I, Sergey Kahn, hereby submit this original work as part of the requirements for the degree of Master of Architecture in Architecture.

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Thinking Outside The Grid: Structural Design Through Multi-parametric Growth and Self-Adaptive Analysis

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Thinking Outside The Grid: Structural Design Through Multi-parametric Growth and Self-Adaptive Analysis

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by

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Abstract

This thesis explores an alternative approach to designing the structural systems of buildings that provides freedom from the reliance on established grid-based design rules that architects are typically limited by. Through the use of Finite Element Analysis software to analyze structure and in conjunction with multiple parameters that influence structural growth a skyscraper is generated in Chicago. An algorithm is designed that establishes rules for structural growth with variables taken from the performance of the structure as it grows as well as various design parameters. These parameters can be specific programming needs in parts of the building, views of neighbouring buildings that are affected by the construction of this skyscraper, openings, and other considerations. The goal of this thesis’ explorations is to give the architect more control of the structural constraints by allowing them to grow structure that is informed by architectural design intent rather than limits the architect to design around the constraints of a structural grid.
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INTRODUCTION
In medieval architectural history, the design of a building from its façade and columns to its doorknobs and tiles was the responsibility of a single master mason hired to make all those design decisions (Cryer, 2006, pp.71-74). However, as technology advanced, particularly during and after the industrial revolution, building projects became more ambitious and the breadth of knowledge required was too great for only one individual to master. Thus, out of necessity, various professionals would specialize in different fields associated with the built world while an architect is tasked with bringing them together and producing the overall design for the building. This division within the field was not without its disadvantages. Because the architect is armed with only a basic understanding of the possibilities of various structural decisions, they must design with just the rules of thumb. Without being in constant collaboration with a structural engineer, which is rare, the architect typically sticks to grid-based designs where they can make some easy assumptions by spacing columns and beams based on material, shape, and size. However, while once the work of the structural engineer was confined to pen and paper, there is now software that can perform structural analysis and is as accessible to the architect as it is to the engineer. This thesis will investigate not only how the architect can use structural analysis tools to liberate their design options, but also how the analysis can be itself integrated as part of the design parameters.
By incorporating structural analysis tools in the early stages of schematic design and design development the architect has the freedom to explore more design opportunities and their consequences on the overall structure. Typically, the organization of space is done with an assumed column grid (Pickard, 2002, p.298), however, with the use of structural analysis tools the architect can make certain design decision first and create a structure that conforms to those design parameters. Should openings be desired based on some factors other than a prearranged grid, that could be done and evaluated. Larger or irregularly shaped spaces where fewer or more dynamically placed columns are desired can also be experimented with and evaluated. This research will look at how different rules can be programmed into the growth of a structure. “Growth” here means that the structure will be produced through a step-by-step process in which the structure will be evaluated at each step and rules based on the evaluation of the current structure at that step as well as other design parameters will affect the growth in the following steps. The rules for structural growth can include parameters that are environmental, such as the wind, gravity, and sunlight, site related, such as easement regulations and consideration of neighbouring buildings, or programmatic, such as open space needs, head clearance, and passageways. A skyscraper will be designed for Chicago that uses these rules of growth and evaluates the performance of the resulting structure.
In order to analyze the design of a building’s structure the design, which is created on a computer, must be broken down into elements that analysis can then be performed on. The procedure for this is called **Finite Element Analysis (FEA)**, which is a method that simplifies a model into certain boundaries and boundary conditions in order to find the approximation of its exact performance (Bhavikatti, 2014, p.2). A model is simplified by discretizing it into a collection of elements and nodes. In the case of this research, an element can be a line that represents the path of a beam or column, while a node can represent the joint that connects one element to another and restricts their rotation and movement in some or all directions. Each element will have different boundary conditions based on the cross section, material, and size that are selected for the beam or column that the element is meant to represent. Likewise, each node can have a different boundary condition as well based on whether transformation and rotation are restricted in all or only some directions. It may be decided that a certain boundary condition is ideal for all elements and nodes in the design, or it can be determined that certain boundary conditions would be more ideal than others based on certain parameters. For instance, larger cross sections are traditionally desired for columns that are closer to the ground versus columns that are higher up. Once the elements and nodes are given their boundary conditions, additional boundary conditions are applied to represent the forces that will be acting on
the structure. These forces can include, gravity, the wind, and live and dead loads. Once all boundary conditions are applied, the software will then perform an analysis that will solve for various conditions including the displacement and utilization at each node.

While the software for performing FEA was separate from software used by architects in their design process at one point, there are now some FEA features and plugins available to be used natively within certain design software. This affords the opportunity to allow for the output of the analysis to influence the design directly through self-adaptive analysis. A self-adaptive analysis is when the output of an equation becomes the new input for the same equation either for a specified number of steps or until a desired value is reached for one of the outputs. For instance, the equation may call for analyzing a structure, outputting the node of greatest utilization, adding a member to brace that node, and running the analysis on the new structure. This can be repeated until the maximum displacement reaches a safe low, at which point the analysis would cease. FEA and self-adaptive analysis will be used in the generative growth of the skyscraper designed for this project.
Grid-based structural design is not without certain advantages. For one thing, it allows a certain level of flexibility by creating an open plan. Open plans are more sustainable because they allow for a longer life cycle for the building since they can be rented out and resold to different users for different purposes (Nicolaou, 2006). One example of this can be found in Google’s headquarters in Mountain View, California, which had previously been built for and used by Silicon Graphics but redecorated to suit the tastes and culture of its new owners (Laing, 2006). Another advantage to the grid-based structure is that by having fixed distances between columns it will make fabrication much cheaper since the same sized members will be used repeatedly and make assembly quicker as the same connections are happening throughout the building (Sebestyen, 2003, pp.119-120). However, column placement can often interfere with some programmatic needs. If a meeting or assembly space is desired that accommodates a lot of people, the existing grid may not offer such an unobstructed space. Columns are also often found blocking corner windows on what might otherwise be a desired outward view. Also, some users of the space may find the repetition of gridded spaces monotonous and uninspiring. Since the 1960’s and into the present, the development and improvement of technology has removed many restrictions that limited architects to a limited number of building types (Sebestyen, 2003, pp.7-8). There are various methods and experiments used
STRUCTURAL PLANNING PRECEDENTS

Sergio Musmeci designed the unprecedented concrete shell that supports the Basento Viaduct in Potenza, Italy in 1969 before computers were available for structural analysis and form-finding work (Gabriele, et al., 2016, pp.543-550). His goal for the bridge was to minimize material through an optimized form and he achieved this through a combination of physical models and mathematics. He started with soap film bubbles, which help demonstrate a minimal surface that has uniform tensile forces in all directions. He then mathematically approximated the behaviour to create a form, which he then tested with a neoprene model (see figure 2 on p.16). The neoprene model was held together through tension in order to represent the behaviour of concrete in compression. The form was further tested by a methacrylate model to test loads and strain and culminated with a 1:10 concrete model before the actual bridge could be built. In this example, Musmeci used lessons from nature to inspire form by asserting that the behaviour of a soap film bubble is synonymous with that of a concrete shell. To validate his irregular design required testing on models of ever-increasing scale. Were the same approach applied to testing an innovative structural design for a skyscraper it would be unsustainable. Furthermore, Musmeci’s inspirations came from the behaviour he could observe in nature or through physical models. He
was thus limited by his ability to create a scaled-down analogous physical model. By applying boundary conditions to a digital model, which can be analyzed, Musmeci’s Bridge, and the natural forms it’s based on, can be recreated digitally without the need for scaled models (Gabriele, et al., 2016, p.549). The research in this thesis affords more freedom by allowing for the testing of behaviour that may be difficult or expensive to test with scaled models and adapting to the results of the test more quickly.

1 Sergio Musmeci (left) in front of the just completed Basento Viaduct

2 1:100 Neoprene mechanically pre-stressed form finding model

3 Force-modelled bridge shape derived using FDM for pre-stress ratio 4 to 1
Frei Otto was another architect who used surrogate models to experiment with form and was a pioneer in the use of computer-aided design in form finding (Otto, et al., 1995, p.76). For Otto, research was a big part of his practice and he developed various methods that allowed for forms to generate themselves. Some experiments included the use of soap film, chains, bandages, sand, and magnets to name a few as well as devices that stretched rubber and other materials to create pneumatically stressed membranes (Otto, et al., 1995, pp.56-57). For the 1957 Federal Garden Exhibition in Cologne, Frei Otto designed several membrane structures through his form finding research (Otto, et al., 1995, pp.78-79). The entrance was based on a form-finding model made from steel wire and spring net while two small pavilions were designed based on form-finding models made with soap film. In 1991, architect Bodo Rasch was inspired by the design of one of these tents and used computer modeling to determine the shape and cut of the membrane structure (Otto, et al., 1995, pp.80-81).
More recently, FEA software has been used for the design and distribution of columns in the Active Energy Building in Vaduz, Liechtenstein by Falkeis Architects and structural design firm Bollinger + Grohmann (B+G) (Futurzone, 2014). Four custom made forked columns are placed and rotated in thousands of combinations until the software identifies the placement with the lowest deflection and least number of columns are needed. This process allows for unique spaces in what would otherwise be identical housing units, as well as increased efficiency and reduced material resources. However, the column placing script did not affect the design until after floor plates, cores, and the program had already been decided on and therefore the software’s contribution towards the design happened late in the process. At the time of publication, this building is still under construction, so it is uncertain how the irregular column placement will impact the residents’ use of the space or whether other programmatic factors or views played a role in limiting the potential column locations. If other parameters were not included then it is possible that some column placement will adversely affect the occupants’ use of space. It is important for the sake of this thesis that those parameters are factors in the growth of the structure and that even the floor plates are a result of the structural form.

B+G has used FEA software on other projects as well. At Frankfurt’s airport, they worked with the architects at Lengfeld & Wilisch to design the Skylink,
a pedestrian bridge linking a car park to the airport (Acciaio Arte Architettura, 2012). Rather than build a simple trussed bridge with evenly spaced diagonal steel structural members, a computer algorithm was used to give the structure the appearance of randomness. Initially, the diagonals are placed randomly and then an FEA is run to determine where there is a higher deflection in order to add additional members, as well as which diagonals are not supporting a load in order to remove them. They used an evolutionary algorithm, meaning that the script ran several possible outcomes in order to determine which yields the best results. In this case, the best result would mean a reduction in overall structure and low deflections, as well as a desirable aesthetic.

Previous experiments in unprec-edened architectural design required a strong mathematical foundation and iterative models at ever increasing scales that tested the feasibility of an untested idea, as in the work of Musmeci. With the introduction of FEA as a design tool, thousands of design iterations could be tested in little time and at no material cost. The randomness of each iteration may take away some of the architect’s agency in the design, however, if the architect is more intentional with their incorporation of design parameters then a more collaborative relationship between architect and software is possible and allow for the architect to gain agency through this process, rather than lose it.
GROWTH IN DESIGN
Watch a time-lapse film of a building being constructed and it appears to grow like a plant. Yet most designs are structurally stable only at some stages of the build and if the scaffolding is removed mid-construction they may fall apart. This is not so for the growth of plants, which do not rely on artificial support for structural stability at any stage of their growth. Growth in nature has been both a field of extensive study as well as a source for inspiration in art, design, and architecture.

There are different systems used to describe growth and movement in the natural world. One such process is called **Diffusion Limited Aggregation (DLA)**. This is a process observed in nature where particles that move about randomly will cluster together when they come in contact and form aggregates, or groups (Sander, 2000, pp.203-218). The resulting aggregate is a fractal and the shape can vary greatly depending on what it adheres to. DLA is studied through computer simulation but also many artists find inspiration and create algorithms of their own that affect the simulation of DLA to create certain patterns and shapes in 2D and 3D. Andy Lomas is a digital artist who creates work by simulating DLA behaviour and other natural processes (Casselman, 2007, p.800). His “Aggregation” series starts with a simple ‘seed’ surface that randomly moving particles will adhere to. Those particles then become a part of the aggregate in which other particles could adhere to should they collide. Different forces of field also affect the shape of the aggregation.
1. Aggregation 9
2. Aggregation 23
In Andy Lomas’ Cellular Growth series, he creates an algorithm to simulate cellular growth and generate complex sculptural forms (Lomas, 2014). By varying the rules in each iteration, the “cell” that is created can look vastly different than those in previous iterations. Lomas states that his intent is not to replicate any one particular organism but rather to find more universal patterns through experimentation. Initially, each cell growth starts as an evenly distributed and sized group of particles in a spherical arrangement with each particle linked to its adjacent particles. The form develops based on the combination of forces that affect the interactions between the particles, or cells, as well as regulate the cell divisions. This growth is affected by rules for cells trying to maintain a certain distance from their neighbours, as well as rules that try to bulge the cells when there are folds and fold the cells when there are bulges. The tension between contradictory rules is part of what creates the complex forms. Subtle variations in the rules can result in cell growth that can look similar to organs, coral, or plants.
Another method using for defining growth in nature are L-Systems, named after biologist Aristid Lindenmayer who developed L-Systems as a method for defining the rules that govern growth in plants (Prusinkiewicz and Lindenmayer, 1990, p.1). The concept of L-Systems center on the idea of rewriting, where parts of a complex object are successively replaced based on certain rules. L-Systems aren’t used only to simulate plant growth but also can create geometric patterns that can start from a simple geometry in the first iteration and become more intricate with each successive recursion.
Some architects and researchers have experimented with the use of L-Systems as a methodology for design generation. Michael Hansmeyer (2007, pp.148-164) explored various ways of interpreting an L-System algorithm architecturally in his series “L-Systems”. In his series, he would start with simple rules for his L-System, such as:

Initial String:    a
Replacement Rules:   a -> aba
                  b -> ac

He would then run the script for a number of iterations:

0) a
1) aba
2) abaacaba
3) abaacabaabcacabacaacaba
   etc...

The final string would then be taken and rules would be created for each value. These rules can affect the relocation of vertices on a surface, the rotation and scaling of objects, or even more complex relationships. Through experimentation, Hansmeyer was able to show how L-Systems could be used for modularity and parametric systems that responded to environmental factors (see figure 2 on p.27). His work, however, is limited within a theoretical, digital landscape and isn’t applied towards a built world. Still, it illustrates the potential of recursive algorithms as design tools by showing how the addition of a few simple inputs
1 Visualizing L-Systems with object replacement by Hansmeyer

2 String created to show modularity and environmental reaction by Hansmeyer

3 Stochastic string replacement by Hansmeyer
can create an output that is complex and architectural.

Both L-Systems and DLA are methods of looking at growth within nature. Both systems can be modified based on certain parameters. This research will create its own system that will dictate growth. Although some inspiration may be gathered from the behaviour of L-Systems and DLA, ultimately this thesis will create its own system in order to properly meet the needs of the building.
STRUCTURAL GROWTH METHODOLOGY
The rules informing the growth of this structure are developed through an iterative process. Through each iteration, issues that hinder the design and growth of the structure are identified and new rules are written for the following iteration that address the problems from the previous one.

The growth of this structure required an initial “seed structure”, much like how an L-System begins with a starting geometry. The “seed structure” here is based on the sizing and location of the core. At the core’s four corners, columns were stacked vertically to the proposed overall height of the skyscraper. From there, an FEA is conducted and the output from the initial input model will indicate which node has the highest utilization and output a vector direction and value associated with that node’s deformation. That output will then be used to create additional structural elements based on an algorithm that informs what sort of structural growth is needed.

Typically, this growth will add a column to the lower floor at a distance and direction that is based on the output vector and angle the column in a direction that is also based on that vector. If the top of an existing column is within 2 meters of the endpoint for the new column, it will connect the new column to that instead. Otherwise, the algorithm will continue to add columns to floors below until it either connects a column to an existing one or terminates at the ground level.
Flowchart showing structural growth loop

1. Node with highest utilization
2. Direction of deformation
3. Magnitude of deformation
4. Allowable build area
5. Top of new column
6. Bottom of new column
7. Near existing column top?
   - Yes
     - Move endpoint to nearest column
   - No
     - Move to closest allowable build area
8. Column angle greater than 45°?
   - Yes
     - End growth
   - No
     - Column at ground level?
Other restrictions are placed on column location based on design parameters. An overall massing potential is determined based on maintaining views between certain buildings around the site. Columns cannot be placed outside of this massing potential. Columns are also restricted from growing into the core or being placed within 2 meters of an existing column. If the starting point column is initially aimed towards an out-of-bounds area it will relocate to the nearest point that is inbounds instead. The same method is true for that column’s endpoint, however, if that results in an angle that is too extreme then it will connect to the nearest column instead.

Triangulating the nodes of the columns will create the beams for the floor plates. Triangular plates will be removed if the beams exceed a certain length. This will allow for the creation of various atriums. Some atriums will span multiple floors creating irregular and dynamic spaces.

Once either a column braces to another column or the column growth reaches the ground, the process starts over with the new structure being evaluated and a new node being chosen based on highest deflection. The script loops over 1000 times until the building has structure from top to bottom and the FEA indicates the structure as being stable.
1 Growth of column structure (from top to bottom steps 0, 50, 100, 500, 1100)

2 Orange indicates allowable build area

3 Triangulated plates with long beams are removed to create atriums.
In addition to site considerations, there are also programmatic parameters that could affect or limit the structure’s growth. Column spacing could be made sparser in spaces that are desired for large audiences or groups. Some spaces may desire a more linear passage that can’t be interrupted by structure, while others may be fine with more snake-like passages. There would also be some code considerations when it comes to column placement in relationship to exits as well as head height concerns if the columns are too angled in high traffic areas. As the skyscraper’s program continues to be designed the growth of the structure can adapt accordingly and reanalyzed to assess whether certain spaces can exist without compromising the structural integrity.

Like the plants that inspired Lindenmayer (1990), the growth of this building takes on a nature-like quality. The structure generated by this script wraps around the program and within the bounds of what can be permissibly constructed. With the integration of FEA software and by creating a generative growth script that integrates design decisions a structural system can be created that is organic and breaks away from the monotonous grid we traditionally see.
THINKING OUTSIDE THE GRID
DESIGN CASE STUDY: HIGH-RISE IN CHICAGO
Site Conditions

Chicago is arguably home to the first skyscraper and has played a key role historically in defining the skyscraper typology (Beedle et al., 2007, p.20). Burnham and Root laid the groundwork in the late nineteenth century, developing the floating foundation that solved the soil constraints typically seen as a limitation to building tall in Chicago (Larson, 2003, p.25). The Chicago Tribune competition brought international attention to the city and made many architects want to build there (Beedle et al., 2007, p.62). Ornamentation became taboo as Mies Van Der Rohe showed the elegance of glass and steel, which has largely remained the trend in Chicago’s skyline up to today. When it comes to architecture in Chicago the forces of history and innovation pull back and forth and it is important to consider the needs of the site and its history critically for the sake of showing an accurate proof of concept.

This project’s site is located at 320 E. North Water St. at what is currently a parking lot. It is along the Chicago River in the neighbourhood of Streeterville, just across from New East Side and The Loop. Its immediate neighbours include NBC Tower to the North, Sheraton Grand Hotel to the East, and University of Chicago’s Gleacher Center to the West. It is also within site of Tribune Tower, Trump Tower, LondonHouse Chicago, Aqua Tower and various other high-rises on the other side of the river. On its east side is William P. Fahey Bridge and a block west is DuSable
Bridge. E. North Water St. is a two-storied street with a road below, where the parking lot is accessible and a road above, where other buildings currently have street access. There is a pedestrian path along the river on the site’s south end as well.

The climate in Chicago can be described as humid continental with all four seasons represented. Lake Michigan, which Chicago presses up against, heavily influences the city’s weather patterns. Some winters exhibit heavy snowfall from the lake effect and heavy storms are frequent. Wind speed averages are from 8 to 11.5 mph but can get much stronger at ground level near skyscrapers in the central business district (Illinois State Water Survey, 2009; BBC, 2015).
Structural Requirements

Skyscrapers typically consist of a grid of steel or reinforced concrete columns with additional structural stability provided by cores. Some skyscrapers in Chicago reduce the internal structural needs by providing diagonal bracing on the exterior of the building to mitigate lateral forces but more often than not the façade is non-structural. Other skyscrapers, such as the John Hancock Center, use a hollow core system, where the entirety of the structure is on the outside in order to allow for a completely open plan, with exception to egress. In Chicago’s central business district many of the high-rises are commercial offices. A grid-based column grid offers these offices with an easy layout and a metric by which they can evaluate the usable space of a certain property. While some people look for value in office space, others seek unique conditions that may not be met by the common grid layout. For this design, 800mm diameter circular hollow steel columns will be used and the beams will be 600mm tall steel I-beams. As described in Chapter 4, the structure will not be configured in a standard column grid.
Programmatic Requirements

The building site has three possible points of entry. The two-storied North Water Street will allow for garage entry at the lower-street and pedestrian entry at the upper-street. There will be an additional pedestrian entry accessible from the river path, which is at the same elevation as the garage entry.

As a proof of concept, the programmatic design of this building will be mixed use. This is fairly common for modern-day urban skyscrapers and will afford the opportunity to test the design implications of the skyscraper’s structure on various programs and scales. The lower floors will be commercial and open to the public. This would include retail, dining, and an athletic center. The hotel lobby, restaurant and bar will also be accessible from the street level. Floors in the midrange will be rentable office spaces while upper levels will be hotel rooms.
Design

Various inputs affected the design generated by the algorithm. The building height is 256.5m, or 57 stories at 4.5m from floor to floor. Views between neighbouring buildings create setbacks through a massing boundary that the algorithmically grown structure would avoid. The algorithm also prevented structure from being grown in the space that was dedicated to the core as well as within two meters of an existing column. Rules were created to encourage column growth to connect to existing structure, similar to the behaviour of DLA, which created a branching aesthetic in the structure’s overall appearance. Additional rules in the algorithm prevent the column tilt from exceeding a 45-degree angle wherever possible, so as to decrease the risk of unusable space from head height issues. Taking inspiration from Chicago’s Hancock Center, columns towards the exterior are exposed and become part of the façade. The glass panels are triangulated between floors, so as to meet the complex geometric demands of the irregular structure. Wide spacing between internal columns will allow for the opening of large, multi-floor atriums that create multi-level opportunities for interaction and views, similar to that of Chicago’s Santa Fe Building.

The floor-by-floor layout and circulation will be determined after the algorithm creates the structure. Any issues that hinder the design of the program based on structure getting in the way
will result in going back and modifying the algorithm with new rules that would prevent that issue.
EVALUATING THE DESIGN
Evaluating Structure

Once the structural algorithm is completed the output of the final structural form has a maximum displacement of 0.68m. The building has an average of one column per 32.8 square meters compared to a traditionally grid-based design, with the same columns spaced 6m apart would have resulted in one column per 28.9 square meters. This means that the process resulted in overall greater spacing than the traditional grid-based system. Even when taking into consideration that this methodology yields longer columns than traditional methods, the overall length of columns is 8% less in the algorithmically generated structure than in the traditional one. The structure created from the algorithm is economically more efficient in terms of material cost and in providing usable space.
Building structure with floor plates
Evaluating Spatial
and Circulation Possibilities

The overall building program has both advantages and disadvantages as a result of the unique structure. Because no two floor plans are alike, knowledge of one floor’s layout does not necessarily translate to knowledge of another’s. Likewise, people will not be able to rely on axis-based navigation through the spaces and it may be possible to get lost. However, getting lost is a desirable outcome in the context of shopping malls, as it results in an increase in spontaneous shopping (Amendola, 2006, pp.91-92). Also, people occupying offices will have enough time to familiarize themselves with the layout, so irregularity would become a non-issue and would, if anything, offer some security by disorienting potentially hostile visitors. Because hotel floor navigation is already heavily reliant on signage, irregularity will no more impact navigation than in an axial floor plan.

Another potential negative of this design strategy is the lack of regular corners. This could complicate the placement of furniture, which is typically designed to occupy rectilinear spaces. If some spaces have too acute of an angle, it would result in dead spaces that don’t get used. For hotels, it’s not uncommon to make custom furniture unique to the hotel, however, it would become more expensive to style each room individually than to have general dimensions that are the same for all the rooms. In office spaces, this may not be an issue,
depending on how densely they employ and whether they value open plans over enclosed office spaces.

One strong advantage of this design is the creation of large, irregular spaces. As in Chicago’s Santa Fe Buildings, large atriums bring in light and make office spaces feel less claustrophobic. The large atriums in the algorithmically designed building can be of service to both office life, as well as in the lower commercial floors by providing large spaces for holiday decorations, art installations, a climbing wall.
Evaluating Site Considerations

The current site is a parking lot; therefore any building placed there would impact neighbouring buildings one way or another. Because the neighbourhood is zoned for new development and is in a highly popular commercial area, building on the site is inevitable. The design of this building is meant to reduce the obstruction of views between many key buildings of interest. While being taller than its immediate neighbours, it won’t be one the tallest in Chicago, so although it will contribute to the skyline it will not dominate it. Currently, most commercial activity happens one block to the west, around Tribune Tower and Wrigley Center. This building will provide a new node to attract foot traffic, as well as a stopping point along the river trail.
Evaluating Economic Considerations

As previously stated, there is an overall reduction in material cost due to a reduction in columns required when generated through the algorithm. This also means that there is an increase in rentable space, as each column accounts for 2 square meters. With 247 fewer columns than a traditional grid-based design that results in the algorithmically designed building having an additional 494 square meters.

Fabrication and construction costs, however, would likely be higher due to the irregularity of the design. Each column and beam would have to be cut to a specific length, rather than in a traditional grid-based building where there would be minimal size variation. Likewise, each glass panel would have to be cut to order and cleaning the façade is less straightforward than cleaning a flat façade.

Some of these costs could be made up however by charging more in rent. With many offices moving towards the Activity Based Working model that focuses less on how many employees they can cram into a space and more on employee retention through the creation of enjoyable office environments, unique skyscrapers can charge higher rents than more typical designs, making up for any lost space due to irregular corners (Knight Frank, 2016, pp.26-30). The novelty of the structure will attract people to visit, shop, and visit neighbouring buildings and attractions as well.
Overall, as a steel and glass skyscraper, this design is a fitting addition to the Chicago skyline. It gives a nod to the Hancock Center with its exposure of structure on the façade, yet innovates modestly in a city that has seen the birth and evolution of skyscrapers.
Building with glass facade
CONCLUSIONS
The aim of this thesis was to explore how the architect can use Finite Element Analysis tools in order to integrate structural constraints into the design process. Through FEA software, an architect can test the structural viability of a proposed structure that diverges from a typical structural grid. The architect can evaluate the impact of various design decisions on the structure as well as design structure as part of the overall design intent.

In this research, an algorithm was written through an iterative process to inform the growth of a skyscraper’s structure based on various design parameters. External and internal factors were used to influence the growth of the skyscraper’s structure. Externally, there were bounding constraints based on views between buildings that were to be preserved. Internally, the core and minimum column distance placement informed where new growth could occur.

This research shows a method that an architect can employ to claim some agency in structural design. However, current FEA software tools alone do not completely replace the need for evaluation from a structural engineer. The use of FEA software requires accurate input, otherwise, the results won’t reflect reality. For instance, if lateral loads are not given a proper value, or live loads are not calculated, the resulting analysis would be inaccurate and building exclusively from those results could be dangerous. Furthermore, the results of this research do not produce an economical model for
structural design, as the resulting columns are of irregular lengths and angles, making them more costly to produce and assemble. This could, however, be resolved through additional restrictions in the algorithm that would reduce the columns to a kit of pre-selected lengths and angles, as was done in the Active Energy Building (Futurzone, 2014). Further advancement is needed for FEA tools in order for them to become more accessible to the architect. However, as this research shows structural analysis software can become a tool for structural design and space design in the early design stages of a building.
LIST OF ILLUSTRATIONS

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3 Gabriele, S., et al., 2016. Force-modeled bridge shape derived using FDM for pre-stress ratio 4 to 1. [image online] Available at: <https://www.researchgate.net/publication/305872003_Revisiting_the_form_finding_techniques_of_Sergio_Musmeci_The_bridge_over_the_Basento_river_Beyond_their_Limits> [Accessed 17 March 2017].

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