parcels. Users have the ability to interactively paint the individual parcels to specify parameters such as, road density and grid spacing of roads. NetLogo [25] focuses primarily on procedurally defining land use and a hierarchy of roadways. Over time, the program simulates growth within the city. Fig. 7 demonstrates

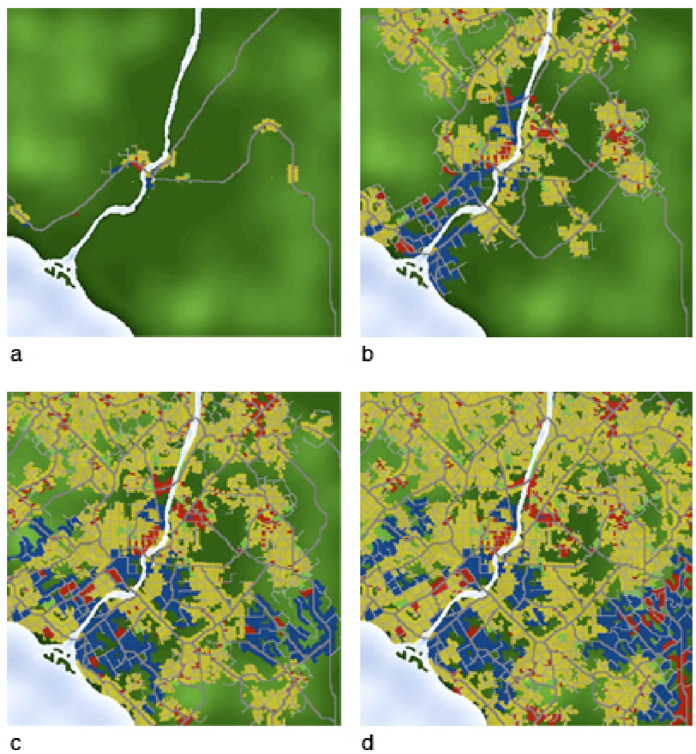

Fig. 7. Snapshots from NetLogo demonstrate land use growth over time

the progression of land use growth from images a to d. To integrate the program with a procedural technique for designing and placing buildings, Watson imported the NetLogo logic into the widely popular video game graphics of SimCity 3000. The virtual city in Fig. 8 demonstrates proposed growth over time, exhibiting the redevelopment and conversion of transportation and land use parcels [25].

Fig. 8. Snapshot of NetLogo logic run inside SimCity 3000 graphics

One of the first city building simulation games SimCity, developed by William Wright, was first released to the public in 1989[12]. SimCity was extremely influential

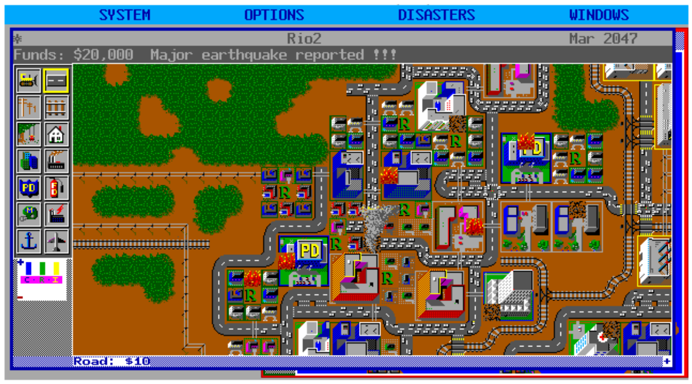

Fig. 9. Snapshot from Wright's SimCity released in 1989

Fig. 10. Snapshot from EA's SimCity 4 released in 2003

as it was one of the first programs to expose large numbers of the public population to the city planning process[9]. The game was unique because it appealed to individuals beyond the typical video "gamer"[12]. The underlying concept behind the SimCity game allows the user to create virtual cities and watch them grow and develop over time. Users could place different land use types, such as residential, commercial, industrial, and open space, on a virtual map and see how the land develops and reacts to the user defined zoning[12]. Several versions of SimCity have been released since the original in 1989 and with each new release, more complexity and user responsibility is included. SimCity4 inflates the user responsibility to manage the city's finances, environmental balance and quality of life for the inhabitants of the city[9]. Fig. 9 shows a screenshot from the original 1989 release of the SimCity program. Fig. 10 shows screenshot of a city created with SimCity 4 released in 2003. Between the two SimCity programs we see a progression from 2D to 3D graphics as well as an obvious increase in detail and quality of graphics. The SimCity program continues to be developed and turn out new and improved versions.

Key differentiating aspects of my tool are the ability to experience environments in an immersive manner and the increased amount of design flexibility provided to the user. The program will allow the user to navigate through the environment and view the space from any vantage point. The user will have full control of the city infrastructure and plot boundaries, as well as, the ability to quickly and easily create multiple design solutions and visualize them interactively.

CHAPTER III

METHODOLOGY

In a broad sense, three of the basic zoning district classifications are residential, commercial and office[27]. Within these three basic districts, it is common to further distinguish smaller subcategories. For example, residential districts can be subdivided into single-family and multi-family uses [27]. Similarly, commercial districts can be subdivided based on density or size of the structure [27]. The city zoning map specifies the location and boundaries of each district within the city. An average city has about 20-30 different districts [8]. For the purpose of this thesis I have dissected at least one subcategory from each of three major categories as it exists in the City of San Francisco Planning Code[2].

Focusing on three very different building districts allows us to compare, dissect and replicate the building forms associated with these differing districts. A visualization tool, which utilizes this study and generates unique architecture within zoning districts, can make visualization easier.

III.1. Form in Architecture

All architecture is derived from form. The Capital Records building in Los Angeles, California is a good example of a building form with a basic cylinder shape. The Luxor Hotel in Las Vegas, Nevada maintains a basic pyramid form and the Soundhouse Building in Sheffield, United Kingdom clearly exemplifies a structure with a basic cube form. Fig. 11 demonstrates some examples of basic form in existing

Fig. 11. (Left)Capitol Records in Los Angeles, CA[7]. (Right)Soundhouse in Sheffield, United Kingdom[22]

built architecture. All other forms are understood as transformations of the basic forms and these transformations are characterized as dimensional transformations which manipulate one or more of the form dimensions, subtractive transformations and additive transformations [5]. In Fig. 12 Ching sketches these transformations. Architectural form can also be derived from a series of interlocking forms of similar or different basic design. In Fig. 13, Ching sketches simple interlocking forms. Fig. 14 captures a built example of form derived from interlocking basic solids with the Transamerica Pyramid in San Francisco, CA. This building interlocks the basic pyramid and cube forms. Additionally, the Habitat 67 housing complex in Montreal, Quebec, Canada is an intricate repetition of interlocking cube forms[18].

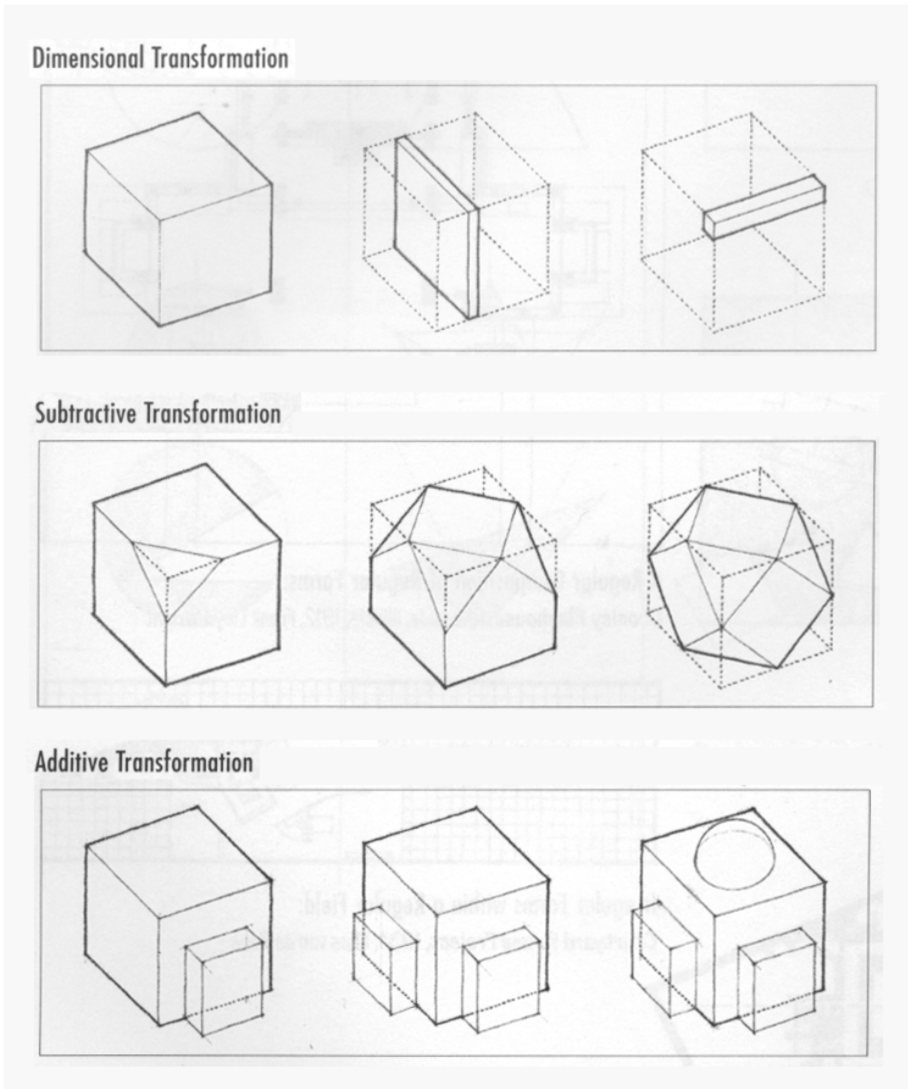

Fig. 12. All non basic forms are transformations of the basic forms

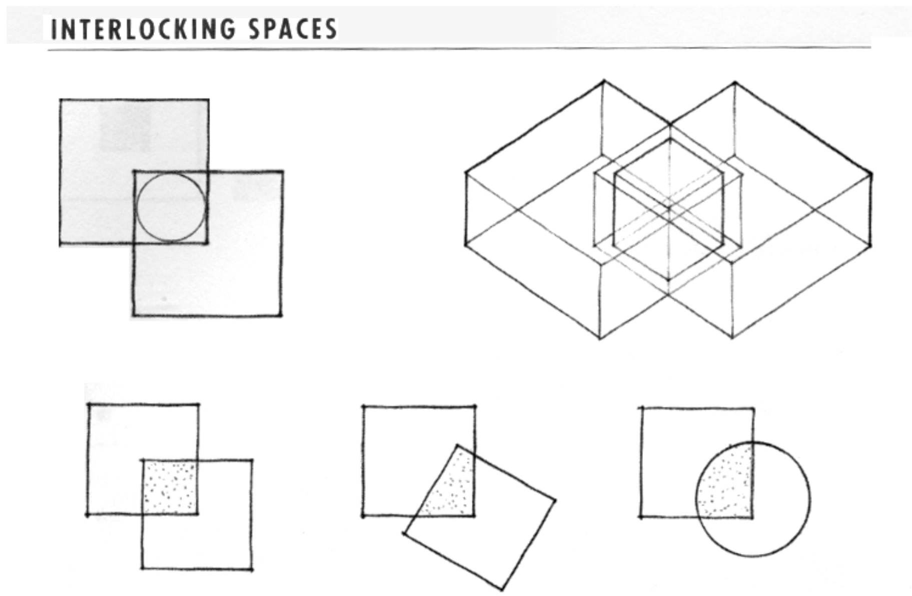

Fig. 13. Ching sketches form as interlocking primitives

III.2. Residential District

The city of San Francisco Planning Code[2] categorizes residential house districts with the prefix RH. The RH prefix is then followed by a number representing the number of families per dwelling. For example, RH-1 represents a one-family home and RH-2 represents a two-family home. This thesis will focus only on the RH-1(D) district. The D in this district name denotes that it is a detached dwelling and resides on a lot in and of its own[2].

Buildings in the RH-1(D) zoning district can be relatively large but rarely exceed 35 feet in overall height. Lots in this district are generally larger in size and provide

Fig. 14. Transamerica Pyramid in San Francisco, CA. Photograph taken by author

the opportunity for front and rear yards of generous size. Houses in this district are placed on lots in rows, one next to another, on neighborhood streets[2].

III.2.1. Uses Permitted for the Residential District

The most common building use in the RH-1D district is the single family dwelling. These dwellings commonly have side yards. Additional dwellings permitted within this building district are those specifically designed for and occupied by senior citizens such as a senior citizen community home[2]. Additional buildings uses in this district are characterized as institutions. These institutional building uses are permitted in the RH-1D building district provided that the structure remains residential in character. Example uses include residential care facilities providing care for six or less persons in need of specialized care, a child care facility, a family care home, nursery, orphanage, rest home or a home for the treatment of diseases or psychological disorders[2]. Spaces defined as open recreation and horticulture areas are also permitted in the RH-1D building district. This type of facility may include a park, playground, plant nursery, rest area or neighborhood garden[2].

There are other uses which are not directly permitted to exist within the RH-1D building district, but are subject to approval by the City Planning Commission as a conditional use in this district. These conditional uses primarily include elementary schools, secondary schools, post secondary school, churches or other religious institutions, community clubhouses or neighborhood centers and stand alone parking garages serving residents in the immediate vicinity[2]. For the purpose of this thesis, I only concentrate on representing those building uses which are unconditionally permitted within the RH-1D building district.

III.2.2. Common Building Characteristics of the Residential District

I took reference from existing residential dwellings when defining basic floor plan characteristics for my residential building library. A common floor plan in residential architecture is an L-shaped configuration of interior spaces [5]. Advantages of the L-shaped floor plan is the oportunity for a private outdoor space shielded by the building, as well as, the opportunity for higher density residential areas. In Fig. 15 Ching illustrates interior and exterior spaces created by an L-shaped floor plan as well as the use of repetitive L-shaped residences placed within a community. U-shaped floor plans can form a container and can place focus on the open end of the plan [5]. I designed some residential front facing U-shaped floor plans to place emphasis on the entry and front of the structure. Similar to the L-Shaped floor plan, the U-shape plan can also create a private outdoor area. In Fig. 16, Ching sketches examples of a U-shaped floor plan theoretically works to create a gathering space, entry way and outdoor focal point. I designed buildings with U-shaped floor plans in the residential, neighborhood commercial and office building districts. The most simplistic form of spacial definition is created simply by four vertical planes, enclosing the space between [5]. This is space in its simplist form and I included a floor plan representing a similar and simple layout in the residential district as well as the following commercial and office districts.

I took reference from existing residential dwellings when regulating the building height constraints and roof design and it was my goal to keep these residential

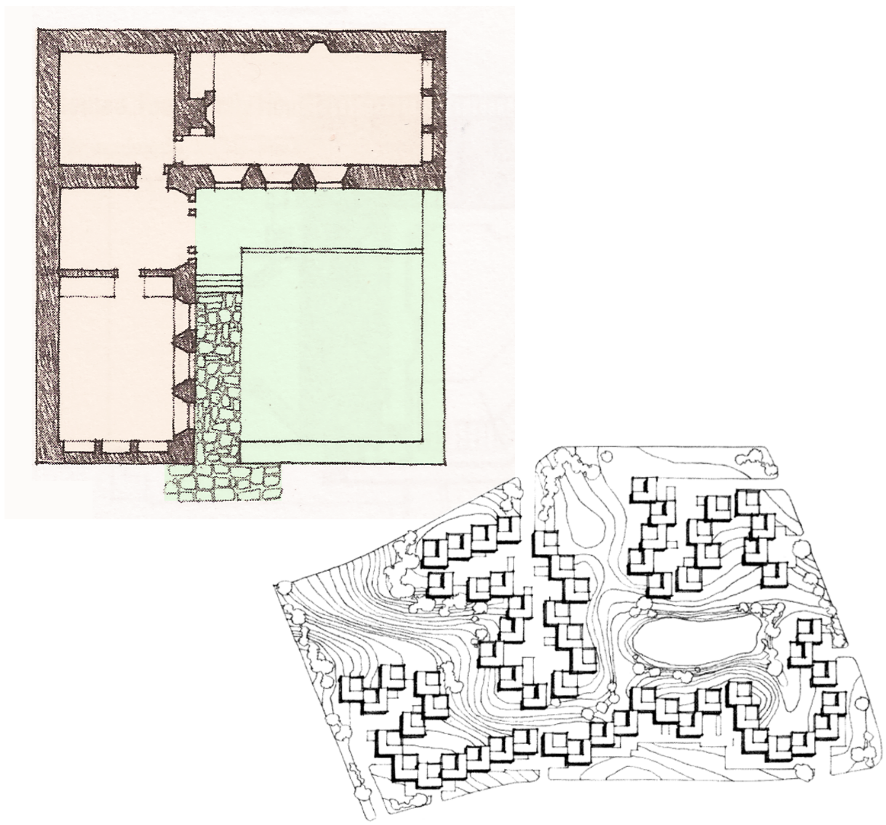

Fig. 15. Ching illustrates the L-shaped floor plan

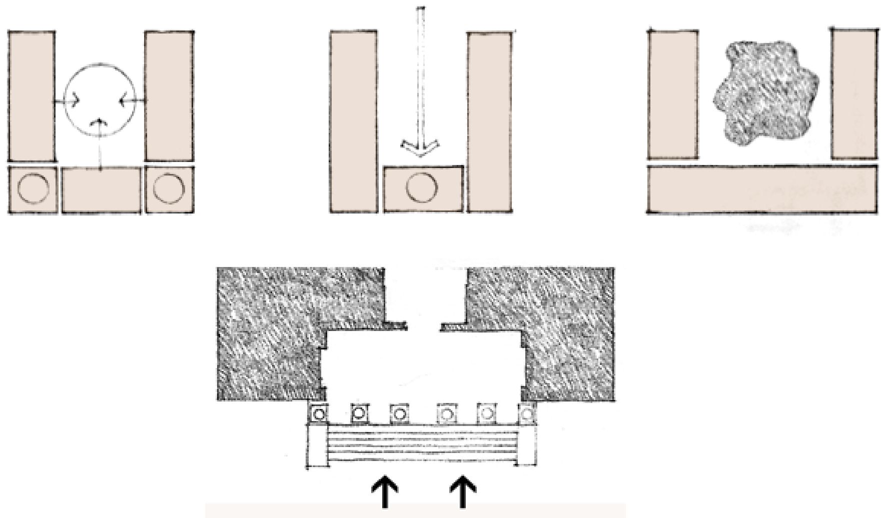

Fig. 16. Ching sketches the theory behind a U-shaped floor plan

forms as simplistic as possible while still providing variation and options for further randomization. A lot of reference was gathered from studying real world residential structures and simplifying them into a series of basic forms. Fig. 17 shows examples of the local residential structures that I studied. As previously stated, residential buildings in the RH-1D building district rarely exceed 35 feet, therefore, I limited my residential structures to a minimum single story and maximum or two stories high. Jefferis [14] categorizes roof shape into eight categories - flat, shed, gable, A-frame, gambrel, hip, dutch hip and mansard. Fig. 18 shows built examples of each roof type. Most roofing materials, as well as, building codes require a minimum roof pitch of 4:12 [14]. A pitch of 4:12 means that for every four units it rises, it will run or span 12 units. The unit of measure is insignificant as long as it is consistently used to measure both the rise and the run. Fig. 19 demonstrates the slope created by a 4:12 pitch. The gable roof is one of the most common roofs found in residential architecture [14]. The existing residential reference I gathered contained a large amount of both gable and hip roofs.

Fig. 17. Residential reference images taken in College Station, TX and San Mateo, CA. All images photographed by the author.

III.3. Commercial District

The Zoning Plan for the city of San Francisco categorizes neighborhood commercial districts with the prefix NC. Just as in the residential district, the NC is then followed by a number. For example, NC-1 represents a Neighborhood Commercial Cluster

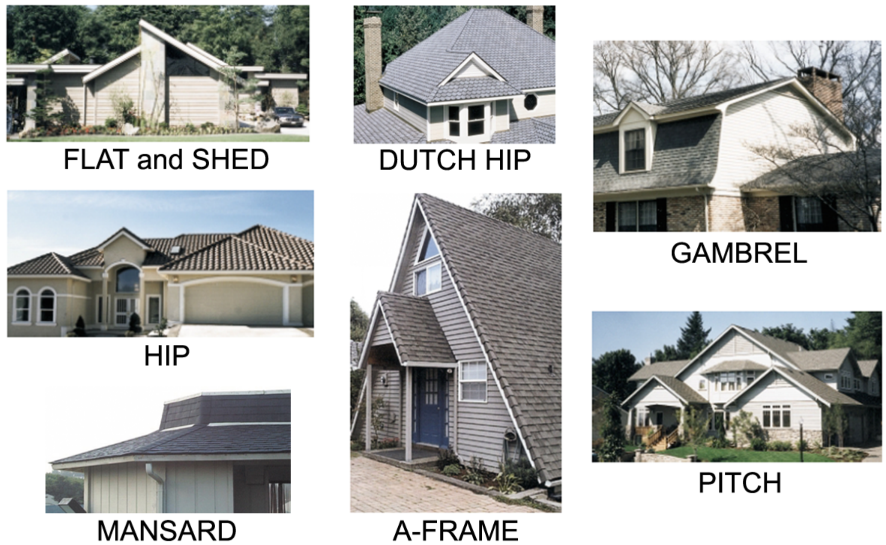

Fig. 18. Roof type examples. Images taken from Jefferis' Architectural Drafting and Design[14]

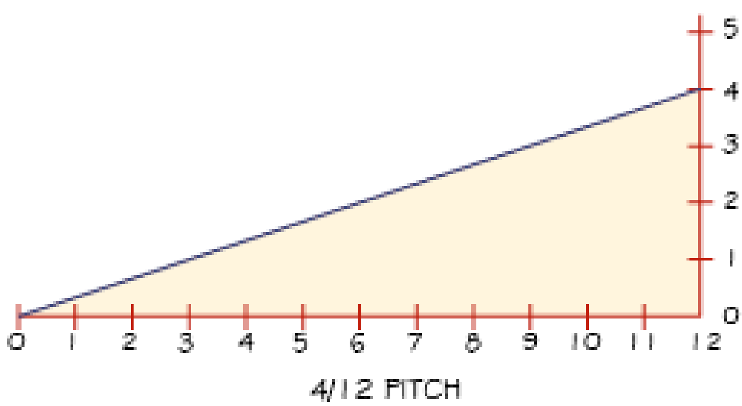

Fig. 19. Jefferis sketches a pitch of 4:12[14]

District, NC-2 represents a Small-Scale Neighborhood Commercial District and NC-3 represents a Moderate-Scale Neighborhood Commercial District[2]. This thesis will subdivide the commercial district into two subcategories and design building representations for both. A Commercial Strip Mall district will be representative of the NC-1 district and a generalized Neighborhood Commercial District with represent the combined NC-2 and NC-3 districts.

III.3.1. Design Laws and Guidelines for the Commercial District

The NC-1 district generally consists of small clusters of three or more commercial units most commonly found surrounded by residential districts. These clusters can have a linear layout or wrap around a corner. The NC-1 district is intended to serve as a convenient neighborhood shopping district. The commercial development is limited to one story in this district and the built square footage is limited to 3,000 square feet. Building use controls promote low-intensity development in order to create areas which seamlessly cohabitate with the surrounding neighborhood districts [2].

Similarly, the NC-2 and NC-3 districts are also intended to cohabitate and serve within surrounding neighborhood areas, as well as, serving a broader area beyond the immediate neighborhoods. Buildings in these areas most commonly range from two to four stories, but occurrences of single story commercial buildings in these districts do exist [2].

Common uses permitted in the NC-1, NC-2 and NC-3 districts include, but are not limited to, ambulance service, amusement game arcade, animal hospital, hospital or medical center, hotel, bar, food-service restaurant, religous facility, wholesale sales, liquor store, mortuary, small neighborhood serving businesses which profit primarily from the surrounding neighborhood clientele, large fast food restaurants greater than 1,000 square feet of floor space, small fast food restaurants with less than 50 seats and less than 1,000 square feet of floor space, full service restaurants where guests primarily dine on the premise, retail sales and services, storage facility and video rentals. Several commercial uses related to automobiles include automobile sales, rental, service, wash, repair and open lot or garage automobile parking. Entertainment related uses include adult entertainment, theater, opera, dance hall, billiard hall, bowling ally, skating rink, movie theater and other forms of recreational entertainment [2].

III.3.2. Common Building Characteristics of the Commercial District

I broke down the architecture of NC-1 strip center buildings into simple forms. I took reference from existing small scale strip centers. Fig. 20 shows reference images of existing strip mall centers of varying scale. Some commercial strip malls include front facing covered walkways while others do not. The commercial district model library I created includes examples of both covered and non covered front facing walkways. Almost all building types introduce ways of incorporating repetitive elements, be it columns on a building or the "Painted Ladys" (see Fig. 21) in San Francisco [5]. Strip malls are a perfect example of built repetition because each unit is unique and set apart from its neighbors, yet it is also a part of a larger whole. My reference revealed average clusters of 3-5 units per strip mall. I decided to clamp the number of strip mall units per plot at a minimum of 3 and maximum of 5. Reference also revealed that strip mall modules commonly have flat roofs lacking pitch. My strip mall building library reflects this observation as well.

Fig. 20. Reference images taken from built strip mall centers. All images photographed by the author.

I broke down the architecture of NC-2 and NC-3 district buildings into simple forms which represent a variety of the permitted uses explained above. A large amount of real world reference was taken to represent the neighborhood commercial district. Fig. 22 shows built examples of neighborhood commercial reference taken in

Fig. 21. Ching illustrates the Victorian facades commonly referred to as the "Painted Ladys" in San Francisco, CA

both College Station, TX and San Mateo, CA. These commercial buildings generally have flat roofs lacking much pitch or a shallow single tiered roof. Show a reference image or existing with shallow tiered roof. Hotel structures most commonly have pitched gable roofs. Most of my models representing hotel structures represent this obsrvation. Free standing commercial structures of moderate size generally have a defined, front facing, entry way. Show reference image of a school or mall or grocery or gas station with a defined, front facing entry. I observed that the neighborhood commercial buildings vary greatly in square footage. Some commercial buildings place a small footprint of less than 10,000 square feet on the property, while others exceed a ground footprint of 20,000 square feet. This observation led me to further sub categorize my building library into large square footage and small square footage neighborhood commercial structures, which will be discussed in further detail in the

Implementation section.

III.4. Office District

The city of San Francisco categorizes downtown commercial districts with the letter prefix "C" which is then followed by a number relating to density of the district. Density varies from 0, the least dense, to 3, the most dense. Furthermore, the district subcategory is proceeded by an additional letter which further distinguishes what type of commercial uses are common to the subdistrict. Subcategories include C-3-O representing Downtown Commercial Office, C-3-R for Downtown Commercial Retail, C-3-G is Downtown General Use and C-3-S is Downtown Support[2]. This thesis will take reference from and model an office district similar to the C-3-O building district.

III.4.1. Uses Permitted for the Office District

The C-3-O district primarily houses high density office buildings. These buildings are the primary contributors to the iconic San Francisco skyline as seen in Fig. 23. Intensity and compactness are key as they allow intermingling amongst businesses to occur with ease and on foot if needed. Central transit caters to the core of the office district and building use is primarily limited to the development and expansion of major office buildings[2]. The City of San Francisco Planning Code [2] defines an "office use" as "space within a structure or portion thereof intended or primarily suitable for occupancy by persons or entities which perform, provide for their own benefit, or provide to others at that location services". The Planning Code

Fig. 22. Reference images taken of built neighborhood commercial structures in College Station, TX and San Mateo, CA. All photographs taken by the author.

Fig. 23. San Francisco skyline. Image taken by the author.

[2] lists services as, but not limited to, banking, insurance, management, consulting, technical, sales, design, the non-accessory office functions of manufacturing and warehousing businesses, multimedia, software development, web design, electronic commerce, and information technology. Additional services provided specifically to the public include, but are not limited to, accounting, legal, consulting, insurance, real estate brokerage, advertising agencies, public relations agencies, computer and data processing services, employment agencies, management consultants and travel services [2]. Additionally offices within this district may provide services, such as executive, management, administrative and clerical services, to the business community but not the general public[2].

III.4.2. Common Building Characteristics of the Office District

I gathered reference images of existing downtown office buildings. Fig. 24 are office building images gathered from Austin, Texas. Fig. 25 is a web image of the Lower Manhattan district in New York and, as mentioned before, Fig. 23 displays the San Francisco skyline. A large portion of the towering skylines in each of these cities can be attributed to densely populated office building districts.

Looking at our real world reference of sky scraper office buildings, we can draw many conclusions about the overall size and form of the structures. The city of San Francisco is divided into classes based on the maximum building height allowed. This height limit information is stored on the Zoning Map. It is also important to notice that although maximum height regulations exist in the office districts, only a small percentage of building structures actually encroach on this limit. Height limits will vary from district to district and differ from one city plan to another. Additionally, the underlying forms of the office district buildings are very basic at the root level. A base level cube which has been scaled differing amounts in all directions, can easily account for the majority of office district building's preliminary form. A secondary level of additive or subtractive form extrusions as discussed in Fig. 12 adds another layer of individuality and uniqueness. Thirdly, building materials establish further distinction between structures.

Fig. 24. Office building reference images taken in Austin, Texas. Images taken by the author.

Fig. 25. Lower Manhattan, New York downtown[3].

CHAPTER IV

IMPLEMENTATION

In this thesis I (1) created four libraries of buildings, each representative of a different zoning district and (2) developed a Python program to run within the Maya Application to walk the user through the design process involved in creating a three-dimensional zoning map. Individual district libraries exist in order to strengthen expandability and modular functionality. Each of the four district libraries contains simplified forms representative of the concerned district. The Python program defines a design process which allows the user to create and control size, placement, and boundaries of the four defined zoning districts on a planar map. In the last step of the design process, the Python program references and randomizes buildings from the corresponding building libraries and populates the user defined zoning map accordingly.

IV.1. Creating Building Libraries

IV.1.1. Office District

I created a library of three dimensional models representative of common office building forms I found when researching existing office building structures. Fig. 26 illustrates the five base models that I created in the office district building library. I will refer to these five models, from left to right, as Office Building 1, Office Building 2, Office Building 3, Office Building 4, and Office Building 5.

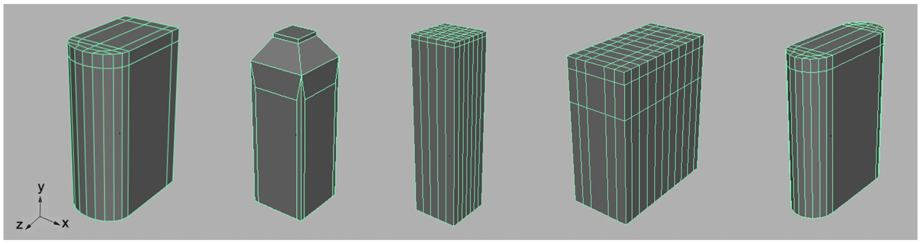

Fig. 26. Base shapes for Office District building library

It was my goal to keep the models in the building library simple in form and introduce randomness and detail in a secondary step. After I created the basic model I defined a series of selection sets individualistic to each model. The selection sets allow the program to quickly and easily select a grouping of vertices, edges, faces, or any combination of the three while creating building detail randomization.

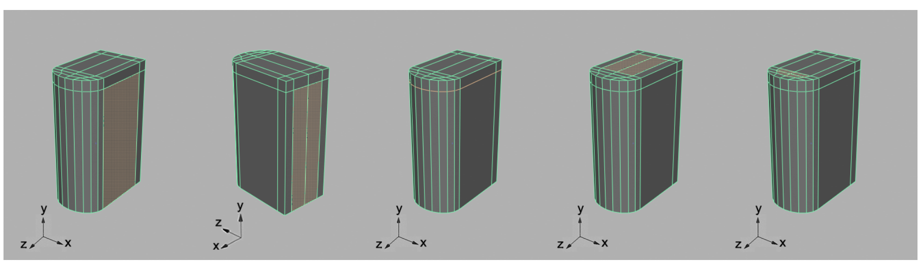

Fig. 27. Example of selection sets of faces for Office Building 1

Fig. 27 illustrates five of the selection sets for office building 1. The first image in the figure exemplifies a face selection set whose identical set exists on the opposite side. Each face selection may be extruded in its respected positive or negative x direction. The second image also represents a collection of faces. These faces have surface normals facing in the negative z direction and when selected, may be extruded in that direction. The third selection set is a grouping of edges which must be coupled with the extrusion of either one or both of the face selection sets previously described. These edges can be translated up and down in the positive and negative y directions to adjust the height of the faces to be extruded, thus creating randomness in the extruded "wings". The fourth and fifth face selection sets contain different rooftop faces. The face normals for each of these sets is in the positive y direction and they may be extruded together or alone along the normal.

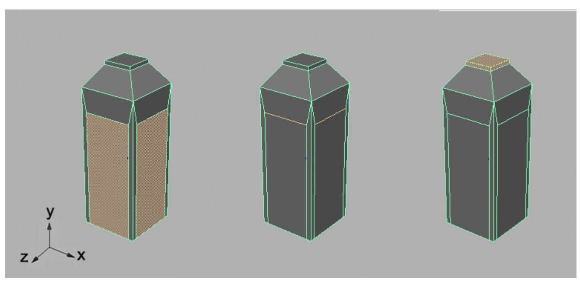

Fig. 28. Example of selection sets of faces for Office Building 2

Fig. 28 illustrates three selection sets for Office Building 2. The first selection set contains faces with normals in the x and z directions. These faces can be extruded in the direction of the normal. An identical face selection set resides on the back side of the model which is not visible in the figure. The second selection set includes a series of four edges, one on each side of the model (left, right, front, back) and is dependent on the an extrusion of the face set. Before the extrusion, the edge set can be translated in the positive or negative y direction to create variant height of the extruded wings. After the extrusion, the edge set can be translated in the positive y direction to create sloped roof faces on the extruded wings. The third selection set includes five faces representative of the building cap at the apex of the roof. This selection can be scaled in the x and z directions and translated in the y direction to create a roof structures of different sizes and slopes. Fig. 29 illustrates the five

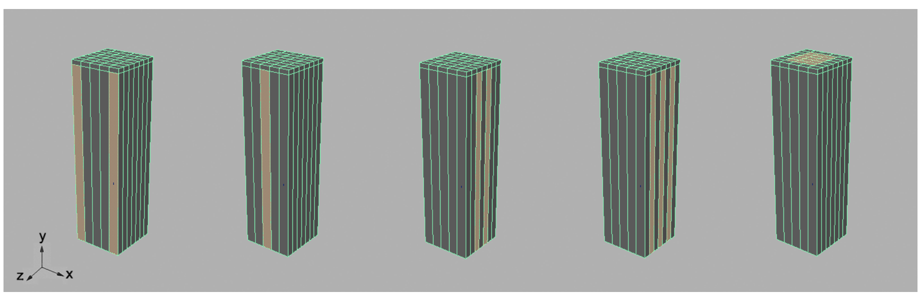

Fig. 29. Example of selection sets of faces for Office Building 3

different selection sets for Office Building 3. All of the five selection sets for Office Building 3 are face selections. The first four selection sets in the figure have face normals along the x and z axis and have the ability to be extruded in the respected direction of the normal to add dimension and detail to the front, back and/or sides of the model. Identical selection sets reside on the back side of the model which is not visible in the figure. The fifth selection set includes faces with a normal in the positive y direction. These faces can be extruded in the +y direction to add dimension and detail to the roof of the model.

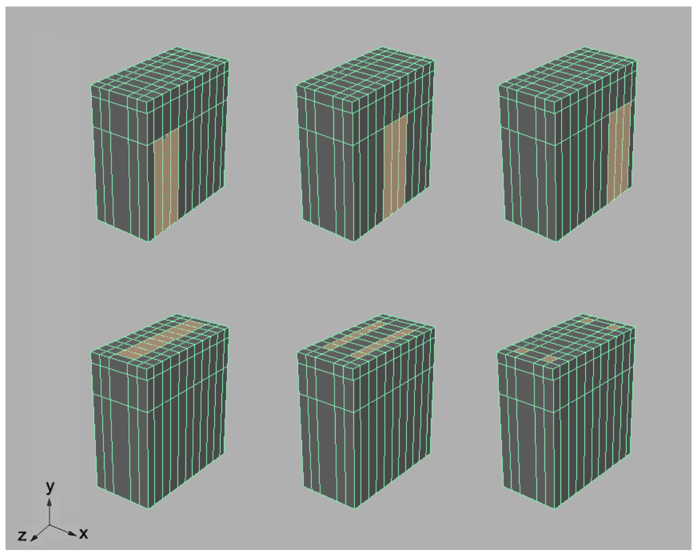

Fig. 30. Example of selection sets of faces for Office Building 4

Fig. 30 illustrates the six different types of face selection sets for Office Building 4. The first three images on the top row of the figure represent wall selections. Identical selection sets exist on the back side of the building facing in the negative x direction. Each of these face sets can be selected individually or in any combination and extruded along the positive or negative x direction. The second row of images exemplifies face selection sets defining the roof. These roof sets may be selected individually or in conjunction and extruded in the positive y direction creating detail and uniqueness.

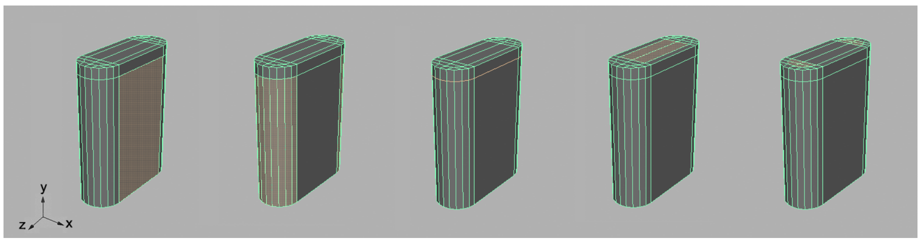

Fig. 31. Example of selection sets of faces for Office Building 5

Office Building 5 is similar in form to Office Building 1 and five of its selection sets are illustrated in Fig. 31. The first and second sets are face selections. Each of these first two sets has an identical set on the opposite side of the building form. The first set and its opposite counterpart can be extruded in the positive x and/or negative x respectively. Similarly, the second face selection set and its mirrored counterpart can be extruded in the positive z and/or the negative z direction respectively. The third selection is an edge set which forms a continuous ring around the building form. The edge selection set can be translated in the positive and negative y direction and works in conjunction with one or both of the face extrusions previously described. The fourth and fifth images define face selection sets defining the roof form. These two sets can be selected individually or in conjunction with one another and extruded in the positive y or negative y direction.

Adding randomization to each of the 5 basic building forms allows us to create over 50 different office building models. Selection sets, as described above, when scaled, translated and extruded varying amounts, transform each of the base office building models into unique forms. These selection sets are focused on specific localized areas of each model. An additional level of randomization is introduced by uniformly scaling the width, depth and height of the model.

IV.1.2. Commercial Strip Mall District

I created a library of modular strip center structures to simplistically represent existing neighborhood strip mall centers. Fig. 32 illustrates the three base building models I created for the Commercial Strip Mall District. Each of the three base models were designed to be modular. The modular functionality allows the models to be duplicated forming a single consecutive row or strip center. I defined a roof selection set for each of the base models. The roof selection sets are displayed in Fig. 33. The sets are used to create randomness in height amongst the commercial strip center buildings by translating the selection in the positive y direction. Additional randomization can be introduced by scaling the base model in the positive x and z directions uniformly, in order to maintain the desired building proportions.

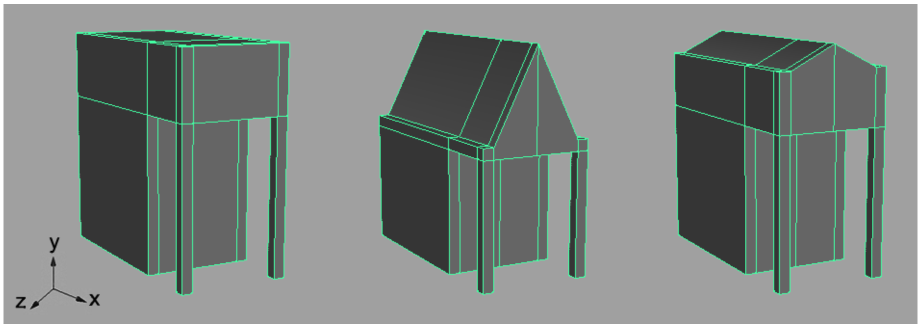

Fig. 32. Three base models created for the Commercial Strip Mall District

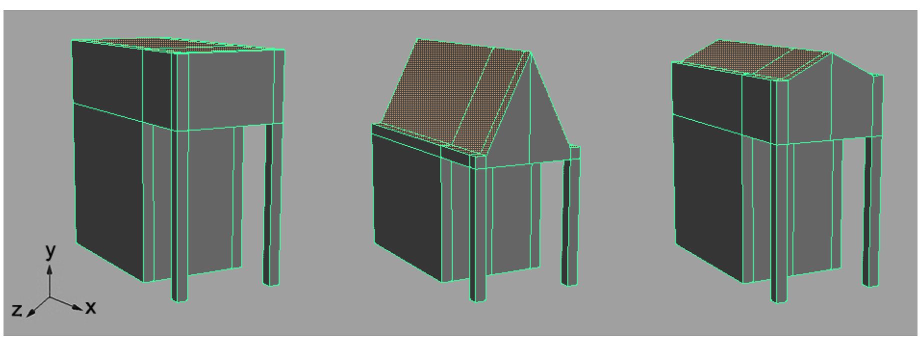

Fig. 33. Roof selection sets for the Commercial Strip Mall District base models

IV.1.3. Neighborhood Commercial District

I created a library of free standing neighborhood commercial building models to represent existing buildings found in my research. As my reference images revealed, the commercial district can house a large variety of different use structures. Many of these different uses require unique and iconic building designs. My approach for modeling the Neighborhood Commercial District was slightly different than the previously described Office District. I created a larger number of basic building forms to cater to the large number of proposed uses in the district. Similar to the Office District, some of the base buildings were transformed based on translation, extrusion and scaling of face and edge selection sets. The base building models I created, while referencing real world examples listed in the permitted uses for this building district, range in foot print square footage from 1,000 square feet to 25,000 square feet. I define the footprint square footage as the building square footage of the first floor plan only. With such a large range of square footage, I found it important to subcategorize my commercial models based on the square footage of the ground floor footprint. I am only concerned with the square footage on the first floor because that is the area which directly responds to the size of the plat. The square footage based subcategories is for use within the Python code. The program user is not made aware that these sub categories exist.

I created a ”small” subcategory, within the Neighborhood Commercial District, which contains only one building model with a square footage of 1,000 square feet. This building model has one selection set which is displayed in Fig. 34. The only selection set for this building is a face selection and it allows the program to extrude the roof in either the positive or negative y direction for a maximum of 3 units. The "small" building category will service plots, in the Neighborhood Commercial District, less than 4,000 square feet. For the duration of this thesis, I will refer to this small sized Neighborhood Commercial building model as Commercial Building 1.

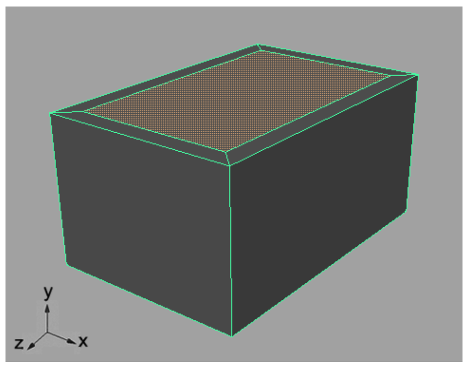

Fig. 34. Selection set for Commercial Building 1

I created another subcategory of the Neighborhood Commercial District containing "medium" sized building models. The ground square footage of base building models in this subcategory range from greater than 4,000 square feet up to 10,000 square feet. There are eight base buildings in this category. Fig. 35 displays each of the eight base building models. For the duration of this thesis, I will refer to the medium sized base models in this figure, from left to right and top to bottom, as Commercial Building 2, Commercial Building 3, Commercial Building 4...Commercial Building 9.

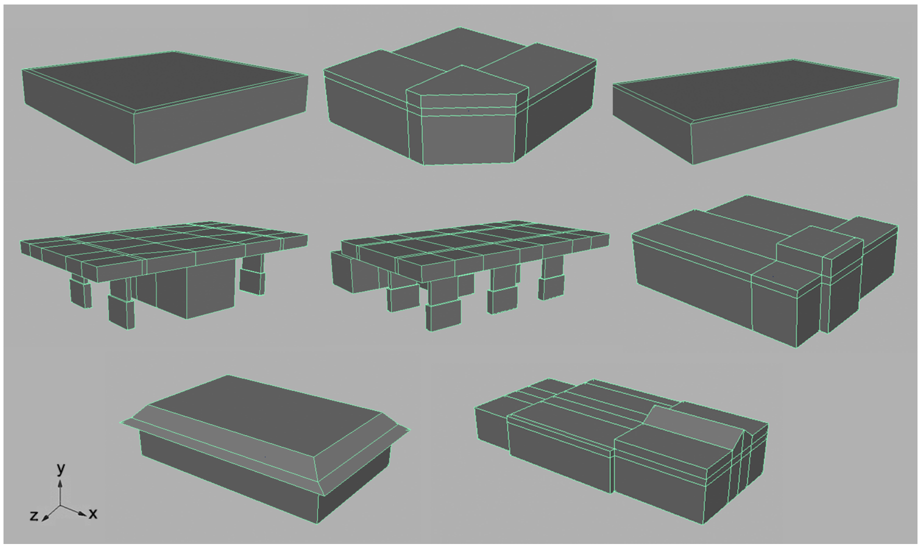

Fig. 35. Eight base models of medium sized buildings in the Neighborhood Commercial District

Commercial Building 2 and Commercial Building 4 contain one selection set each, as displayed in Fig. 36 with identical functionality. Each of the selection sets contain one roof face. The program has the ability to create random variations of the base building forms by extruding this roof selection set varying amounts along either the positive or negative y direction.

Commercial Building 3 contains three selection sets. Fig. 37 displays the three selection sets available to Commercial Building 3. The first set is a grouping of edges

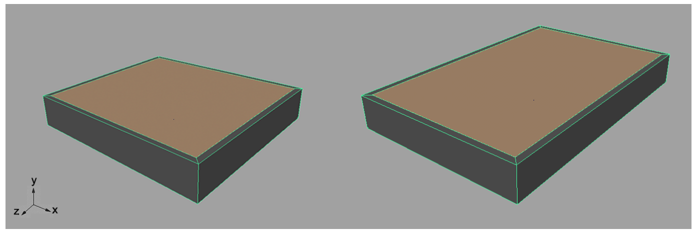

Fig. 36. Selection set for Commercial Building 2

which can be translated varying amounts along the negative z axis. The second selection set is also a grouping of edges which can be translated varying amounts along the negativee x direction. The third selection set is a grouping of roof faces which can be translated varying amounts along the positive y axis. Each of these selection sets may be used individually or they may be used in different combinations of one another to transform the base form.

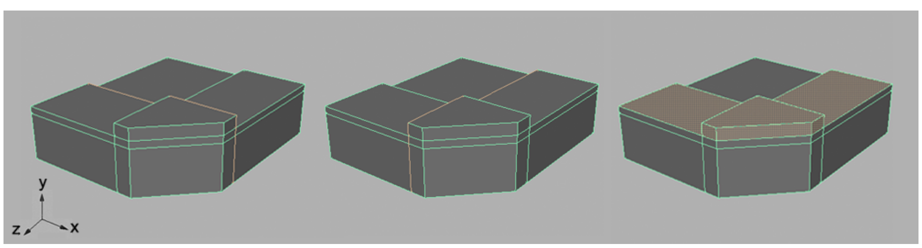

Fig. 37. Selection sets for Commercial Building 3

Commercial Building 7 contains three selection sets. Fig. 38 displays the three selection sets available to Commercial Building 7. The first selection set contains roof faces. When selected, this group may be translated in the positive y direction to raise the height of the ceiling or create a space large enough for two stories. The second and third selection sets contain edges. The second set is to be translated in the negative x direction, while the third set is to be translated in the negative z direction. These three selection sets may be utilized by the program individually, or as a combination of two or more.

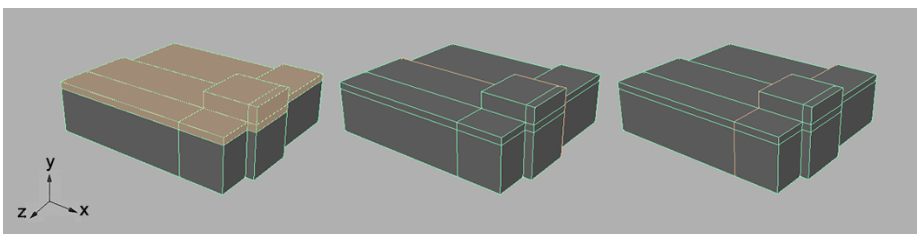

Fig. 38. Selection sets for Commercial Building 7

Commercial Buildings 5, 6, 8 and 9 do not have selection sets. These buildings, in their base form, are the most iconic and already contain a larger amount of detail than the rest. For these reasons, I chose to always implement these buildings into the city map in their base form and add randomness through varying degrees of uniform scaling. Buildings in the ”medium” subcategory will service plots, in the Neighborhood Commercial District, ranging from 4,000 to 15,000 square feet.

I created a third and final subcategory of models within the Neighborhood Commercial District for the "large" building models. The square footage of the base building footprints in this category range from greater than 15,000 square feet. The purpose of these larger scale buildings is for placement on larger plots of land. Fig. 39 displays the nine base models that I created to represent structures in this subcategory. For the duration of this thesis, I will refer to these models, from left to right and top to bottom, as Commercial Building 10, Commercial Building 11, Commercial Building 12...Commercial Building 18.

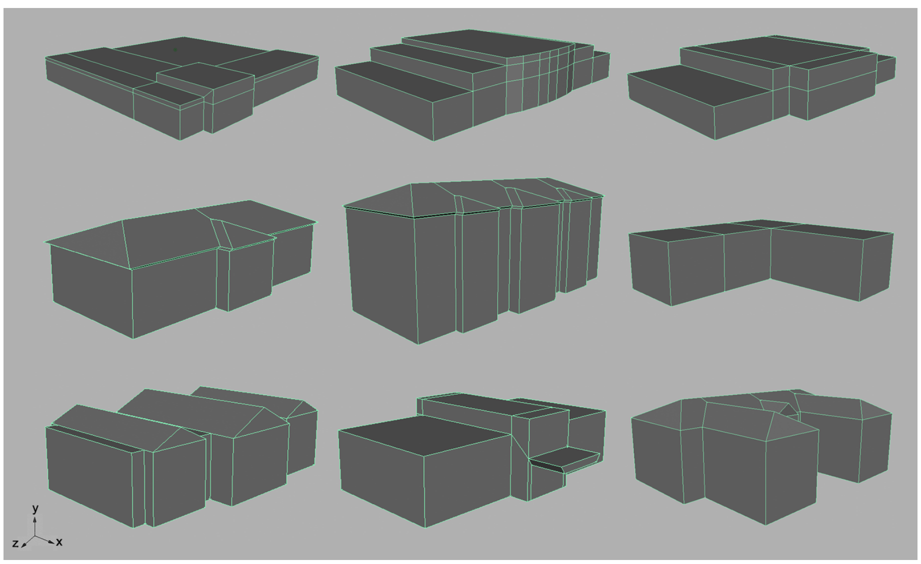

Fig. 39. Nine base models of large scale buildings in the Neighborhood Commercial District

Similarly to the previously described subcategories, the largest size of building models contain selection sets which allow the program to create diversity and variation for each base model. Commercial Building 10 contains several selection sets which create randomness amongst the building form. Fig. 40 displays the four selection sets used for Commercial Building 10. The first and second sets pictured are edge groupings. The first set allows the program to translate the edges along the negative x direction, while the second set allows the user to translate the dges along the negative z axis. The third and fourth sets pictured are both roof face selections. Both of the roof selections allow the program to manipulate the building form in the positive y direction to raise the height of the first floor ceiling or create a space large enough for two stories. Each of these selection sets may be utilized individually or as a multiple set combination.

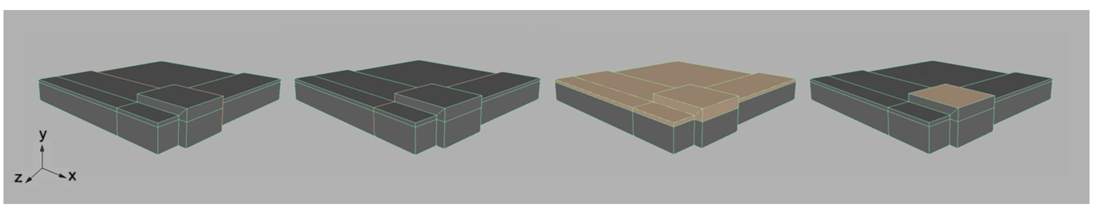

Fig. 40. Selection sets for Commercial Building 10

Commercial Building 13 contains one single selection set. Fig. 41 displays the selection set for this model. The set is a grouping of roof faces. The base building as it stands is two stories in height. The roof selection may be translated in either the positive or the negative y direction with a limit of 12 units in either direction. The 12 unit limit exists to clamp the minimum number of floors between one and three.

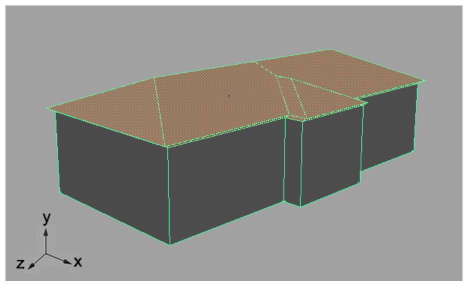

Fig. 41. Selection set for Commercial Building 13

Commercial Building 14 contains two face selection sets. Fig. 42 displays the selection sets for this model. The first face selection allows the program to translate the entry facade faces along the positive x axis to varying amounts. This translation creates a more prominent entry way and distinguishes a unique form. The second selection contains roof faces. The base form is a three story model, so we allow the program to translate varying amounts along the negative y axis, creating opportunities to produce single and double story models. These selection sets may be used individually or in conjunction with one another to create unique reference models.

Commercial Building 15 contains three face selection sets. Fig. 43 displays the three selections. The first face selection can be extruded varying amounts along the

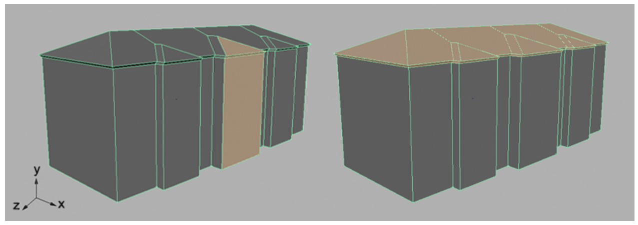

Fig. 42. Selection sets for Commercial Building 14

positive x axis. This process creates an additional wing on the original model. The second face selection has the ability to be translated in the negative x direction. This process results in removing a wing of the base model. The third face selection is a roof selection. The base model is a single story in height. The third selection may be translated in the positive y direction to a maximum height of 36 units or three stories.

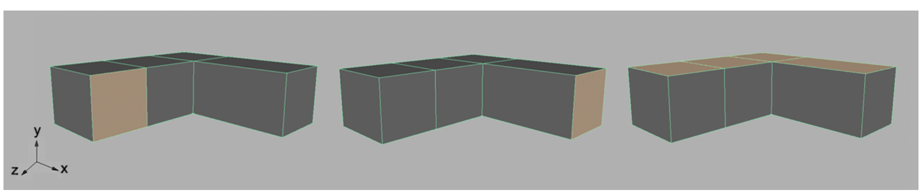

Fig. 43. Selection sets for Commercial Building 15

Commercial Building 16 contains three face selection sets. Fig. 44 displays the three selections. The first selection is a roof face group. This selection can be extruded in the positive y direction creating a vaulted or double story in the core of the building. The second selection contains the entire roof structure. This selection may be translated in the positive y direction for a maximum of 24 units. The third selection set contains two identical face selections, each on opposite sides of the model. This selection can be scaled in the positive z direction in order to expand the outer boundaries of the model. Each of these selection sets may be used individually or in conjunction with one another to create unique building forms.

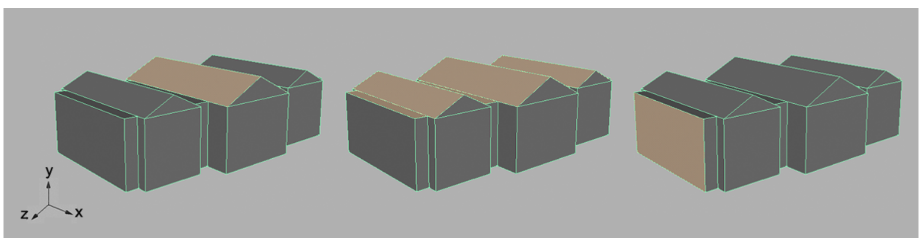

Fig. 44. Selection sets for Commercial Building 16

Commercial Building 17 contains five face selection sets. Fig. 45 displays the five selection sets. The first selection set can be scaled in the positive z direction in order to expand the outer boundaries of the model. The second face selection can also be scaled in the positive z direction. This process results in a wider foyer area. The third selection set contains all of the back faces. This selection set may be translated in the negative x direction in order to increase the overall size of the model. The fourth selection set contains all of the roof faces. These faces can be translated in either the positive or negative y direction. The base building model is two stories high. The maximum translation amount in each direction is 12 units, resulting in a minimum single story building and a maximum three story building. The fifth selection set contains the roof faces on the sides of the model. This selection may only be translated in the negative y directions for a maximum of 12 units. Each of these selection sets may be utilized individually or as a combination of multiple sets.

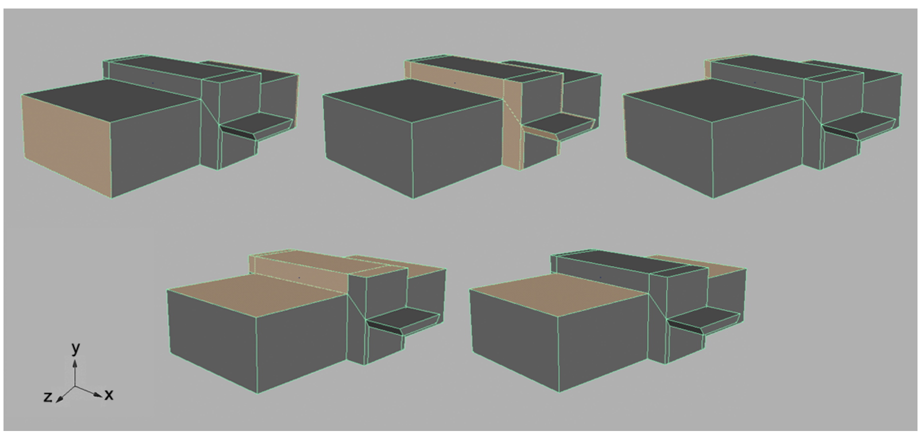

Fig. 45. Selection sets for Commercial Building 17

Commercial Building 18 has one selection set. Fig. 46 displays the only selection set for this building. This selection contains all of the roof faces and may be translated along the y axis. The bas building stands two stories tall, therefore the selection set may be translated a maximum of 12 units along the negative y axis and a maximum or 12 units along the positive y axis. The result of these translations is a building model which stands with a minimum of one story and a maximum of three stories tall.

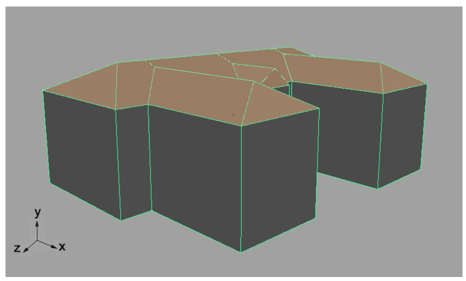

Fig. 46. Selection set for Commercial Building 18

Not all buildings have selection sets. Neighborhood Commercial Buildings 11 and 12 do not contain any selection sets. Those buildings are referenced into the map in their base form and slight randomization is created through uniform scaling transformations. The ”large” subcategory of Neighborhood Commercial Buildings serves plots greater than 15,000 square feet in area.

IV.1.4. Residential District

I created a library of three dimensional models representative of the most common residential building forms I found when researching existing residential building structures. Fig. 47 illustrates the eight models that I created in the residential district building library. I will refer to these eight models, from left to right and top to bottom, as Residential Building 1, Residential Building 2, Residential Building 3...Residential Building 8. It was my goal to keep the models in the residential building library simple in form and introduce randomness and detail in a secondary step.

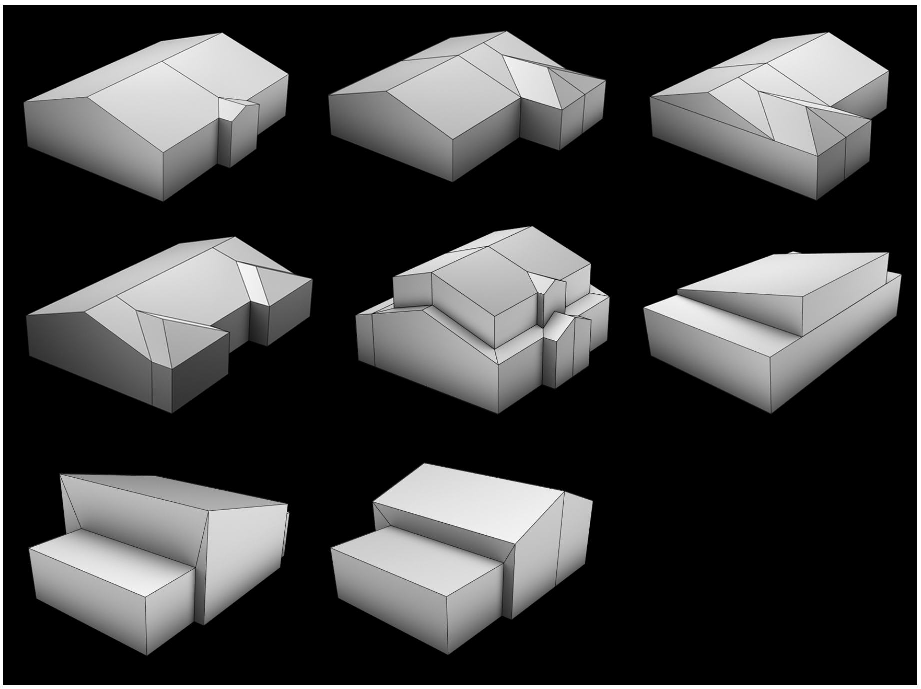

Fig. 47. Base shapes for residential building library

After I created the basic models, I defined a series of selection sets individualistic to each model. The selection sets allow the program to quickly and easily select a grouping of vertices, edges, faces, or any combination of the three and transform the form through extrusion, translation and scale.

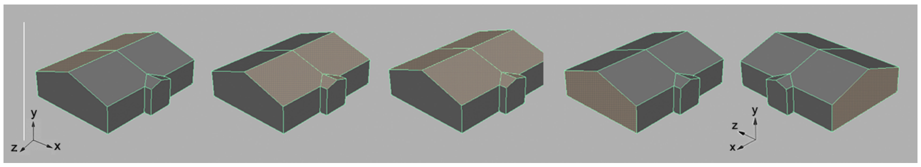

Fig. 48. Example of selection sets of faces for Residential Building 1

Fig. 48 displays five selection sets I created and used to randomize the form of Residential Building 1. The first and second image in the figure are both roof face selection sets which can be extruded in the positive y direction, resulting in a split level roof design. The third image in the figure is also a roof face selection set which can be translated in the positive y direction, creating randomness in building height. The fourth and fifth images represent are identical selection sets located on opposite sides of the building. The fourth selection set can be translated in the positive z direction while the fifth selection set can be translated in the negative z direction.

Fig. 49 displays the five selection sets I created and used to randomize the form of Residential Building 2. The first image is a roof face selection set which can be extruded in the positive y direction resulting in a split level roof design. The second image represents a selection set containing all roof faces which can be translated in the positive y direction to created randomness in building height. The third selection

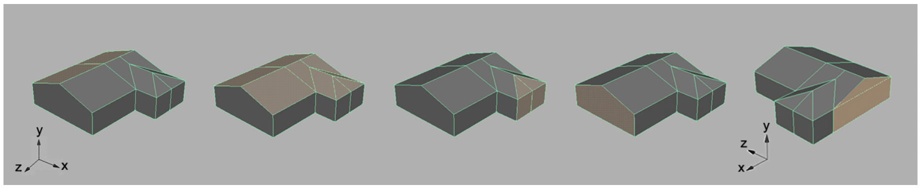

Fig. 49. Example of selection sets of faces for Residential Building 2

set is a face selection set which can be translated in the positive x direction adding randomness to the building form. The fourth and fifth selection sets are identical, but reside on opposite sides of the building. The fourth selection set can be translated in the positive z direction and the fifth selection set can be translated in the negative z direction, both adding randomness to the building form.

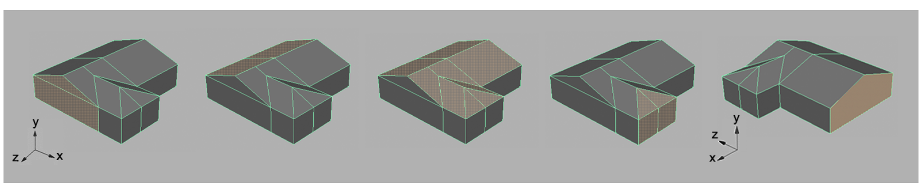

Fig. 50. Example of selection sets of faces for Residential Building 3

Fig. 50 displays the five selection sets I created for Residential Building 3. The first selection set consists of faces which can be extruded varying amounts in the positive z direction. The second and third selections both contain roof face polygons.

The second selection may be extruded in the positive y direction for a maximum of 4 units. The result is a split level roof which allows bounce light to illuminate the spaces below. The third selection set may be translated in the positive y direction, resulting in the opportunity to create a two story space. The fourth selection set contains faces which may be translated in the positive x direction. This selection set has the opportunity to create a more defined L-shaped floor plan. The fifth, and final, selection set is similar to the first, but resides on the opposite side of the model. This selection set may be translated in the negative z direction resulting in a wider building model. Each of these five selection sets may be used individually or in combination with others to add variation to Residential Building 3.

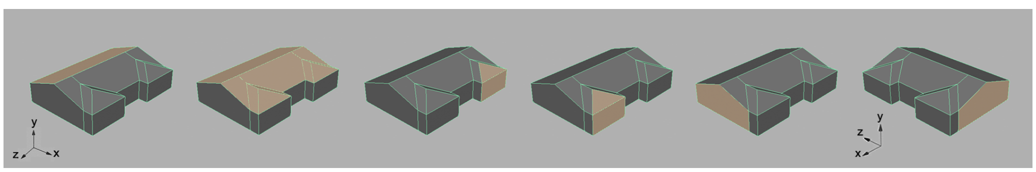

Fig. 51. Example of selection sets of faces for Residential Building 4

Fig. 51 displays the six selection sets I created and used to randomize the for of Residential Building 4. The first image is a roof face selection set which can be extruded in the positive y direction resulting in a split level roof design. The second image is a roof face selection set, containing all roof faces, which can be translated in the positive y direction to create randomness in building height.

Selection sets three and four are both face selection sets. These two sets can be selected individually or together and translated in the positive x direction to create randomness for Residential Building 4. The fifth and sixth selection sets are identical but reside on opposite sides of the building. Selection set five can be translated in the positive z direction and selection set six can be translated in the negative z direction, both resulting in randomization of the building form.

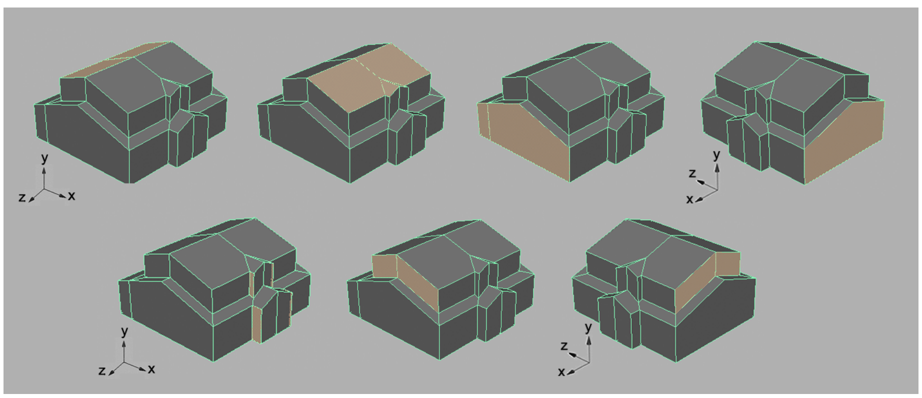

Fig. 52. Example of selection sets of faces for Residential Building 5

Fig. 52 displays the seven selection sets I created and used to randomize the form of Residential Building 5. The first selection set is a group of roof faces which can be extruded in the positive y direction, creating a split level roof design. Similarly, the second roof face selection set can also be extruded in the positive y direction to create a similar split roof design. The third and fourth selection sets are identical, but are located on opposite ends of the building. When selected individually, the third selection set can be translated in the positive z direction, while the fourth selection set can be translated in the negative z direction. The fifth selection set contains four faces which frame the facade entry. These faces can be scaled in the z direction to add randomness to the size and prominence of the front entry. The sixth and seventh face selection sets are identical, but mirrored about the x axis. The sixth selection set can be translated in the positive z axis, while the seventh selection set can be translated in the negative z direction to create randomness in the residential building form.

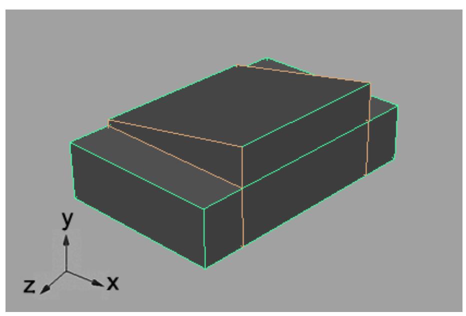

Fig. 53. Example of selection sets of faces for Residential Building 6

Residential Buildings 6, 7 and 8 contain only one selection set each. Fig. 53 displays the single selection set for Residential Building 6. This set contains identical groups of edges which reside on opposite sides of the model. This selection set may be scaled in the positive or negative z direction, resulting in a slightly different building form. Additionally, this selection set may be translated in either the positive or negative z direction. These two processes may be utilized individually or together. Fig. 54 displays the single selection set for Residential Building 7. This face selection

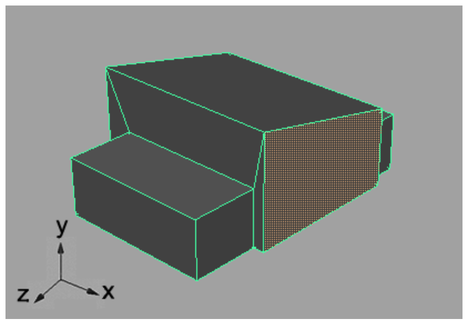

Fig. 54. Example of selection sets of faces for Residential Building 7

can be translated in the positive x direction. Translating the selection set may result in a more prominent entry. Fig. 55 displays the single selection set for Residential Building 8. This selection set may be translated in the positive x direction resulting in a more prominent and defined entry way.

IV.1.5. Park District

Public green space plays an important part in any community plan. I thought it was essential to create a Park District which is available to the user during the zoning process. The park district is empty of any building geometry. The simple Park

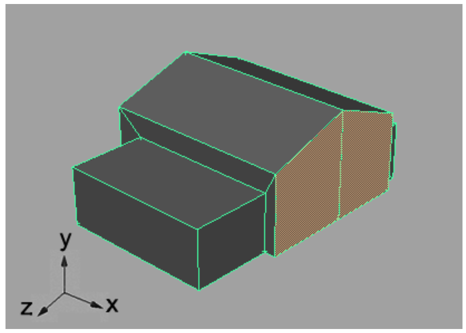

Fig. 55. Example of selection sets of faces for Residential Building 8

District allows the user to designate areas of green space on the zoning map.

IV.2. Build Zoning Map

To take the user through the process of building a zoning map, I wrote an extensive Python program to run within the Maya framework. The user interface is also written in Python and utilizes Maya's Embedded Language functions for interface design and display. To build a complete zoning map the user must follow a series of design steps, each one depending on the previous. Initially, the user is supplied with a drawing plane of which he or she may specify the dimensions in feet. The complete series of design steps include:

- Create planar map geometry.
- Drawing in and labeling roads.
- Smoothing roads.

- Specifying individual road thickness.
- Subdividing build areas into smaller parcels.
- Color painting build areas on the map to place and define different zoning districts.

IV.2.1. Create Map Geometry

The first step of the process to create a zoning map, initializes a scale and square map plane. Once the base square plane is in place, the user has the ability to scale the plane to a desired size and proportions. Fig. 56 shows a base plane which has been scaled to the desired proportions alongside a scale.

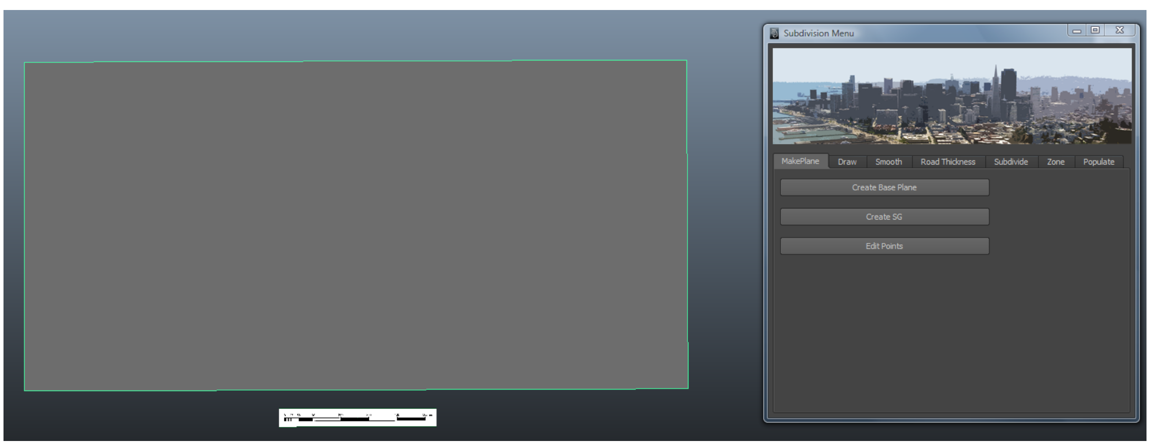

Fig. 56. The first step of the GUI creates a base plane which can be edited to a desirable size

IV.2.2. Draw Roads

The next step in the process to create a zoning map requires the user to rough in road placement for all of the desired roadways. Before each road is created, the user may supply an individual road name. Though I do not expect all of the final built road names to be determined at this time, the names supplied here may act as placeholders and identifiers. If a name is not supplied a generic name with an appended number will be supplied. Roads are created by placing a series of vertices on the ground plane creating a continuous string of edges. The first and last vertices of each road must intersect an existing edge. Dead end roads cannot be created in this program. In Fig. 57 we show a zoning map which has several roads drawn in.

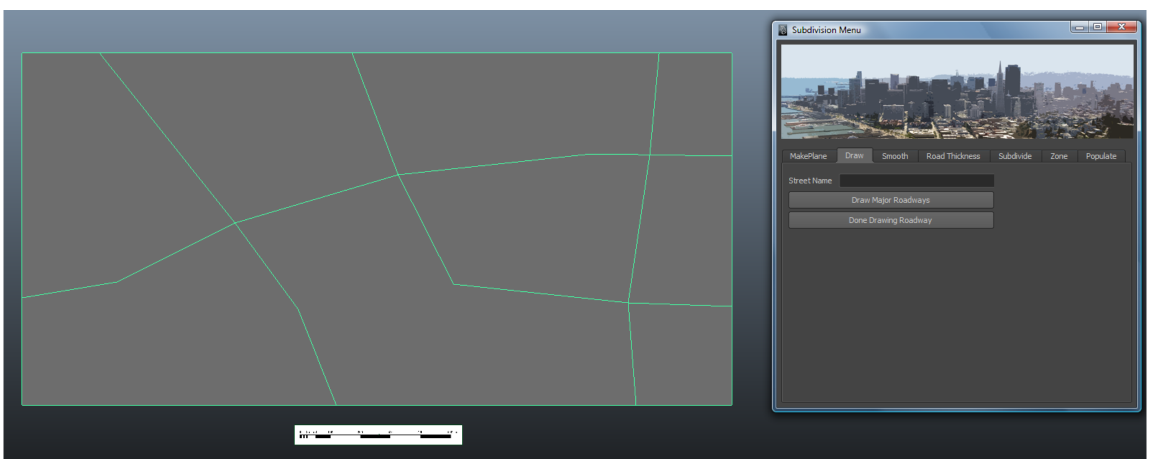

Fig. 57. The user draws in desired roadways and defines a unique road name for each road.

IV.2.3. Smooth Roads

Once all roads are roughly in place, the basic shape of the roads can be manipulated by translating vertices and smoothing curves. Up to this point, each road consists of edges and internal vertices. From this point on I will refer to internal road vertices as those confined by two defining road edges and I will define external road vertices as those which join a road edge with its ending destination of either another road or a map border edge. The road smoothing step allows the user to individually select and smooth any internal road vertex. The percentage each road is smoothed is user defined and can range from 5 percent to 20 percent. For simplicities sake, each original road vertex can only be smoothed once and vertices created from smoothing an original road vertex, cannot themselves be smoothed. Fig. 58 displays two new vertices created after a road corner has been smoothed.

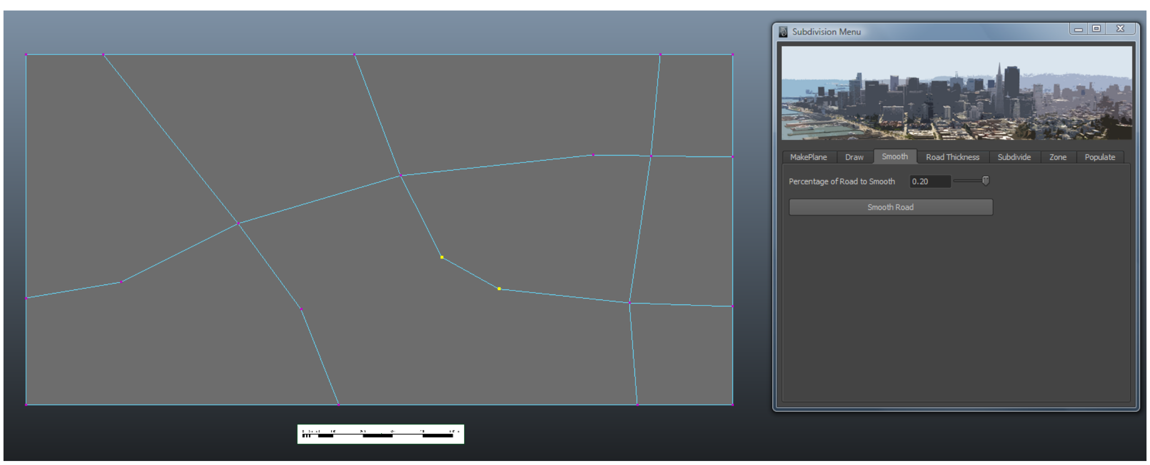

Fig. 58. The user may choose to smooth road corners.

IV.2.4. Apply Road Thickness

In order to transform a string of edges into an actual representation of a road on a map these roads must be given a width. The road thickness step supplies the user with a list of existing roads. The user may select each road individually or select a series of roads, each defined by the name provided in the creation step, as shown in Fig. 59. The user defines the width amount, in feet, to pave each road selection. Different roads may be assigned different road widths in different selection steps. Each road may only be assigned a road width once. All roads must be given a width. Once the road width is created, the new road faces are assigned to a road shading group.

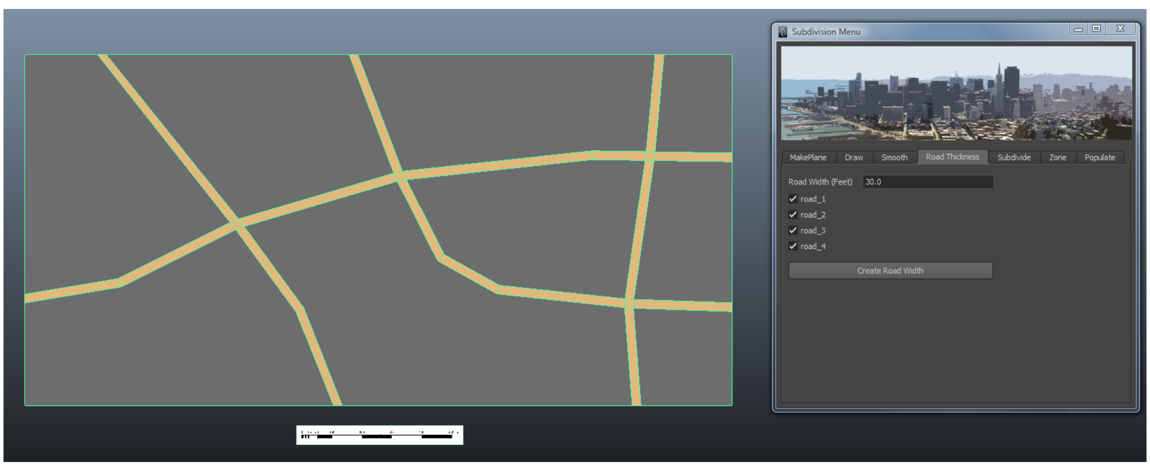

Fig. 59. Each road is given an individual width amount and assigned to a road shading group

IV.2.5. Subdivide Build Faces

The Subdivision step occurs in two phases and assumes the user has knowledge of the program rules in order to divide the existing build faces into plots of land to build on. When we first enter the Subdivision step, we have two categories of faces on the map. One category is the previously user defined road faces and the second category includes faces which we intend to build on but are not yet divided into appropriately sized plots. For the remainder of this thesis we will refer to faces in the later category as "build faces".

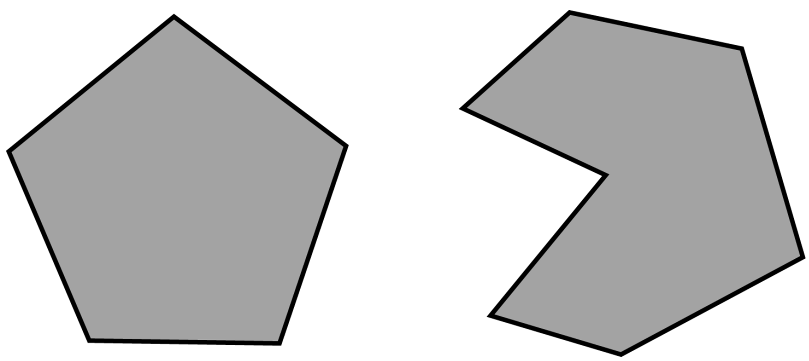

Fig. 60. Convex and concave polygons

The first step of the subdivision process requires the user to analyze each build face individually to determine if the polygon is concave or convex, locate edges which create a concave angle on the polygonal face, and manually subdivide the face, removing the concave angle. A convex polygon is described as one in which every internal angle on the polygon is less than 180 degrees and a concave polygon always has at least one internal angle that is greater than 180 degrees. [17] An example of both a convex and a concave polygon is shown in Fig. 60. The user is responsible for repeating this manual subdivision step until all concave polygons are eliminated. Fig. 61a exemplifies a simple case where one road lies between two build faces. Face 1 is a convex polygon and face 2 is a concave polygon. Fig. 61b displays build face 2 after it has been subdivided by the user into a series of convex polygons. The second phase of the subdivision process utilizes the built in Maya

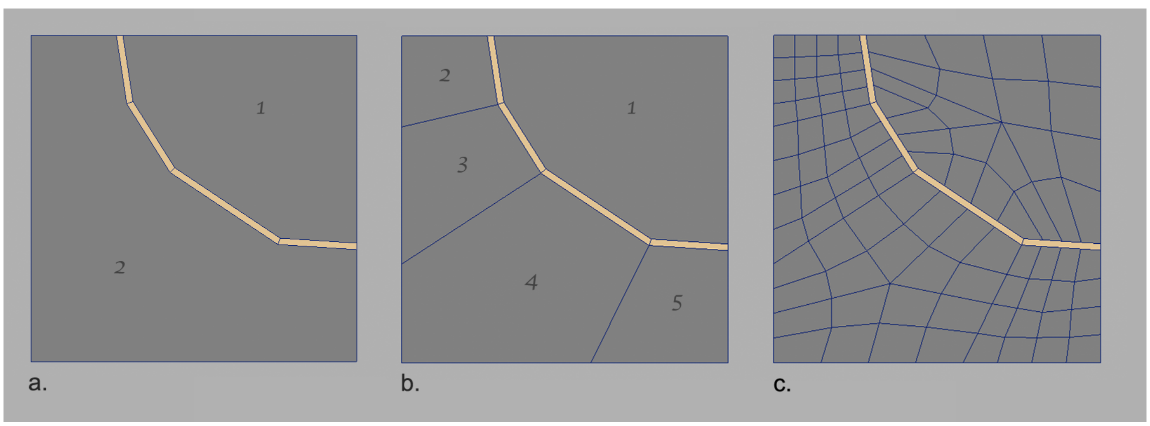

Fig. 61. Subdivision step

subdivision algorithm. Fig. 61c shows the map after Maya's subdivision algorithm has been applied. The user has the ability to implement the subdivision algorithm by selecting the desired faces and clicking the "Subdivide" button. The face selection and subdivision process can be repeated as many times as desired. Fig. 62 shows our example zoning map after both subdivision steps have been implemented.

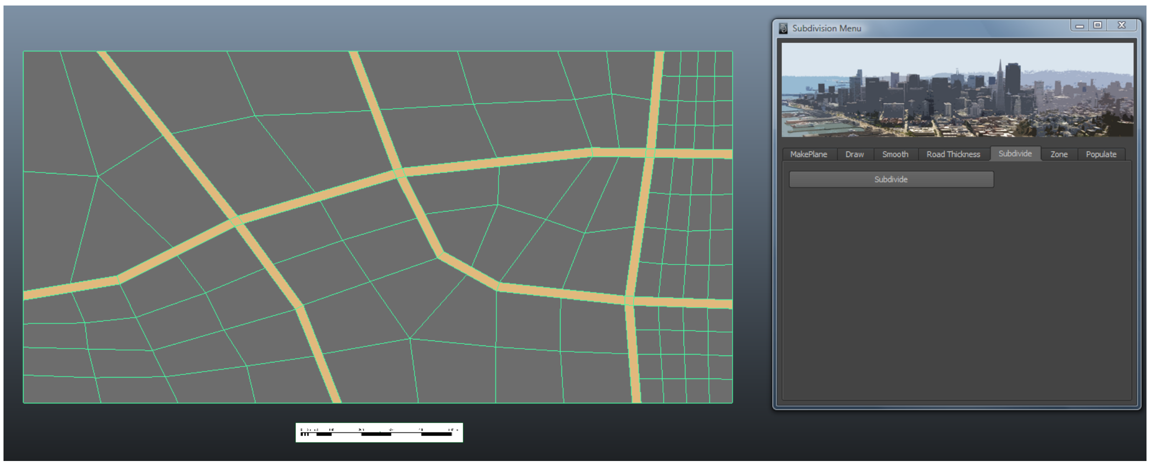

Fig. 62. Each road is given an individual width amount and assigned to a road shading group

IV.2.6. Paint Zoning Districts

The final step to building a two dimensional map is to paint each face on the map to represent one of the four zoning districts previously defined. As previously described, the zoning map, at this point, consists of build faces and road faces. Road faces may not be assigned to a zoning district, so the user must focus on painting and zoning the build faces. The user may choose to assign each individual face to either Residential District, Neighborhood Commercial District, Strip Mall Commercial District, Office District or Park and Recreation District. Faces may be assigned to districts individually or with group selections. Once a face is assigned to a zoning district, it may be reselected by the user and assigned to a different district as many times as desired. Faces not assigned to a zone will be zoned as Park and Recreation by default and no building will be placed in that zone. Fig. 63 is a zoning map which has been painted according to the previously defined zoning districts. The GUI displays the four zoning districts available and the unique map color assigned to each district. Once the user is satisfied with the two dimensional zoning map, the map may be saved by selecting the "Save" button.

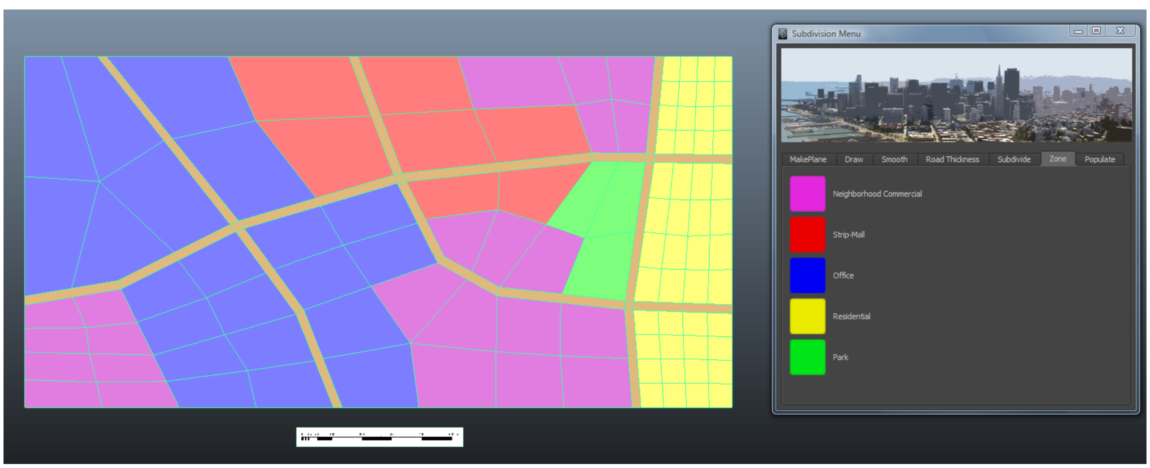

Fig. 63. Zoning map painted to represent each of the four zoning districts

IV.3. Populate Map

To transform the two dimensional zoning map into a three dimensional zoning map we populate the two dimensional map with randomized buildings which identify with the appropriate zoning district and concede to the user defined parameters for that district. A single building is referenced to each build face, with the exception of the Neighborhood Commercial District which references in a multiple instances of the same base building. Fig. 64 displays our map populated with three-dimensional models. The Population GUI illustrated in Fig. 65 allows the user to specify building parameter constraints for buildings in each of the four zoning districts. The logic behind the population step in this program varies slightly according to each zoning district.

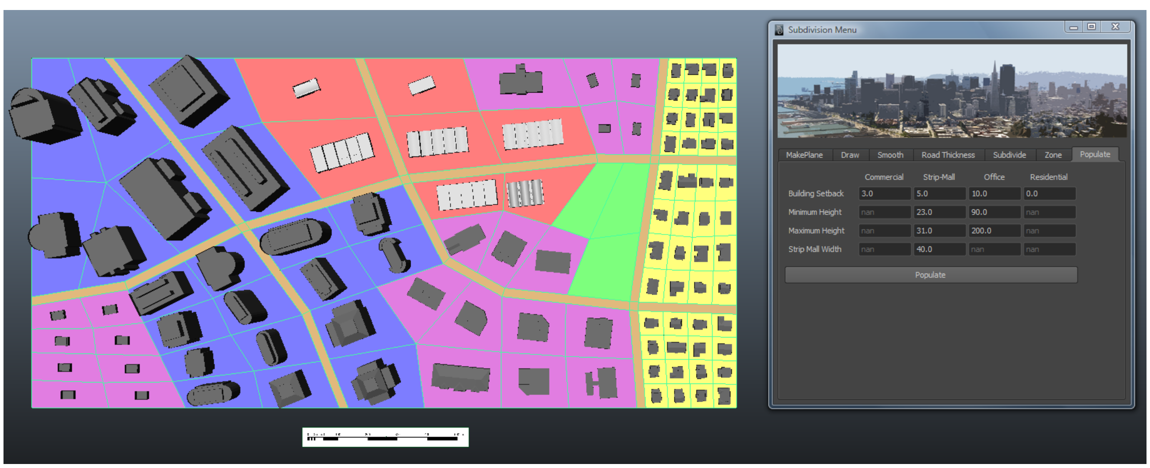

Fig. 64. Populated 3D zoning map.

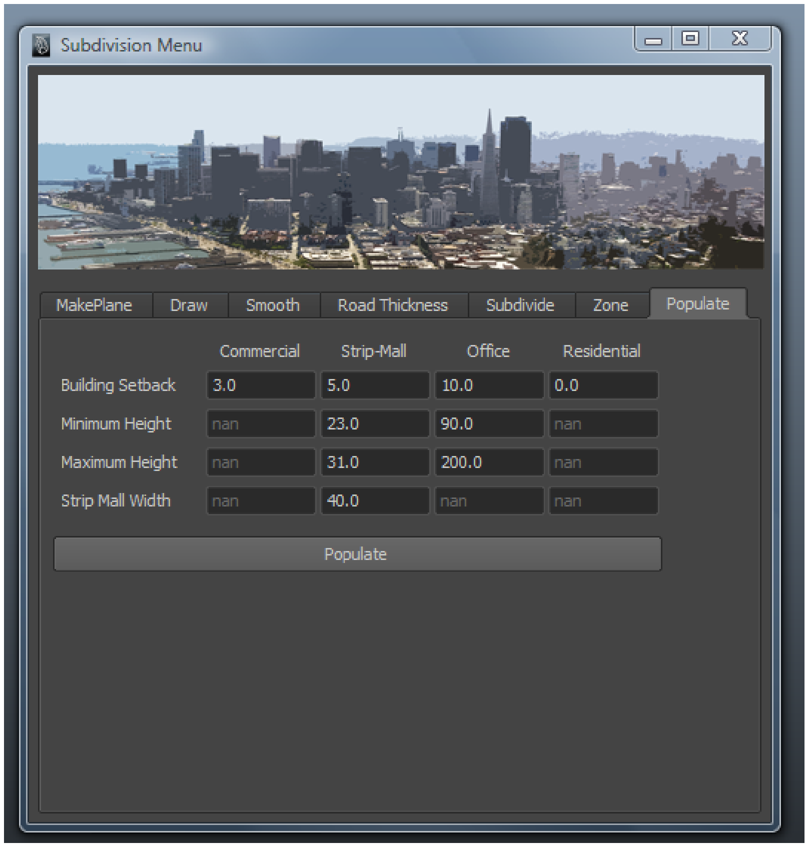

Fig. 65. Population step GUI.

IV.3.1. Building Rotation

Each building must be rotated so the front facade faces one of the four edges of the current plot. I have defined a set of rules to determine which edge the front facade of the building will face. The initial population step places each referenced office building in the center of the respective zoning map face, or plot, with the x, y and z axis of the building model aligned with the x, y and z world space axis. At this point, the front facing facade of each building faces along the positive x axis in object space. The rules for determining which edge the front facing facade of the model will face, after rotation, are:

- If the current build face shares an edge with a single road face, the building model should rotate to face that shared edge.
- If the current build face shares an edge with more than one road face, the building model should rotate to face the longest of the shared edges.
- If the current build face does not share an edge with any road faces, the building model should rotate to face the longest edge on the current face.

As illustrated in Fig. 66 we must derive the rotation angle Θ. The unit vector $\overrightarrow{A}$ points in the positive x direction which is aligned with the front facing facade of the reference building model. The unit vector $\overrightarrow{B}$ points in the desired front facing direction the building after rotation. Once Θ is derived, the building model is rotated by the angle.

$$\theta = \cos^{-1} \frac{\overrightarrow{A} \cdot \overrightarrow{B}}{|\overrightarrow{A}| * |\overrightarrow{B}|} \tag{4.1}$$

IV.3.2. Populate Office District

The population step for the Office District creates a single randomized building form for each plot of land zoned to the Office District on the previously created zoning map. Building randomization happens in two steps. First, the program selects a base

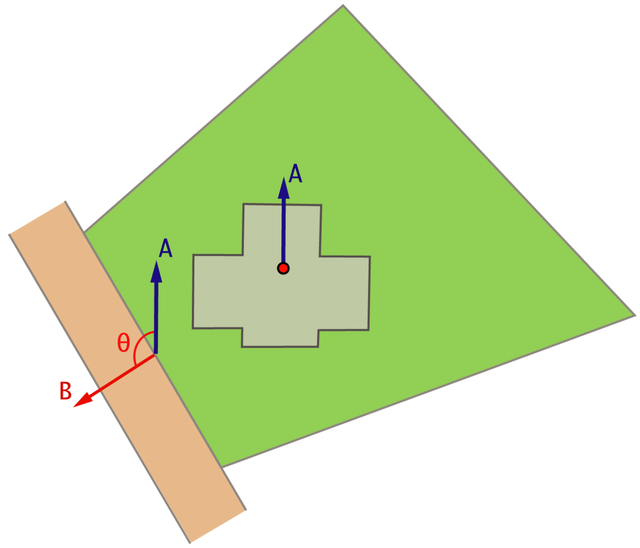

Fig. 66. Each building model should be rotated to face the adjacent road.

building form from the Office Building model library. The second step uses any one or combination of selection sets, previously defined for the selected base form, to add variation and individualism to the form. As previously described, Fig. 28 illustrates the selection sets for Office Building 2. Fig. 67 illustrates several possible building form variations for Office Building 2. The figure demonstrates how the selection sets may be used alone or in conjunction with another selection set to create increased form variety.

The user defined parameters provided in the Office District population step are building setback, minimum height, and maximum height. A building setback line defines the minimum distance between a building structure, at any given point, and the property boundary lines of the lot in which the building resides. The values

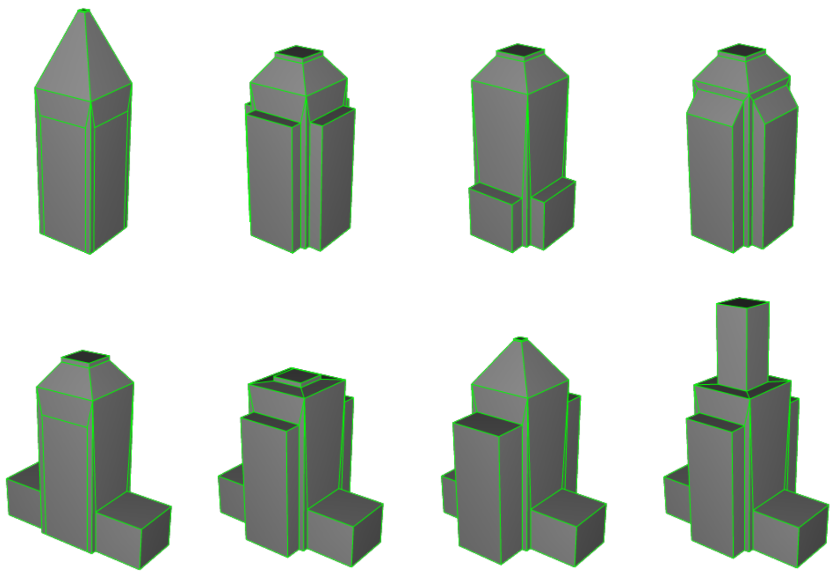

Fig. 67. Randomized Office Building 2

between the minimum and maximum height parameters provide a range of eligible building heights which I will periodically refer to as the *height range*. Building heights are randomly assigned which fall within the specified range. In order to provide more realistic results the building heights are clamped to represent a weighted probability curve. Fig. 68 illustrates the clamped height probability. For every 10 generated office buildings, 3 will fall within the first quarter of the height range, 4 will fall within the second quarter of the height range, 2 will fall within the third quarter of the height range and 1 will fall within the last quarter, which is the tallest, of the height range.

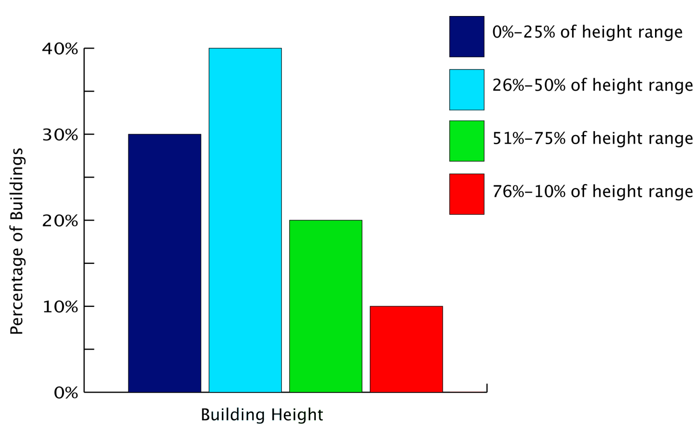

Fig. 68. Percentage of buildings clamped to each height range

IV.3.3. Populate Neighborhood Commercial District

The population step for the Neighborhood District creates a single randomized building form for each plot of land zoned to the Neighborhood District on the zoning map. Building randomization happens in two steps. The first step selects a base building form from the Neighborhood Commercial Building model library. Based on the area of the current plot, a building will be chosen at random from the corresponding subdivision of the building library. The second step uses any one or combination of selection sets, previously defined for the selected base form, to add variation and individualism to the form. The building models within the Neighborhood Commercial District have tighter restrictions placed upon size and height, therefore the user is not able to supply a minimum and maximum height for this district. Height constraints are hard coded into the neighborhood commercial district, clamping the maximum height at 35 feet and the minimum height at 12 feet. The height is randomized between the minimum and maximum.

IV.3.4. Populate Strip Mall Commercial District

The population step for the Commercial Strip Mall District is slightly different from the other 3 districts because multiple building models are referenced into each plot that is zoned as a Strip Mall Commercial District. The user may supply a Strip Mall Width amount in feet which refers to the building width of each individual building referenced into a strip mall district. All strip mall buildings are scaled uniformly in x and z, until the building dimension in z is equivalent to the user defined width amount. The user has the ability to specify a minimum and maximum height, in feet, for each referenced building model. Models are randomly chosen from the building model library and are randomized by translating the selection sets in the positive y direction, to varying amounts, as previously described. We must determine

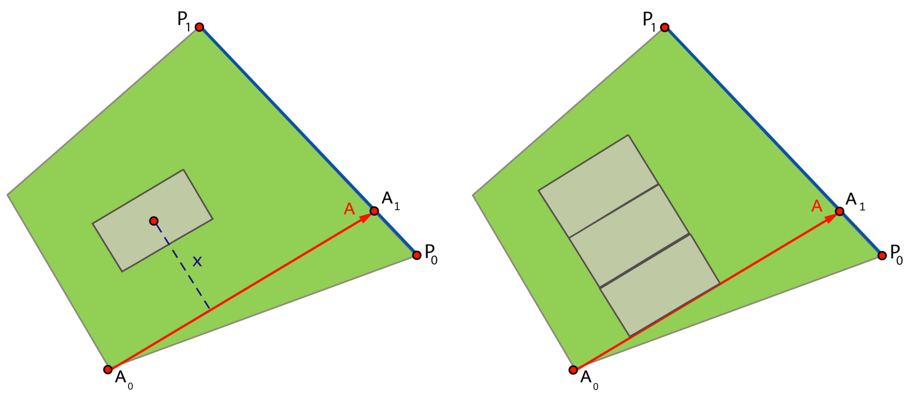

Fig. 69. Cast a perpendicular vector from the front facing edge to check for intersection along the back edge. Successful intersection results in multiple adjacent models referenced on the plot.

the maximum number of building models to reference and placement of each of these buildings within each plot. The initial placement and rotation of the building models is identical to the other districts. Because models are initially placed at the center of the face, we must determine the distance to translate each referenced building in order to maximize the number of models on each plot. Fig. 69a illustrates how we cast a perpendicular vector $\overrightarrow{A}$ from the front facing edge of the plot to its opposite

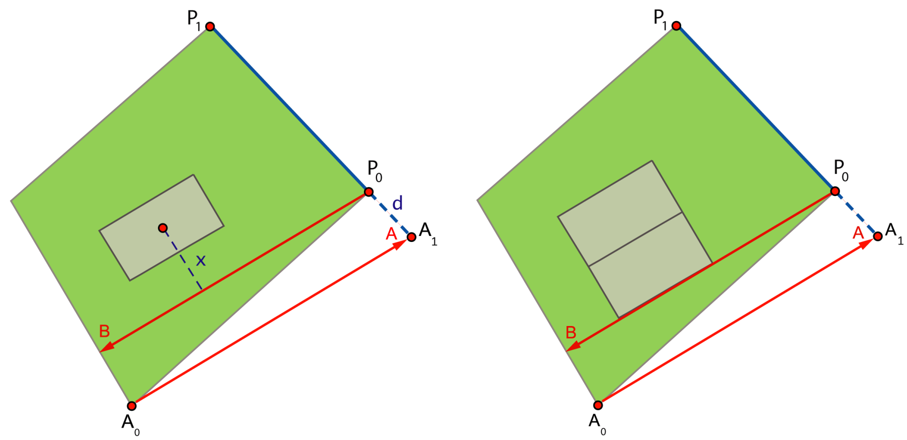

Fig. 70. When the initial perpendicular vector does not intersect the opposite edge, cast a vector from the nearest opposite edge point to the front edge. The successful intersection allows us to derive x and reference multiple adjacent models into the plot.

edge on the polygon and the intersecting point A_1 lies in between the points P_0 and P_1. With this information, we are able to derive the distance x and use that distance to translate the first referenced building model. Once the initial translation distance is defined, we can easily repeat the process subtracting one building width from the translation distance each time. Fig. 69b illustrates an example of multiple referenced buildings on the same plot. In the event that the intersecting point A_1 does not lie between point P_0 and P_1, we must then cast a vector $\overrightarrow{B}$ from the opposite edge in the opposing direction as illustrated in Fig. 70. Once the initial translation is defined, we must determine the boundary of buildable area on the back end. Fig. 71 illustrates how we execute the same technique casting a perpendicular vector $\overrightarrow{A}$ from the front edge and checking for intersection with the opposing edge. In this case, point A_1 lies in between points P_0 and P_1. If point A_1 was determined to lie outside of points P_0 and P_1, we would have to cast a second vector $\overrightarrow{B}$ from the opposite edge in the opposing direction, similar to Fig. 70. In either case, we are able to derive the length y. Below we define units as the maximum number of strip mall units allowed on the building plot.

$$units = \frac{x + y}{width} \tag{4.2}$$

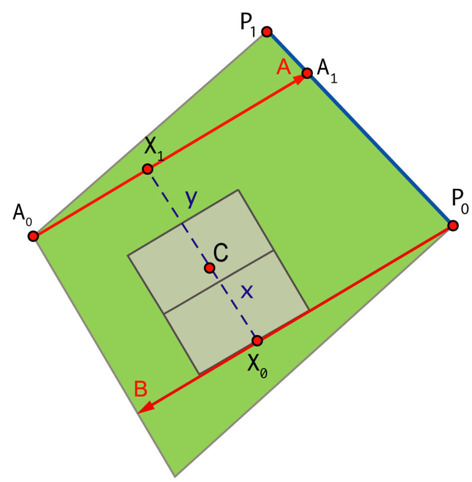

Fig. 71. Casting a perpendicular vector from the opposite front edge point to determine the number of strip mall models that will fit on the plot.

IV.3.5. *Populate Residential District*

The population step for the Residential District creates a single randomized building form for each plot of land zoned to the Residential District on the previously created zoning map. Building randomization happens in two steps. The first step selects a base building form from the Residential Building model library. Fig. 47 displays the five base shapes in the Residential Building district library. The second step uses any one or combination of selection sets, previously defined for the selected base form, to add variation and individualism to the form. As previously described, Fig. 49 illustrates the selection sets for Residential Building 2. Fig. 72 illustrates several possible building form variations for Residential Building 2. The figure demonstrates how the selection sets defined in Fig. 49 may be used alone or in conjunction with multiple selection sets to create increased form variety. The user has the ability to specify a building setback distance for this district. SImilar to the Neighborhood Commercial District, strict height limitations are placed on buildings within this district, therefore the user may not specify a minimum and maximum height range for this district.

IV.3.6. *Scaling to the Property Lines or Building Setback Lines*

For each building model we define four extent points to be used when determining a uniform building scale amount. Each building is assigned four extent points which creates a bounding box around the building footprint. Fig. 73 shows two different building footprints and places the four extent points, E_1, E_2, E_3, and E_4, for each.

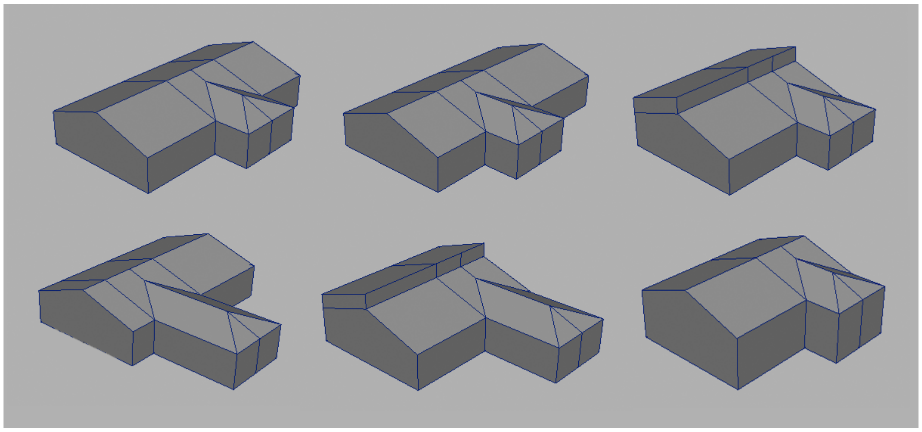

Fig. 72. Randomized Residential Building 2

As the building is scaled and extruded, the extent points are updated accordingly. If a building setback distance is provided by the user, the plot boundary lines must be offset by the specified setback distance. For each edge on the face, let $\overrightarrow{A}$ be the unit vector from one edge vertex to the center of the face and let $\overrightarrow{B}$ be the unit vector along the current edge as shown in Fig. 74a. Let $\overrightarrow{C}$ represent the unit vector along the line x multiplied by the magnitude of the user defined setback distance. Let $\overrightarrow{C_0}$ represent the first edge vertex multiplied by $\overrightarrow{C}$ and let $\overrightarrow{C_1}$ represent the second edge vertex multiplied by $\overrightarrow{C}$. The resulting points P_0 and P_1 define the setback line for the current edge. Fig. 74b displays the building plot with setback lines defined for every edge.

$$\theta = \cos^{-1} \frac{\overrightarrow{A} \cdot \overrightarrow{B}}{|\overrightarrow{A}| * |\overrightarrow{B}|} \tag{4.3}$$

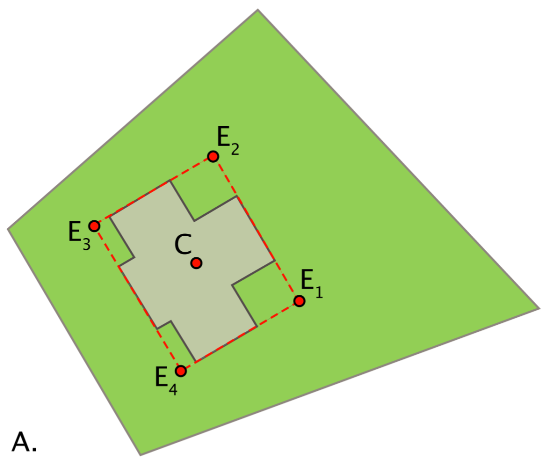

Fig. 73. Building extent points

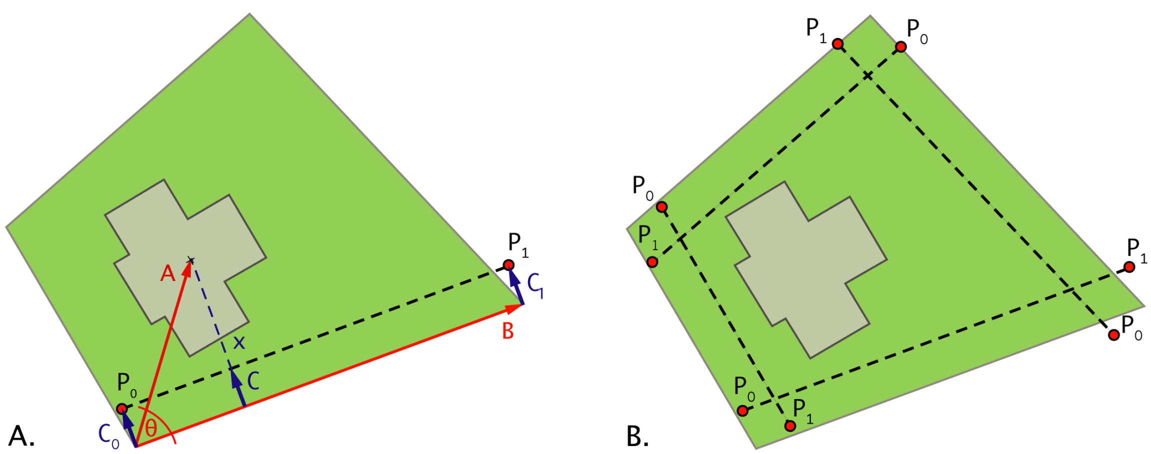

Fig. 74. Define property setback lines for all property edges

$$x = \sin(\theta) * |\overrightarrow{A}| \tag{4.4}$$

For the Office, Neighborhood Commercial and Residential Districts, a single building

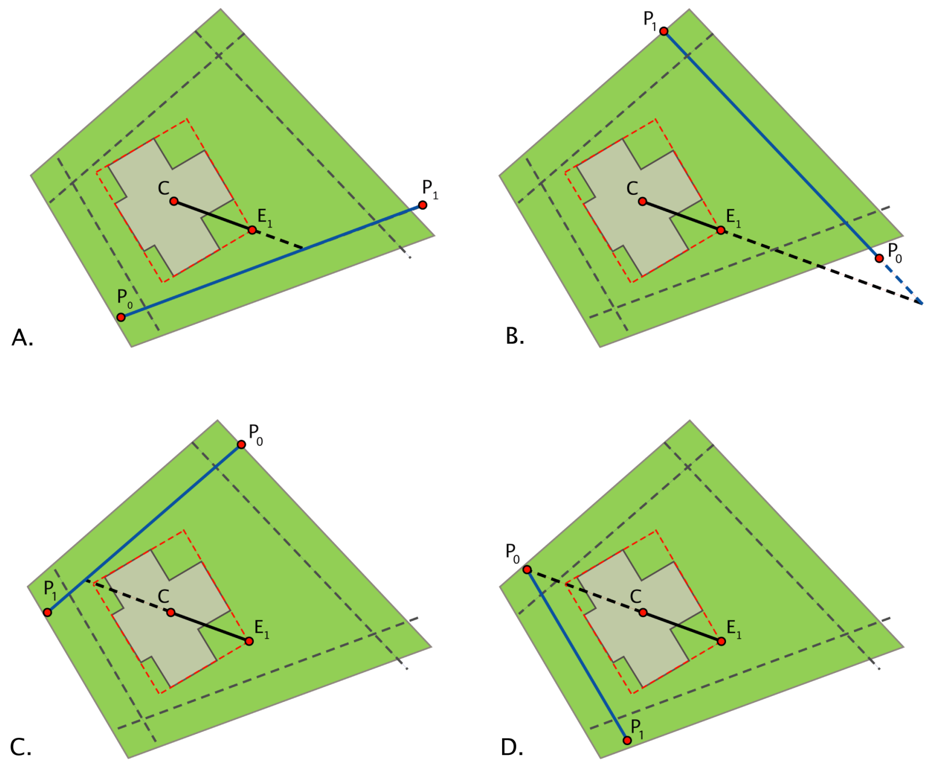

Fig. 75. Line intersections

is placed on each face. We check and compare several line intersections in order to determine the maximum amount we can uniformly scale each unique building as it sits in its building plot. First we establish a line from the building center point C and the building extent point E_1 as illustrated in Fig. 75. Then we find the point of intersection between this line and each of the four building setback lines and measure the distance to the point of intersection. If no building setback distance was supplied, then we simply use the four boundary lines of the plot. The distance to each of the four setback lines is represented in Fig. 75 as a dashed line. This process must be repeated three more times forming lines between the center point and each of the remaining extent points, E_2, E_3, and E_4 respectively, and checking each of those lines for an intersection distance with the 4 setback lines or plot edges. When the shortest intersection distance is found, we can derive our uniform scaling amount. In Fig. 76 we define s as the distance from the center point C to the extent point E_3. We define x as the distance from the extent point to its shortest intersection with an edge or setback line. From these values, we derive the uniform scaling amount in the formula below. The uniform scaling amount defines the maximum amount the building may be scaled, without overstepping boundary or setback lines. However, in the Neighborhood Commercial and Residential Districts, this uniform scaling amount it clamped at 30% in order to maintain an accurate scale between the different districts.

$$UniformScaleAmount = x/s \tag{4.5}$$

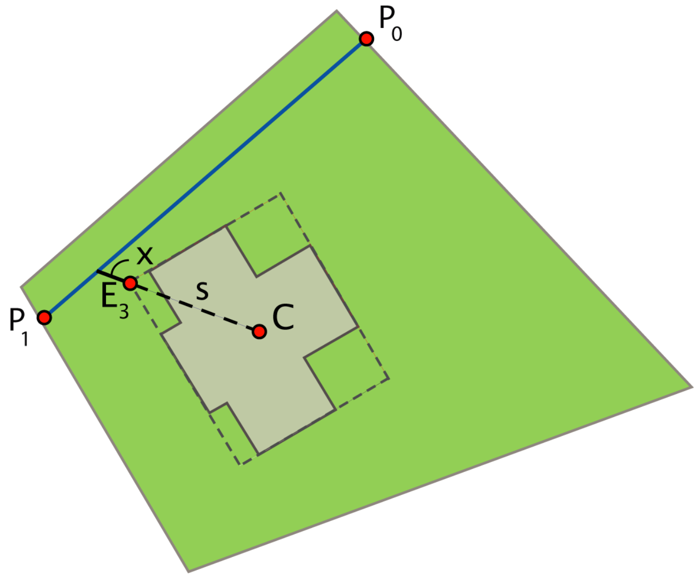

Fig. 76. Shortest line intersection distance

CHAPTER V

RESULTS

The objective of the 3D zoning map is to allow for the visualization of a city before it is built. The user is able to observe the relationships between building models within an individual district. Fig. 77 displays an entire city map composed of only office district buildings. In this map, we are able to visualize the distribution of varying building heights within a specified range. This map also allows us to visualize how just our five base building models described in Fig. 26, can be randomized to create a wide variety of unique building forms. Fig. 78 displays a top orthographic view of an Office District map. This view demonstrates how each referenced building model is correctly rotated according to the previously described rotation rules. This view also demonstrates building models correctly scaled with a building setback of zero.

Figures 79 and 80 display a 3D Map zoned entirely to the Residential District. These two images allow us to visualize the land populated entirely with hypothetical residential structures. We are able to visualize both positive and negative reactions to user defined parameters such as, building setbacks and road placements.

Fig. 81 displays a 3D Map zoned to both the Neighborhood Commercial District and Strip Mall Commercial District. Along with Fig. 82 we are able to see how the Strip Mall Commercial District behaves by populating a single plot of land with variant repetitions of the base strip models. We are able to observe how the minimum and maximum height constraints work, or do not work, within the given zoning map. We are able to observe the relationships developed amongst several contiguous strip

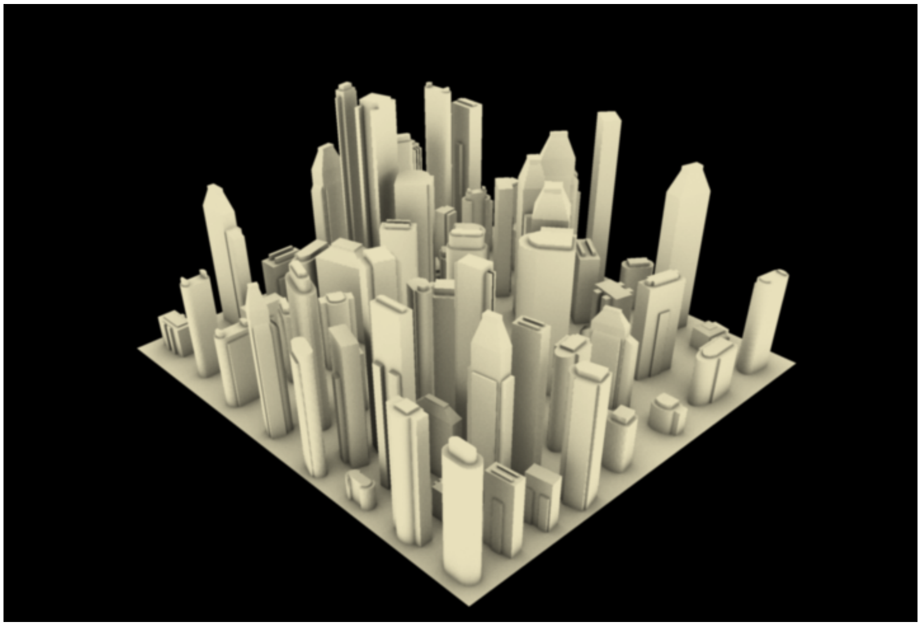

Fig. 77. Office District 3D zoning map

mall commercial district plots. Fig. 82 shows the 3D zoning map from the perspective of an inhabitant and from that perspective we are able to get a sense of the space created by a continuous street of front facing strip center models within the same district. The figure displays height and design variation within a continuous strip mall on a single plot of land, as well as, between neighboring strip mall centers. The figure also exemplifies the consistency of street facing building facades. The 3D map pictured in 81 allows us to view the Neighborhood Commercial District as it exists on its own and in conjunction with the Strip Mall Commercial District. The user can gain a better understanding of how the building setback amounts both positively and negatively react with the proposed environment.

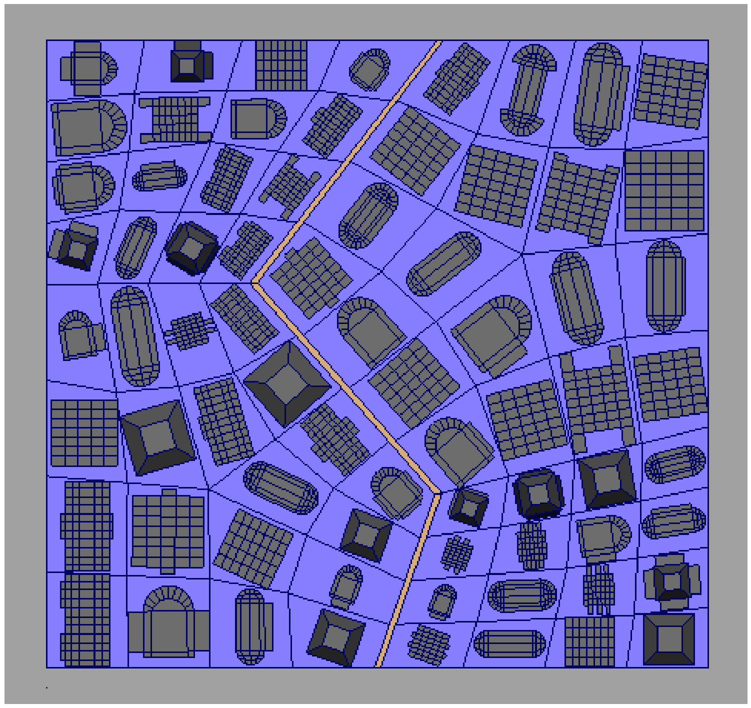

Fig. 78. Office District building placement

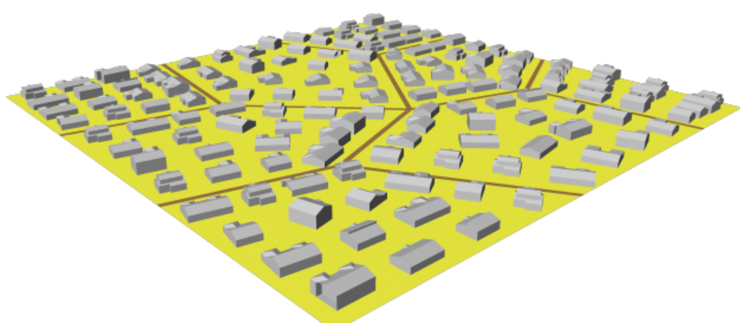

Fig. 79. Residential District 3D zoning map

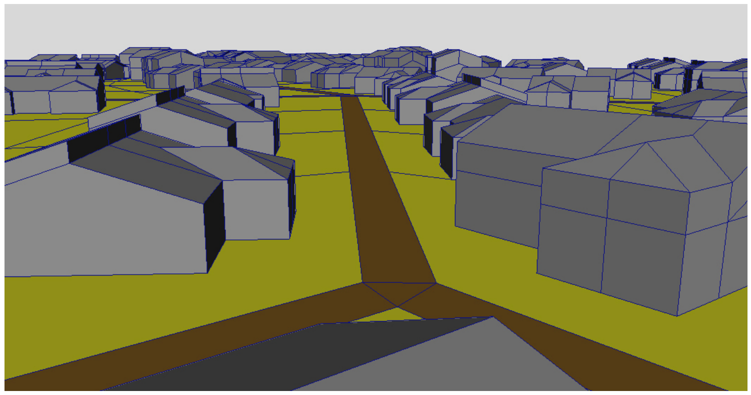

Fig. 80. Residential District building placement

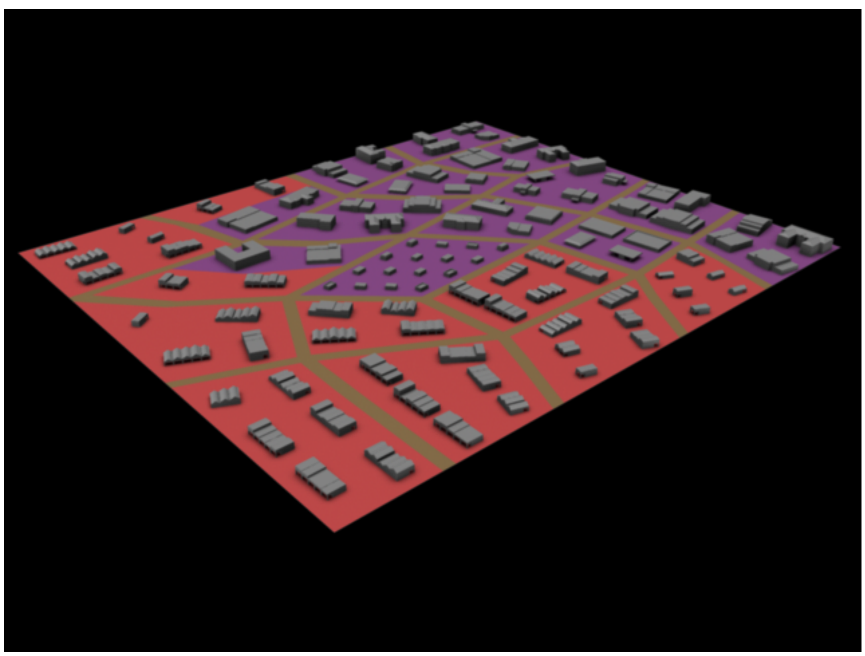

Fig. 81. Neighborhood and Strip Mall Commercial District 3D zoning map

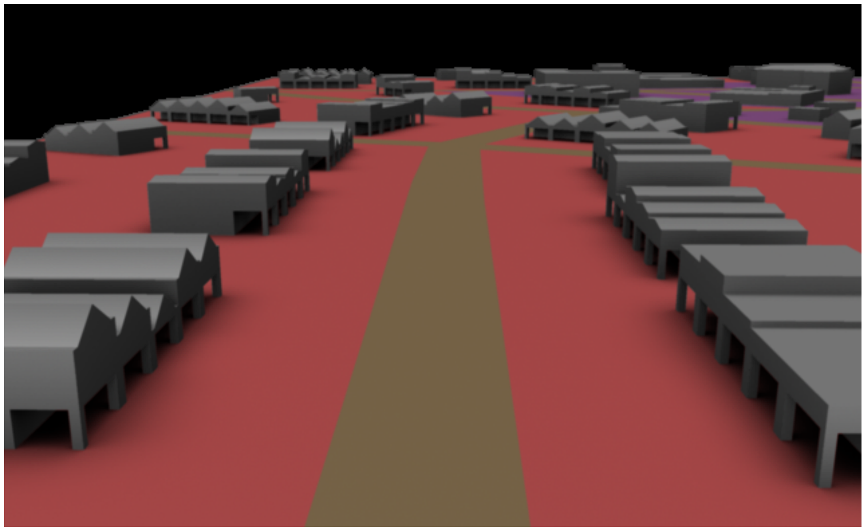

Fig. 82. Commercial zoning map perspective

Additional to observing relationships within a single zoning district, an important purpose of this program is to allow the user to observe relationships occurring when multiple building districts are zoned on the same 3D Zoning Map. Fig. 83 and Fig. 84 display different angles of a multi district map created with this design tool while utilizing all four previously defined zoning districts. Within these maps we are able to see the differentiation between use districts. At this point, the user has the ability to simulate the sunlight and project shadows being cast from the taller office buildings onto the shorter, neighboring commercial buildings. Figures 86 and 85 are additional examples of 3D Zoning Maps incorporating all four previously defined zoning districts.

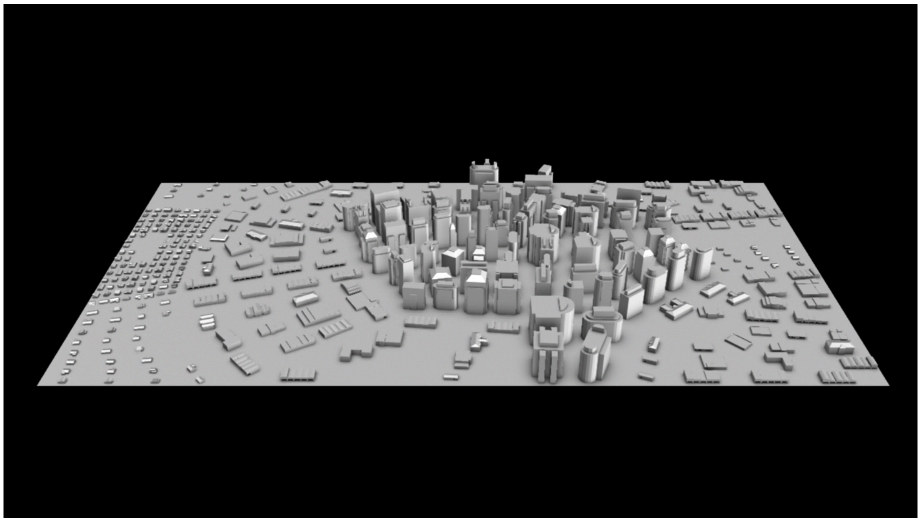

Fig. 83. Front perspective of multi-use district map 1

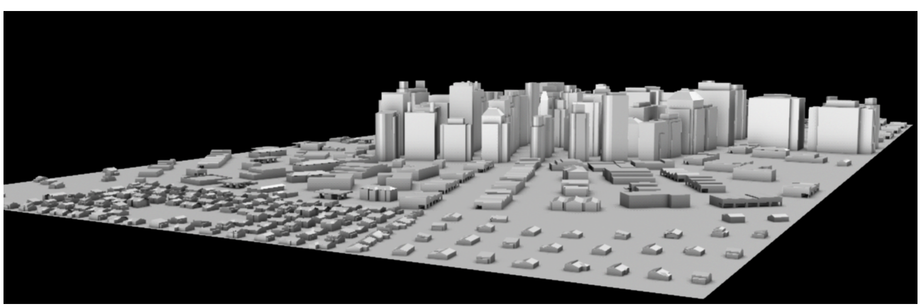

Fig. 84. Side perspective of multi-use district map 1

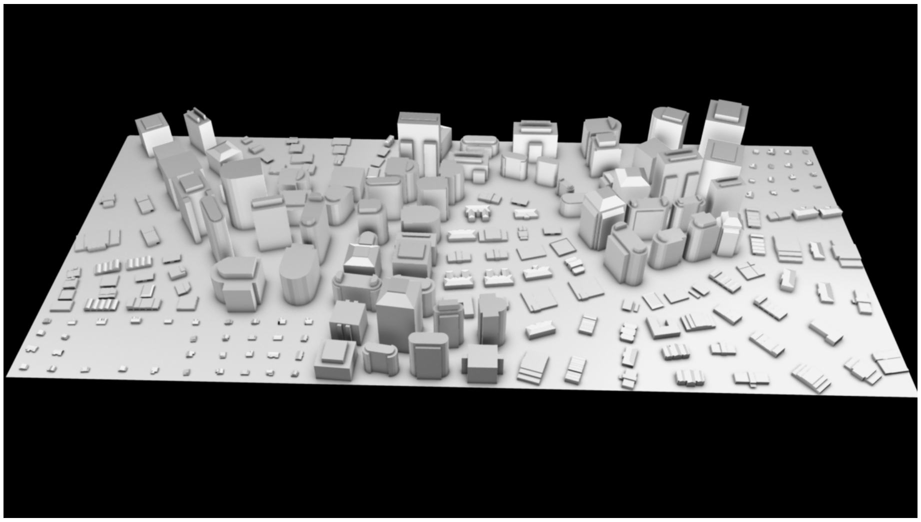

Fig. 85. Front perspective of multi-use district map 2

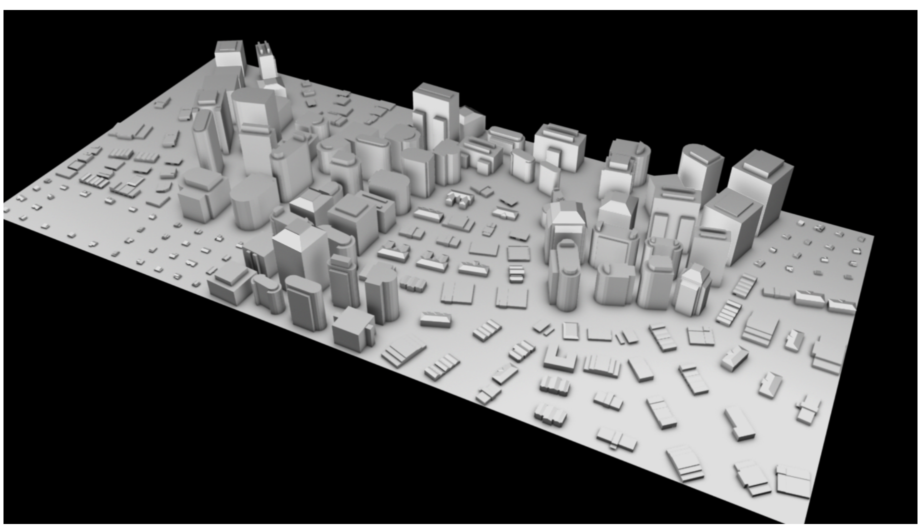

Fig. 86. Side perspective of multi-use district map 2

CHAPTER VI

CONCLUSIONS

When a city is zoned and planned in a three dimensional world, we are able to simulate real world relationships existing between different building districts, as well as, within a single building district. A three dimensional zoning map allows for study and adjustment of the future built environment. Additionally, a three dimensional zoning map, provides planners with the ability to quickly visualize multiple built city solutions. Based on the work completed in this thesis, we are able to successfully build and analyze hypothetical cities quickly, using three dimensional zoning maps.

This thesis provides a detailed understanding of four existing zoning districts. We are familiar with the common buildings and building characteristics found within those four districts. We are also familiar with the design and randomization techniques developed in this thesis.

This thesis utilizes a modular design structure representative of four distinct existing zoning districts. The modular design allows for infinite expansion of additional districts and further representation amongst the districts studied in depth in this thesis. This thesis is a successful working proof of concept for a three dimensional, modular zoning and planning tool.

CHAPTER VII

FUTURE WORK

VII.1. Larger Scope

This program was designed to be modular, therefore it can easily be expanded. Existing building districts that I created will always have the ability to be expanded by adding more buildings to the district building library. As proof of concept, I only created a small sample of base building models for each district library, but these libraries can be expanded to contain hundreds of base models if desired. Additionally, as a proof of concept, I only designed and implemented four different zoning districts. In the real world, complete zoning maps may contain 20 or 30 different zoning districts. This program has the ability to be expanded to contain as many zoning districts as desired.

This thesis was focused on creating randomness though building form and design. Further research can be done to explore the different building materials common to each building district. Adding textures to each building will add an additional layer of detail to each rendered model. Implementing the ability to randomize the type, pattern, color, and size of texture applied to each model will create further randomness amongst building models. The textures can work to add increased detail to the building models without compromising much program simulation time.

VII.2. Added Features

This thesis is intended as a proof of concept and in doing so makes many generalizations, concerning the depth and level of detail utilized in the planning process, which may be further explored in future iterations of this program. For this thesis, I programed in the ability to add building setbacks to each plot of land. The building setbacks are uniform, receding back the same distance from each boundary edge on the build face plot. In order to give the user more control in the future, the ability to setback different distances from the front, back, and side edges would be beneficial. Additionally, during the subdivision process, this thesis requires the user to manually add a primary level of subdivision eliminating concave angles by hand. In future work, it would be beneficial to program an algorithm to remove these angles without requiring the user to do anything. This program is a learning tool which is meant to be used by professionals with planning knowledge. As previously explained, certain building characteristics are controlled by the user. Numerous additional building rules and regulations exist. Future iterations of this program can focus on studying and implementing additional building laws.

In the first zoning step, the user is supplied with only a square shaped base drawing plane after which the user is able to scale and translate individual vertices as desired. Future iterations of this program could benefit from supplying and interpreting more complex initial ground geometry. More complex XZ planar geometry could be used. Example geometry shapes could include a circle, pentagon, or a variety of organic planar shapes with a vertex count greater than 4. Further, it would be beneficial for the program to have the ability to comprehend ground geometry which reflects topology. No mass of land will ever be perfectly flat to build on so it is important for the program to have the ability to account for these conditions.

In its current state, this program works to build virtual cities placed arbitrarily in space. Future iterations of this zoning program could benefit from integration with existing GIS data. Instead of constructing these zoning maps in an arbitrary location in the virtual world, it would be beneficial to have the ability to ground the zoning simulations to a physical location in world space geography. Example functionality could allow the user to locate the desired build area on a map and pull into the program information about that build site, such as topology, existing land use information, and real world coordinates.

Pushing the level of realism and fully simulating a hypothetical city, future iterations of the program could aim to simulate secondary elements to the buildings. I consider vegetation to be a secondary element. Aside from zoning an empty Park District, the program currently does not represent any individual vegetation. When zoning and building land, it is important to represent the existing vegetation because it must be considered during the zoning process. If building a large complex in an area where there are lots of trees, the planner must consider the placement of the trees and how they may conflict or best compliment the future buildings.

VII.3. Improvements in the GUI

Currently, the user interface for this thesis utilizes Maya's Embedded Language functions for interface design and display. Future improvements on the user interface could utilize the Qt application framework as a replacement to Maya's Embedded

Language. I think that opening up the user interface design to Qt will allow opportunities to expand the functionality of the user interface.

VII.4. Use in Other Industries

Currently this program aims to mimic the form, style and guidelines of the actual built world. However, this program can be easily adapted and programed to respond to any set of rules and additionally, the base models may contain any form desired. For these reasons, I think this program has the ability to adapt and work well in other fields and industries. For example, I think the animation industry has needs for a program similar to this one. Due to its adaptability, this program can represent any type of stylized 3D environment. I think it would be interesting to build a few Dr. Suess inspired stylized building model libraries and supply each with adequate rules for randomization. The same zoning process and techniques would apply, but the final product would be a model city representative and fit for a stylized universe. This is the type of functionality that would be useful to the animation industry.

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