Abstract

Architects have a magnitude of design approaches with an ever-growing interest towards digital design approaches that harness the power of coding. Through coding architects can break free from premade design tools with their inherent limitations, thus the only limit being the human imagination and physical computing power. Algorithmic design offers an innovative way of using computational capabilities to create contemporary architectural design.

This thesis work presents a textbook example of a digital design approach for architecture through the creation and implementation of an algorithmic design tool. The digital design process utilized in this thesis can be defined as follows: analysis of inspiration and formulation of design concept, creation of digital design tool, analysis and experimentation of the design tool and finally creation of design proposals using the design tool. The purpose of this work is to introduce one possible digital design approach in an understandable and clear way. The digital design approach is expressed through illustrations and real-life examples, in hopes to familiarize architects with an algorithmic design approach and its process, as well as with the usage of scripting.

In the meanwhile, this work explores the possibilities of the described algorithmic design approach in architecture through the seemingly simple concept of wrapping behavior. Wrapping behavior implies the act of wrapping linear strip elements around an object. Through an analysis of the thesis inspiration, the Serpentine Pavilion 2002 by Toyo Ito and Cecil Balmond, the algorithmic rules governing the pavilion are unraveled. Inspired by the Serpentine pavilion a more versatile digital tool imitating wrapping behavior is developed, with the same ambition to fuse architectural and structural intent into one holistic design. The creation of the tool is selectively described in chapter two, without going too deep in the technicalities of the Python and Grasshopper code itself. After a series of experiments and explorations with the algorithmic tool, an understanding of the wrapping behavior is visualized and finally put into architectural design use through three speculative design proposals. The three design proposals highlight three possible scenarios of properties, scales and functionalities. The proposals, hence, successfully address the versatility of the digital design process.

This thesis work proves how even a simple concept such as wrapping behavior can be turned into a digital tool capable of relevant architectural design. This thesis work can hopefully inspire future digital design works in architecture by laying down a path to future research, by presenting a solid roadmap to a successful digital and algorithmic design process. The topic of wrapping behavior is open for further research, through further development of the wrapping script or through ideas branching from the main concept of wrapping behavior.
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Chapter 1.
Motivation: Serpentine Pavilion by Toyo Ito & Cecil Balmond
Chapter 1. Motivation: Serpentine Pavilion by Toyo Ito & Cecil Balmond

A motivation for this thesis came from the Serpentine pavilion designed by Toyo Ito together with artist and structural engineer Cecil Balmond and engineering firm Arup. The pavilion was finished in 2002 and was exhibited as the annual Serpentine pavilion in Serpentine Gallery in the Kensington Gardens, City of Westminster, London, United Kingdom.

The pavilion is about one story high with an area of roughly 310 m² and it has a distinctive pattern that covers the whole design. [Toyo Ito & Associates 2002] The pattern seems like a complex mess of randomly oriented steel frames that flow through the simple rectangular shape of the pavilion. The beams form triangles and other polygonal forms that are checkered with glass and aluminium panels to create an interesting contrast between transparency and opaqueness as well as lightness and weight. It is almost as though these solid polygonal forms are balancing by only touching the tips of one another. The beauty of the pavilion arrives from its honesty. There is no hidden structure behind it, everything you can see is pure structure much like the web of a spider.

The seemingly random and complex pattern of the pavilion forms from a simple algorithm developed by Balmond. Balmond has been working with many famous architects including Rem Koolhaas, Álvaro Siza, Daniel Libeskind and Frank Gehry and using complex forms and geometric algorithms for generating form are an essential part of his repertoire. [Becker, L 2009] The logic behind the pattern is quite delicate and derives from concentric rotating and diminishing squares. The algorithm is visualized on a video on Balmond studios Vimeo page. [Balmond Studio 2014]

The base pattern visualized in figure 1 forms as follows:

1. Create the initial square
2. Create a line from one third of the way of a square side to one half of the way of the adjacent side. Repeat for every side.
3. Extend or cut the lines to create the next square with the corners now overlapping the previous one.
4. Repeat steps 2 and 3 for five total cycles and two more cycles but from half of the way to two thirds of the way.
5. Prepare the shape of the pavilion by transforming the original square.
6. Extend and trim all lines to the pavilion’s shape.

From this algorithm pattern final adjustments are made to create the whole pavilion in three dimensions. First the sides are turned down and some of the lines extended to meet the ground, the lines are then extruded into beams and connected by rectangular plates in the corners. The beams are categorized as primary load bearing, secondary bracing and tertiary as the binding motif. [Balmond Studio 2014] In the end the checker pattern is applied for the appropriate window and panel constructions.

Fig. 1 The formation of the Serpentine pavilion pattern
What makes the pavilion stand out is its holistic structure that can visibly be examined. The structural pattern solves all functional requirements. First of all, the rigid steel frame structure ensures the physical stability. It is a mono-structure which does not need any hidden, or visible, secondary structure to keep the pavilion standing. The structure is homogeneous in the sense that it covers the walls of the pavilion as well as the roof. This confirms that the same structural principle could be used in more wild forms where it is not so certain what is labeled as the wall or roof or floor for that matter. Secondly the structural pattern creates the various openings of the pavilion. This eliminates the necessity for a secondary logic that would place the windows in the facade. This makes the openings naturally fuse with the pavilion and become something thrilling. The benefits of the pavilion lie in the translucency it exhibits bringing in light and emphasizing on the overall lightweight of the structure. This is a fresh take on how even larger buildings today could certainly be designed. The structural pattern could be used in different scales of buildings by just scaling it appropriately.

There are many advantages for the mono-material nature of the pavilion. Although the structure is moderately complex, with modern technologies of mass customization it can quite easily be produced. Hence the structure becomes quite simple because it consists of only one layer. The structure can henceforth be developed with one manufacturer and material provider entirely that have the whole picture intact in their plans. This can minimize human error by keeping the parties involved in a minimum. The holistic structure is also fairly easy to use in physical simulations to for example test the structural stability and find the optimal thickness for the slender beams. Once manufactured the structure can be constructed quite fast as well as deconstructed and moved to another place. This offers valuable flexibility and helps with the maintenance and therefore sustainability. "The design went straight from sketch to computer and then to site. Not through traditional architectural drawings. And only two men put it up," Baillie has stated.

Fig. 2 Historically, a very similar algorithm has been used by architect Guarino Guarini in the design of the cupola of the cathedral San Lorenzo in Turin, Italy

Fig. 3 Explosion drawing of the pattern
The Serpentine pavilion exhibits a new kind of flexible and open-minded thinking. This new kind of thinking has made even The Guardian to declare Balmond as "one of the most important forces in contemporary architecture" (Glancy, J 2007). The pavilion excels in breaking down the key design concept to the bare fundamentals and then reinventing or reconstructing the idea with a sensible system. The pavilion is eminently constructive in its nature and brings out the best aspect of structure in a rational and sensible way where structure and architecture merge as one. Breaking loose from the norms of today did not stop the pavilion ending up back as a box, but that can probably partly be the cause of time and monetary restrictions. Structures that architects have partly tried to hide for decades, being a central key to the architectural value and composition makes an absolutely honest and rational impression. Besides, the applications of an algorithmic approach can be traced as far back as to ancient Greece where architecture and art was based on different kinds or rules of relationships and proportions. The rules of the algorithmic pattern guide the design. This underlies the relationship designers can have with computers nowadays. As Balmond comments about working with computers: "it can turn sketches into complicated patterns and designs. But algorithms can continue, so where you stop is an aesthetic judgement." (Raje, A P 2017)

This project is one of the motivations for creating a strip-based script that utilizes wrapping behaviour. The idea is to expand on the key concept used in the Serpentine pavilion; the use of an algorithm as a guiding force of design. The Serpentine pavilion uses a somewhat minimalistic approach and the algorithm used to produce the pattern is utilized on a flat two-dimensional plane, before being transferred on to the cubical shape. Thus, the purpose is to elevate the wrapping algorithm from merely producing a pattern into producing behaviour. The interest is to test different types of wrapping behaviour that work immediately on the underlying geometry. Working with a multitude of parameters as well as three-dimensional geometries, will make the algorithm a valuable tool that can lead to new discoveries. An algorithmic or parametric approach is excellent for swift experimenting, new ideas might emerge in the shift of a few values. The goal of this thesis is using an algorithm to explore wrapping behaviour in order to create mono-structural entities. The next chapter will be deciphering the logic behind the algorithm that will produce the wrapping behaviour.
Chapter 2.
Wrapping logic
Chapter 2. Wrapping logic

This chapter is unwrapping the logic behind an algorithm simulating wrapping behaviour that drew its inspiration from the Serpentine pavilion. The purpose of this chapter is to explain how the wrapping is achieved and how it can be modified with different parameters. The wrapping algorithm will be the groundwork for the rest of the thesis, which will first indulge in experimenting on what kind of features can be produced and later produce speculative design proposals.

The algorithm produced is finding the straightest geodesic on a discrete surface. This means the script is a pathfinding algorithm that can be thought of as an ant walking through a surface. A geodesic is a straight curve on a surface, which means a line on a plane but a circle on a sphere. Straightest geodesic means that locally, meaning at every point where the ant must choose the next point, it will always choose the straightest path starting from the initial angle or direction. In other words, the ant cannot turn and once starts to move it will maintain the chosen path going straight on the surface. Globally on the surface however, the path is not always perceived straight, as it might be spiraling along the surface, but nevertheless it is still the straightest geodesic. Discrete surface in this context translates to polyhedral mesh surface, which means that the script is working with mesh polysurfaces consisting mainly of triangles or quadrilaterals. This means the surface has a level of approximation with the resolution of the mesh being a factor to take into consideration.

The next paragraphs will provide a detailed description of the script for replicating wrapping behaviour, produced for this thesis. The script is divided into two main parts, the first being the pathfinding and data gathering through the underlying initial geometry provided as a mesh. The second part is the change from the found path into a strip-like form and a tube-like form.

The inputs for the first main part of the script are a mesh surface, starting point(s), starting angle(s) and maximum limit for iterations, where the mesh is the initial geometry, the points mark the pathfinding start location and the angles give the initial directions of the paths. For every point and angle introduced to the script, the script works as follows: Firstly the script finds the mesh edge closest to the point, marks a point on the edge as the starting point, rotates the edge with the corresponding angle to create the direction vector and lastly marks down the current mesh face. With the knowledge of the current mesh face, a corresponding face normal can be gathered for later use, as well as the adjacent mesh faces to check the next point from. For every iteration the point then moves to the next adequate adjacent mesh face, based on the direction of the vector. Some mathematics is introduced, as the vector needs to be rotated as it moves from one face to another, in case the faces are not coplanar. In the end the script will stop once a naked mesh edge is reached, which means, once the rim of the mesh geometry is reached. If the geometry is solid, the script only stops once the iteration limit is reached. As the script has moved along for every iteration it has collected a point, a direction vector which is the tangent vector and a normal vector from the mesh face. Further with a vector cross product of the two known vectors the binormal vector is produced. This concludes the first part of the script and the list of points can then be turned into a path curve and in the second main part of the script a surface and a tube, with the help of the three vectors.

Fig. 7 The wrapping algorithm explained step by step on a simple mesh polysurface
The purpose of the second main part of the script is to transform the found paths of points into strips. The essence is that by extruding a path of points along the direction of one of the corresponding normal or binormal vectors a strip-like surface is produced and further by extruding these strips with the other vector a tube-like form is produced. Now with these essentials a multitude of different possibilities open up. First of all, changing between the normal and binormal vector the strip can fluctuate between going along the surface versus pointing perpendicularly out from it. An interpolation between the two vectors can also be used for creating turning and rotation. Secondly the magnitude of these vectors can be played around with, thus creating different widths and sizes as well as oscillating designs. As the first main part of the script is kept fairly straightforward with its minimal inputs, the second part is kept more open and wild for its endless configurations. Instead of explaining all the realized options for the second part the next chapter of this thesis will visualize some of the possibilities in the forms of experiments. Nevertheless, to understand the strip creation, the next paragraphs will highlight some of the underlying challenges.

The change from curve into surface has its difficulties. Depending on the input geometry, different approaches may be more suitable than others. For example, on a sphere where globally the path is constantly curving should the resulting strip also stick to the surface of the sphere or only touch it in the centerline of the strip's surface. Comparing this to a prism where the surface and resulting strip is completely flat until the path reaches a corner where the direction changes drastically, which easily leads to imperfections in the corners and the strip not sticking to the prism. The problem is based on preference of how loosely versus how tightly the surface should follow the shape. Figure 8 is illustrating this struggle by showing the different scenarios: The tight fit is more exact until a certain threshold is met and after difficult artifacts emerge. A choice between loose versus tight fit is highlighting one of the many design choices in the script, and the approach may be switched case by case by the designer. All these big or small road bumps in a script are evidence of how creating an all-inclusive general code, managing any surface as intended, is a difficult task. It is best to accept that there is no one button solution. As an architect pursuing a perfect design tool might not be wise, for one because of the large time investment and secondly since some artifacts caused by script malfunction might lead to new spontaneous discoveries and ideas. Once the experimentation phase is over and the chosen approaches are picked, the tool can be perfected for those specific cases. Furthermore, at the end stage of a real to be built project, a collaboration with experts in other fields such as engineers, might lead to them having a go at the script.

Fig. 8 Illustrating the different approaches with their flaws and compromises: A more loose fit leads to some uncontrolled curving in the strips. The tight fit is more exact, yet undesirable folding appears after a certain threshold.
With an established logic of the inner workings of the wrapping behaviour algorithm, the next chapter will move to the experimentation part of the thesis. The experimentation part is organized from subtle changes to more wild concepts. The intention is to distinguish the essential properties of wrapping and to gain control of the outcome via the variables in the built algorithm. Furthermore, the hope is to discover new types of behaviours, ideas and designs that may inspire new architectural thought. The findings are evaluated in an architecturally meaningful way, to reason how the ideas could be incorporated into design.

A simple cubical form (also known as the parallelepiped) was chosen as the starting geometry for the experiments, to minimize some of the effect produced by the geometry itself. A round form like the cylinder, with constant small changes of angle, would have had an even smaller effect, but would have been less informative. The form has abrupt 90°-degree corners which will be great for testing the problems occurring with sharp turns, as figure 8 already showed. Any possible artifacts caused by bugs will be used as extra inspiration or fixed in the end.

All the experiments will not be practical in an architectural context, which makes a key part of the experiment to determine the right scale in which the experiments find architectural value. A critical evaluation is necessary to conclude what parts of the experiments’ parameter range are useful in different kinds of architectural scenarios. For example, some experiments might only seem useful in the context of a facade and some in one scope of parameters as the structure of a pavilion, as well as in another scope, as the concept of a high-rise. It is worth noting that at this point there is no built-in optimization (other than the human eye tweaking the parameters). Optimization is commonly connected with parametric design and is the introduction of a fitness value that the computer will strive towards by trying out different combinations of parameters. A fitness value could be for example the combined value of maximal openings versus maximal structural stability. However, for these experiments optimization is not meaningful, and the possible optimization could follow after the initial concept is chosen.
Chapter 3.
Experimentation phase
Chapter 3. Experimentation phase

Part 1: Strip parameters

Experiment #1 - Density and angle

In the first experiment the parameters are density and starting angle. Horizontally the number of strips is 2, 5, 10, 15 and 25 and vertically the parameters for the starting angles are 5, 20, 45, 60 and 90 degrees.

The increase of starting angle leads from a horizontal layout into a vertical one, which can be used mostly in change of cladding direction in facade use. The change in density is from singular units to more cohesive pieces. The singular units can represent simple conceptual forms of buildings and the more holistic mesh types resemble facade prototypes. The specimens in the magenta and yellow regions are interesting in their value as simple concept ideas: showcasing either the circulation in a building or two towers having an entwining dance. Especially the specimens in the yellow region, in their bare conceptual form, share resemblance with OMA’s CCTV tower in Beijing. The specimen from the middle column and to the right could be used to create regular structures or facade patterns. Some of these facade-like mesh pattern results are like the diagrid visible on the CCTV tower facade.

To sum the parameters up: firstly, an increase in density changes between conceptual and individual units into uniform facade-like results. Secondly, the starting angle relates to the orientation and partitioning.

Fig. 11 CCTV tower by Rem Koolhaas and his office OMA.

The building shape resembles conceptually the specimen in the yellow region and also the facade pattern is comparable to some of the mesh looking specimen.

Fig. 12 Experiment #1
Horizontal parameter: density
Vertical parameter: angle
Experiment #2 - Interpolation between two angles

This second experiment studies linear interpolation between two angles resulting in a range of starting angles. Both parameter values are angles of 5, 20, 45, 60 and 90 degrees, but the horizontal parameter represents the first angle, while the vertical parameter represents the last angle. The 9 strips are given a starting angle with even steps from the first angle to the last. This leads to the diagonal line, highlighted with cyan, where each specimen’s strips share the same angle.

The left bottom half of the specimens have an interesting way for the strips to bundle up. Bundling up is visualized clearly with specimens in the yellow area, where all the strips start in even spacing but end up in close proximity. This phenomenon can be used as a particular logic for creating an aparting envelope for a building: The building would be less open in the bottom part and more open in the top, with the opening direction naturally rotating when moving upwards. The concept resembles the playfulness of Ribbon wedding chapel by Hiroshi Nakamura where two spiraling staircases meet and wrap around the building envelope as an architectural metaphor for the union of two souls. The two spirals leaning on each other, create a stable structure, that counter both horizontal and vertical vibrations. [Cosma, A 2015] The spiraling chapel is quite stunning visually as well as structurally. The top right half of the specimens are more arbitrarily scattered because the angles and rotation are changing in conflicting directions. This more erratic style could be used to make a facade pattern, where the seemingly random pattern would yet originate from a certain logic.

To sum the parameters up: With the interpolated starting angles increasing, the strips become increasingly vertical and as a result, bundle up in a coherent way. With the interpolated starting angles decreasing, a disorganized composition is produced. The starting angle can be controlled to guide the strips into desired directions causing points of bundling or designs with dispersed distributions of strips.

Fig. 13 Ribbon Chapel by Hiroshi Nakamura & NAP Co.

Fig. 14 Experiment #2
Horizontal parameter: first angle
Vertical parameter: last angle
Experiment #3 - Width and sine amplitude

The parameters of the third experiment are strip width and sine amplitude modifier for the strip width. The sine amplitude means the strength of the sine wave modifier affecting the width. The horizontal parameter’s width values are 15, 25, 50, 100 and 150 arbitrary units and the vertical parameter’s sine amplitude values are 0, 0.5, 1, 2.5 and 10.

Most of the outcomes of this experiment resemble experimental facades. Like in the first experiment, from left to right the specimens change from singular strip elements into uniform assemblies. Especially in the two last columns, in the cyan region, the specimens are perceived as a unit instead of singular strips. The upper right corner specimen, highlighted with yellow, is fascinating with the overlapping taking place. It could be a system to interlock structural tectonic plates in a material system, excellent concept for producing a pavilion for example. An example of this is the ICD/ITKE Research Pavilion 2010 in figure 16. The pavilion’s plywood strips are in constant tension, trying to straighten up, keeping the structure in a stable bending active state. The one specimens below the top right corner could also be wedged into a bending active state by using the overhangs without the need of extra cuts. The overlapping foldings, of the top right specimen, could be considered as openings in a high rise with clear direction of sight. The folds remind of turbine blades that could harness the power of wind for a building’s air circulation. An interaction with wind could provide a cooling effect for a building during summer heat. The foldings remind of the Bjarke Ingels project for Shenzhen Energy headquarters in China. BIG’s intentions were both reducing solar loads and glare as well as directing views. In the ground level the folding functions as an inviting main entrance. [BIG 2018]

To sum the parameters up: Changing the width of the strips alter their intrinsic nature turning groups of strips into units. Wide strips can be used as building elements no longer identified as strips. The sine function can be used for special designs of interlocking and wild facades.
Experiment #4 - Depth and angle

The fourth experiment investigates the parameters of depth and starting angle. Depth in this case is the width of the strips but oriented normal or perpendicular to the geometry. Horizontally the width parameter values are 15, 25, 50, 100 and 150 arbitrary units and vertically the starting angles are 5, 20, 45, 60 and 90 degrees. The experiment focuses on the depth parameter as the angle parameter has already been covered in previous experiments.

Changing the orientation of the strips perpendicular to the surface creates a more three-dimensional understanding of how this code could be used. It breaks free from sticking to the initial geometry’s surface and expands our interpretations, breaking free from concepts of facades to structural building concepts and circulations. When the starting angle is low, the strips insinuate sloped building floor slabs slowly rotating for vertical connection. Such a delicately sloped floor slab circling upwards could be used as a building concept, with some obvious complexities to be resolved. An inner void forms naturally inside the rotating shapes acting as a courtyard and light well. When going down the table of specimens the expression changes from rotational movement inside buildings into structural bending pillars holding buildings together. Four specimens in the yellow region in the bottom right corner represent vertical structures creating rotating spatial partitions, framing views and restricting lines of sight into specific directions. These elements can make space feel less repetitive by surprising the viewer with different views from each gap. In addition, the monolithic structures could have some openings in themselves. The idea of the bottom right corner partitioning shares resemblance to Myymälä church by architect Juha Leiviska, where vertical slabs partition the space in interesting ways.

To sum the parameters up: The depth parameter rethinks wrapping three-dimensionally and not only as something sticking to a surface. The new orientation to the surface insinuates new kinds of circulations and partitionings in different angles.

[Figs 18-20]
Experiment #5 - Folding and width with varying orientation

The fifth and last parameter experiment explores folding in combination with width, alongside with the strips having varying orientation. The randomized strip orientation, clearly visible in the yellow region, is implemented to align some strips perpendicular to the geometry, nevertheless with all the specimens sharing the same strip orientations. Horizontally the width and depth parameter values are 5, 10, 25, 50 and 100 arbitrary units and vertically the number of folds is 0, 1, 3, 10 and 25.

The folding results in engaging designs that expand more on the spatial qualities the strips can have. Insets and extrusions created from the folding change the spatial quality inside the shape and form smaller more or less confined spaces. The insets create sheltered balcony-like spaces and make all specimens in the two last columns look like apartment buildings. The balconies resemble the design on the figure 21, with the apartment fronts facing in different directions affected by the randomized orientations. The two last designs with maximum folds resemble a honeycomb nest or a capsule hotel from a sci-fi movie. The narrower strips yet again give more of a facade or fence-like result. The slim and folding strips create captivating patterns that change in accordance to the frequencies of folding, nevertheless they are not very useful in an architectural context except in the detailing of railings or fences.

To sum the parameters up: The folds are interesting in their way of modifying the spatial qualities of the design and together with the varying orientations interesting subspaces appear. Yet the folding feels more like a tool to create different concept ideas to be produced unrelated to wrapping. Moreover, with the randomization of orientations skimming through innumerable concept ideas can be made easy.

Fig. 21 Housing in Barracas, Argentina by MSGSSS

Fig. 22 Experiment #5
Randomly-oriented strips & Horizontal parameter: width
Vertical parameter: amount of foldings
Part 2: Different geometry

Apart from the strip performance, the initial geometry is also an essential factor which leads to dramatically different geometric results. Beyond just giving the shape of the final design the initial geometry can be considered a key parameter with major influence on the resulting strip paths of the wrapping. Just like the previously introduced parameters, the initial geometry can be modified to produce diverse outcomes. In this second part of studies the strip parameters are kept to a simple minimum to focus on the initial geometry to determine how the geometry influences the outcome.

Experiment #1 - Cylinder

Compared to the previous rectangular shape, introducing a rounder and smoother geometry results in a more even wrapping result. With no sharp corners the geometry is easy to handle and no unintended nor unpredictable artifacts appear. As explained in chapter two, this is because the changes between the geometry’s mesh faces are more subtle, leading to the changes in the strips being more subtle opposed to more radical. In short, the closer to coplanar all the adjacent faces are to each other, the fewer complications there are. Topologically the cylinder is a plane that is bent into the shape, so the wrapping will behave in the same way as on a flat piece of paper, there are no unexpected results. The geometry is easy to handle, and the resulting strips behave in accordance to the parameters. Architecturally this sort of initial geometry can be used in an approach where there is a need for a genuinely uniform result. The same applies for any other shape that is topologically the same, so any straight extrusion or a shape you can make from a paper just by having bends in one direction.

Fig. 23 Left: Part of the cylinder unrolled and flattened. Right: A straight extrusion with an irregular base is still topologically the same as the cylinder.

Fig. 24 Geometry Experiment #1 Cylinder
Experiment #2 - Cone

Stepping forward from the cylinder, this experiment with a cone is already showing some results that are harder to predict. A cone, much like the cylinder, is a developable surface, meaning a surface that can be flattened without distortion as in stretching or tearing. Vice versa a developable surface can be created, without said distortion, from a flat but not necessarily rectangular piece of paper through bending, folding and rolling. This means that topologically the cone and cylinder are the same and both can be cut from a piece of paper and then bent into shape. Yet the cone is behaving differently because of it tapering. Figure 26 visualizes how a single straight path on an unrolled (or flattened) cone's surface appears straight, but in fact changes into a curved path on the actual three-dimensional cone. This example is also the mathematical shortest path around a cone starting from the base. So, the tapering or bending already affects the outcome and without a large enough starting angle the strips might not get very high up on the cone.

Fig. 25 Geometry Experiment #2
Cone

Fig. 26 The topology of a cone.
From left to bottom right: the unrolled surface, elevation and top view.
Visualized how a straight path through the surface topology becomes a curved form in 3D.
Experiment #3 - Hyperboloid

Unlike the cylinder and cone, the hyperboloid is an intrinsically curved, doubly curved, surface and therefore a non-developable surface. Although the doubly curved shape cannot be replicated from a sheet of paper, it is still symmetrical, which makes the end result easier to manage. Designing the initial geometry with some amount of symmetry might be a good idea for reaching more predictable results. The hyperboloid acts similarly to the cone and results are as predictable as with the cone. In the same way if the initial angle is left too small the strips starting from the base will not make it to the upper part of the shape. Below is the same experiment but with a much more refined smoother mesh, as you can see some of the irregularity disappears as the mesh is more precise, and its curvature more subtle. The resolution of the initial mesh will determine how exact the outcome will be, with a trade-off with computational performance of course.
A deeper understanding of how the initial geometry affects the outcome of the wrapping algorithm can be achieved by comparing differently deformed cylinders. In figure 29 a comparison has been conducted of a positively curved cylinder where the surface topology expands, a normal straight cylinder and a negatively curved cylinder where the topology contracts. Horizontally the starting angle of the strip is changing 20°, 45° to 80° degrees.

In the yellow section the strips are unable to spread up through the whole geometry as the angle is too low. It is clear to see that when the geometry contracts the strips get pulled together and bundle up. On the contrary the expansion pushes and separates the strips further. When examining the last column highlighted in blue, it is clear to see how the strips disperse versus contract synchronized with the expansion. In the positive cylinder the strips are more straight compared to the straight cylinder and furthermore on the negative they are even more inclined.

In conclusion the positive curvature works inversely as a repelling force and the negative curvature acts like an attractive force. In combination these concepts can be used when designing to create sections of attraction and repulsion. For more sparse sections, positive curvature can be used and conversely for more dense sections, negative curvature can be used. This understanding of the curvature is a key concept that can be used to control the density of the strip wrapping and thus the final design pattern. Controlling the wrapping pattern translates to controlling different design intentions such as the overall structural framework and openings for different views and passages. Designing with the wrapping script through modifying the initial geometry can be an engaging and interactive process, where the initial spatial configuration changes concurrently. This could be a fresh outlook on designing.
Gaussian curvature

To truly understand the strip's behavior in different curvatures a deeper examination is needed. The effect the initial geometry has on the strips can be measured with Gaussian curvature \( K = k_1 k_2 \). Gaussian curvature is an intrinsic measure of curvature embedded in any surface. Gaussian curvature \( K \) can be measured at any point on a surface and it is the product of the principal curvatures \( k_1 \) and \( k_2 \), which translate as the maximum and minimum bending at said point. The concept is visualized in figure 30: Firstly, any point on a surface must be chosen, secondly from that point there is a normal vector perpendicular to the surface and lastly perpendicular to the normal vector on the point lies a tangent plane. The first principal curvature is found from the plane's tangent direction and the second one is found orthogonally to the tangent. The bending value changes from negative to positive depending on which side of the plane it is bending to and is zero if there is no bending. If both principal curvatures are positive or negative the Gaussian curvature is positive \( K > 0 \), and the surface is convex. If at least one of the curvatures is zero \( K = 0 \), the surface is flat in at least one direction and developable, for example planes, cylinders and cones. And lastly if the other curvature is positive and the other is negative then a negative Gaussian curvature \( K < 0 \) is inherent and the surface is saddle shaped. [Weisstein, Eric W 2020] [Rhinoceros 2015]
Experiment #5 - Irregular shape

The influence of an irregular form like this deformed cylinder is undeniable. The outcome pattern of strips of the wrapping is impossible to predict, so in an irregular shape like this an unquestionably irregular erratic pattern will appear. To find regularity you would need to adjust each strip and its parameters separately, but it is safe to say that with the wrapping method a regular outcome from an irregular initial geometry is fairly impossible. An irregular geometry can be used if a randomized pattern is the design intent, otherwise a more regular initial geometry is preferred. With geometry like this a back and forth design technique is best, where one continues to modify the initial geometry based on the result of the wrapping. With the concepts of attraction and repulsion attached to the Gaussian curvature, one can modify the initial geometry to disrupt and guide the wrapping strips into desired paths. Of course, this style of design will modify the spatial qualities of the geometry as well, so it might not be desired always. Another way to approach an irregular shape is to develop further algorithms to sort the design out. For example, one additional algorithm could take care of merging the strips that start bundling up, to clean the overall look of the design. Another additional algorithm could simulate flocking behaviour, steering the strips as a coherent whole with the use of separation, alignment and cohesion.
Part 3: Strip connections

The connections between strips vary significantly especially in the more complex designs. Alternating surface curvature, rotation as well as the fact of how loosely or tightly the strips stay on the base geometry, all lead to different connections. Therefore, the connections between strips need to be designed case by case. The design of connections starts from the wrapping. If a certain type of connection is preferred, the wrapping parameters might need to be constrained. For example, if the strips should always meet in a planar sense at the point of connection, then there cannot be rotation unless the rotation undulates so that the strips always manage to be flat at connections. To make some of the connections work, an intricate design algorithm could be produced to adjust the strips to align perfectly at the points of interest. Depending on the connection case, an algorithm like this might need quite a bit of development, thus it would be more for specific construction-oriented joint design than experimental studies.

However, the most common and possible connections between strip elements could be discussed and classified. The possible connections can be visualized in a combination of mainly two factors that can help categorizing the various connections, these categories are represented in Figure 34. The first factor, shown horizontally in the figure, is the angle between strips as they can meet in different angles mainly due to the rotation parameter or the curvature. The factor is divided into three main cases, two of them being the boundary cases of flat or planar joint and perpendicular joint, and the third being some other angle between these two. The second factor, shown vertically in the figure, is basically the surface of contact: Do the strips fully intersect, only partly cut each other or either only have one single point of contact or none. Different connections can be designed to manage the different connections but in general the boundary cases like two planar strips meeting can be the easiest to manage.

The materiality of the strips is imperative to be considered when designing the connections in more detail. For example, some connections are naturally much more manageable when the structure is plywood whereas they might be near impossible with concrete. All these factors should be considered from the beginning of the design to keep the digital design process rational.

Fig. 34 An attempt to visualize the variety of connection types between strips that might appear depending on the used geometry and parameters

Fig. 35 Some more detailed connection examples
Fig. 36 Connection examples implemented in Grasshopper code
Chapter 4.
Speculative design proposals
Chapter 4.
Speculative design proposals

The idea behind creating multiple design proposals in this chapter, is to showcase the versatility of a digital design approach, even in the underlying simplicity of the wrapping tool. The wrapping design tool is capable of a multitude of approaches that can lead to endless amounts of designs. The following three design proposals/speculative design proposals/ will present three different ways of using the developed tool in various design processes. The designs vary typology, scale and materiality. The first proposal will be a lightweight wooden pavilion, the second one is a large-scale high-rise building that grows vertically, and finally the third proposal is a multifunctional spatial landscape structure. The designs are based specifically on the speculated sites, but some contexts are given in the final visualizations to build up the architectural narrative.

Design proposal #1 - Pavilion

My desire for observing the wrapping behavior and developing the simulative algorithm is inspired by studying the Serpentine pavilion. Thus, to close the circle, a new pavilion design had to be produced. After a series of design iterations, a tall vertically shaped pavilion which consists of strip-like louvers was selected. The pavilion comprises a simple and regular wrapping pattern that can be fabricated with individual strips of plywood or cross laminated timber, twisted and glued into the required shape. In addition to the louvers a supportive secondary structure is necessary in this case, therefore, a set of vertical beams made from the same material is added to finalize the pavilion’s rigid structure.

The most obvious usage of the script is at the surface level, populating an initial surface geometry with strips without the spatial qualities of the design drastically changing. In other words, it is like designing a naked geometry and then clothing it by wrapping it in strips. This reflects an infamous yet classic practice in architecture where the overall geometric shape is first designed and after that the materiality follows up. Of course, the wrapping and initial geometry are fine tuned in the end once a desired result is on the track. With this simple design process a million different kinds of pavilions can be positively designed only by inventing different initial geometries after which, architects need to explore and decide the desired wrapping pattern: regular organization, intertwined, concentrated and so forth.
Fig. 37 Four pavilion design iterations
The design started with creating a base geometry, which in this case was generated from a swept form. This swept form could be altered with a planar curve which serves as the cross-section profile and a vertical curve which controls the vertical outline of the shape. The sweep created by the two contrary curves can be seen in figure 38. Two edges of this shape were then populated evenly with starting points for the wrapping script so that the whole shape would be covered with strips. The shape could then be modified with the two curves to produce different wrapping outcomes. The intent was to keep the wrapping pattern neat and simple, so the initial shape would not be too complex to develop, even some small changes could bring irregularity and make the strips crossing paths. Finally, a moderately simple initial shape, that left the strips in a reasonably regular pattern, was chosen.

Thenceforth, to generate the logically wrapped strips along the initial geometry, the most appropriate values should be fed to the parameters. Firstly, the starting angle applied for all the strips is 65 degrees, and surprisingly it does not require any further tweaking at this stage as it worked well for all the strips. Secondly, during the design process, the strip generating values were tweaked by adding basic twisting to every strip. At the same time the value of looseness, or in other words how tightly in comparison to how loosely the wrapped strips are glued to the surface, was altered and reflected on the interesting final results. When the wrapping is set fairly loose in combination with the twisting, it creates a surprising bulging in the shape. This unexpected result, created by coincidence while trying out different values and inputs, is kept as the final design to showcase how minor tweaks in values might have an unexpected yet desirable impact on the end result.

After the desired design was found, some finishing touches followed up: on the one hand, the starting points and angles were fine tuned. On the other hand, the twisting was limited based on the length of the strips, so that the shortest strips would not have as much unnecessary twisting. Finally, the secondary vertical structure was generated with a separate Grasshopper script.

**Fig. 38** Left: The two curves used to design the swept shape
Right: Surface curvature of the resulting geometry

**Fig. 39** The initial mesh geometry
The eventual result of the speculative design is an engaging pavilion that opens up to the surroundings in a fluctuating manner. As the strips twist and spin around their path’s and the pavilion’s surface, the whole design opens up in a spiraling manner starting from the bottom corner and moving diagonally to the opposite corner in the top. This playful gesture makes the pavilion intriguing to go around and explore or spin around in the middle of it. The pavilion is a shelter and a hiding spot, with easier sight out than in. When looking from outside the pavilion the people inside the pavilion can barely be seen. As the sun shines through the louver-like strips it only passes through a certain region at once, making the light dance around in the pavilion as the sun sets. The overall feeling of the pavilion is lightweight and breathing from the thin veneer strips that let the wind flow through the structure. The pavilion is a mind palace for a moment of stressless peace and quietness, where one can take a deep breath and feel the small breeze pass by while watching the clouds float on top.
Design proposal #2 - High-rise building

Heading forward from the pavilion design, this speculative design proposal holds a much larger scale. The intention is to create a typology of high-rise building facade structure. As with the pavilion, the high-rise's structure will be created through the wrapping algorithm thus affecting the overall design. The generated structure will be acting as the facade partitioning giving the building a distinct look that would make it a renowned landmark.

Worth mentioning, this speculative design is to illustrate how the wrapping algorithm can be used throughout a design process, opposed to the method that is applied at the end of a design process like in the pavilion design. To compare, the pavilion design was more or less about designing a decent initial geometry, though in this case the focus is on what happens after that. Through the design process utilized in this example the shape and spatial configuration of the initial geometry concurrently transform into something new. In conclusion the wrapping script will be used in a more holistic design manner than only a cladding generator.

Another purpose of this design is to walk in the footsteps of the Serpentine pavilion and present a design with a monostructural system without secondary structures. A holistic mono structure is a desirable aspect in its minimalistic elegance and a key concept of design that hopefully captures the interest of its viewers. In this proposal the envelope structure is considered as a holistic primary structure ignoring the substructures for the building’s insides such as the slabs and flights. Ideally, running the wrapping generation alongside structural analysis provided by structural engineers, the wrapping can be optimized, and the structural resilience confirmed. This design is inspired by the findings in chapter 3, by the reference of CCTV headquarters designed by OMA located in Beijing, China. The diagrid structure visible on the CCTV tower facade works as the buildings load bearing primary structure carrying the weight of the unusual cantilevered shape of the building. The structure creates a tube-like hollow mesh shell, providing the structural stability even able to withstand the area’s frequent earthquakes. The visible pattern is an expression of the forces travelling through the structure, where the denser the pattern, the stronger the load and the greater the support. [Arup 2012]

Fig. 41 CCTV headquarters by OMA

Fig. 42 Horizontal and vertical section cuts of the high-rise design
The design process differs slightly from the pavilion proposal with a distinct role of the initial geometry. In this speculative design, the initial geometry started with exploring a generic high-rise typology that would combine typical qualities of high-rise designs. The initial geometry is created by key aerodynamic concepts that optimize the shape of the high-rise, as well as result in a compelling design that provides views into multiple directions from the building. The design is left symmetrical as there are no specific site restrictions such as wind or sun direction.

The initial high-rise geometry is created by starting with a triangular prism, which is then treated by rounding the cross-sectional corners and tapering and twisting the design as a whole. A curvature analysis (figure 44) shows that the curvature varies on the initial surface, where the bent corners of the surface area have positive curvature and the flat sections have slightly negative to close to zero curvature. The observed variation in curvature is adequate to create a fairly erratic initial wrapping as shown in figure 45. The next step in the design process was to rationalize the wrapping cover and to focus the structural strips to places of need, so in other words the essential plan was to try and even out the strip cover. Figure 44 displays the design process of modifying geometry and therefore the strip wrap cover, where the modification is done by pushing and pulling different points on the surface with varying pressure strengths and areas of effect. These modifications create adjustments in the surface curvature that forces the strips to change their paths according to the rules established by the understanding of Gaussian curvature. Furthermore, the modifications simultaneously alter the spatial qualities of the high-rise. As a finishing touch some of the strips merge together when they bundle up, removing unnecessary overlap in the structure. Alongside with a structural analysis, the ending result is a structurally sound yet provocative high-rise design.

**Fig. 43** Base form for the high-rise

**Fig. 44** Shape modification process used to achieve the design
The described design approach has a unique step where modifying the strip wrapping simultaneously alters the spatial qualities of the overall design. By guiding the flow of strips through the manipulation of the initial geometry, a desired wrapping pattern can be found and furthermore concurrently the design shape has transformed drastically. This feature of the designing process creates interesting and unexpected spatial variations. The space inside has been deformed leaving parts smaller and larger than when starting. These deformations can be considered by for example creating some balconies and loft spaces into the deformed parts. With such ideas the design quirk can be taken fully into advantage, subsequently leaving the space inside richer and less repetitive.

For the high-rise, the strips themselves work as a load bearing structural system made from steel. The shapes of the columns are optimized for the vertical loads, as they are thicker in the base of the building and taper off and become thinner as the strips move up. In other words, the strips are designed to be able to bear more loads where the forces accumulate in the foot of the design. As a whole, the network strips work as a reinforcing mesh wrapped all around the design.
Design proposal #3 - Spatial structure

The third and final speculative design proposal is a spatial landscape structure covering a large area such as a park in this case. The premise of designing for a large flat area requires a distinctive approach from the previous two. Therefore, this last design proposal is to reconsider the dimensions of the strips completely, hence instead of having multiple strips, there will only be one substantial strip. The underlying idea is to break free from the stagnant way of thinking in traditional structural categories, such as wall or roof, and instead, let the design be fluid, morphing through space. With the ideas, the eventual architectural result turns out to be a playful and multifunctional landscape installation acting as a pathway, an overpass, a canopy, a guide, a playground and a place to stay by.
The design steps are straightforward: Firstly, an initial landscape which the strip will flow through, is chosen. Secondly different obstacles are placed for the strip to counter and react on. These obstacles are key points that are spread out in the landscape and represent different points of interest in a park. This concept idea can effortlessly be deployed in almost any similar scale spatial structure design, in city and in landscape. Each key point will have a different purpose or function attached to it, such as a canopy, overpass or hangout place. The key points can easily be moved around to try different setups, as well as the obstacle sizes and shapes can be adjusted accordingly. The landscape and the key points are fused together to make the initial geometry for the wrapping. In essence the most substantial part of the design process is one hefty initial geometry generation. The design process works by feedback, moving back and forth from simulating the wrapping back to moving around the key points. Finally, when a desired organization and wrapping result is reached, further values can be tweaked in the wrapping script. The tweaked values used in this case are the looseness of strips while wrapping, the spinning value and strip width. A concurrent play with these values and the ‘obstacles’ comprises the main part of the design process. Once a desirable outcome is found, the values of spin and width of the strip can be set more precisely for different parts of the strip. The fine tuning in the end makes sure the outcome is exact as hoped for the different key points for example the canopies are made wide enough and the orientation is precisely fixed. The final touches for the design are modelled manually for exact results.

Fig. 46 The process used to modify the base geometry and design.
The spatial structure intertwines through the park providing different functions for the park. Varying parts of the structure have distinct natures, providing meeting places for social contact. First of all, the design gives clear direction to the park where people cross the park along the side or on top of the strip. Some crossings are opened up by lifting the strip up. These lifted spots naturally work as canopies, acting as cover when the sun is too hot or when it is raining. When the strip is horizontally close to the ground level it can be used as a sitting spot. A high vertical spot can be used for some ball games or as a bouldering wall. Kids and other parkour enthusiasts would be intrigued to climb the structure to reach up to the different viewpoints on top. For easier access to a special scenic viewpoint a ramp with a gentle slope is embodied. The part under the viewpoint is used as an open event space for the community used for social events and art shows.

The geometric outcome is most naturally produced from concrete, as it is one of the easiest materials to bend into the strips’ intriguing shape. Furthermore, concrete could potentially stay intact in the extreme natural conditions with minimal upkeep. The design is finalized with glass railings and a glass facade for the event space. This design is considerably scalable and could be implemented in much larger as well as smaller scales. Further designs could possibly be produced with a couple more strips to produce some wild entwining designs. One could even use different initial geometries for each strip for more control. The same design could be used in a more urban context, connecting different levels of walkways. Apart from providing a meeting place for urban life, the design would be perfect for urban activities such as skating.

Fig. 47 Design phases (down to up): Initial geometry, chosen wrapping path, adjustment of parameters, fine tuning of parameters and final design
Sector A
The strip forms a bridge for crossing a stream

Sector B
Point for easy access on top of the strip

Sector C
Accessible overpass and canopy

Sector D
Main structure acting as an event space and scenic viewpoint

Sector E
Canopy providing shelter

Sector F
Vertical section for interaction and spatial partitioning
Chapter 5.
Conclusions
Chapter 5. Conclusion

With an interest aroused by the Serpentine pavilion 2002, this thesis work began with an analysis about the pavilion in both aesthetic and structural aspects. From the analysis and admiration of the structural principles of the exceptional pavilion, the idea of an algorithmic design approach came forth. The goal of the thesis was to depict an archetypal digital design approach and unravel the digital design process. The idea of the wrapping behavior throughout linear elements, also inspired by the Serpentine pavilion, was harnessed as the driving idea for the overall digital design approach. A script simulating wrapping was henceforth developed. As a versatile digital tool, the wrapping simulation script was further extended along with some experimentation. The ambition of the experimentation was to stir up ideas and demonstrate the flexibility and endless possibilities of a digital design approach. The experiments were consequently analyzed and related back to well-known architectural examples, thus making the experiments more comprehensible and adaptable to architectural work. Further experimentations were concluded to grasp the inner logic of the developed wrapping tool and gain the understanding to efficiently use it in architectural design. With the gained knowledge the tool was put to action, and three speculative design proposals were demonstrated, each with varying properties and scales. The three designs elaborately showcase the versatility of the digital design approach.

The first chapter manages to introduce the concept of algorithmic design through the stunning Serpentine pavilion 2002. The pattern of the pavilion is captivating but the deeper understanding behind it would not unfold without knowing more about it. The first chapter gives a clear impression of what algorithmic design essentially is and what it can do. The rest of the thesis sets off to exhibit what else the algorithmic design approach can achieve. The merit of this thesis is making the digital design process comprehensible to architects by relating the digital observations and experimentations to real-life examples, as well as showing the expandability and diversity of the digital design approach, all without getting too complicated. The digital jargon is forced to a minimum and illuminating illustrations are presented for easier digestion. The final design proposals are intentionally left speculative, with the fine details of the showcase projects left open to interpretation. Hopefully this thesis can inspire and arouse new ideas of digital and algorithmic design and their possibilities.

Through a successful implementation of algorithmic design, this thesis manages to showcase an innovative way to produce architectural design. Algorithmic and parametric design have been present in nature as well as in patterns intrinsically emerging in nature. The application of algorithmic design in a digital context is ever growing in popularity. The possibilities and applications for algorithmic design are endless and furthermore the deployment is becoming increasingly available. In the future algorithmic design tools will be an essential part in the arsenal of successful architects. Digital design can challenge the traditional ways of architectural design thinking by creating new and innovative ways of designing.

One of the most challenging parts throughout the thesis was to keep everything rational, without being too stiff or boring. When coding a generic digital tool, it is relatively easy to experiment and adding additional rules to a ruleset that forms a code is fairly simple. On the other hand, it is also an easy way to waste precious time. There is a misconception with digital design that it is always involving randomizing; on the contrary everything happens with a reason. In a way the digital approach is as rational as possible, because the computer works exactly as it has been told. On the other hand, some of the most interesting things in the experimentations happened in the extremes, where the outcomes were unpredictable. Thankfully, this does not make the process unpredictable, but it actually is one of the uniqueness and strengths of digital design: With digital means such as parametric design, the designer could produce a bigger array of design options (or experiments) faster than with conventional methods. Therefore, if by conventional means the designer has only considered and visualized tens or hundreds of design concepts, with a digital design approach the designer could have considered and visualized thousands and more of design concepts.

An essential part of this thesis is undoubtedly learning while doing. Observing and setting up the wrapping rules, and thereupon coding the wrapping algorithm took a sizable amount of time and even a couple of iterations. Most of the problems in coding arise from not knowing the code syntax, not enough knowledge in mathematics or general coding procedures and simply not visualizing things clearly enough. Especially for architects, visual feedback is crucial. The problem in pure coding is that there are times while writing code when there are no visual reflections. When visualizing the different components causing a bug, it is easier to fully understand the reasons behind and distinguish if the problem is in the logic or if it is merely an accident or typo. For a simple example, vectors as digits are abstruse in contrast to drawn arrows on the screen, when drawn it is obvious if some vector arrows are pointing towards unwanted directions.

The application of algorithmic design in a digital context is ever growing in popularity. The possibilities and applications for algorithmic design are endless and furthermore the deployment is becoming increasingly available. In the future algorithmic design tools will be an essential part in the arsenal of successful architects. Digital design can challenge the traditional ways of architectural design thinking by creating new and innovative ways of designing.
The wrapping script has its challenges to work with because the resulting wrapping rarely matches designers’ initial expectations. Even a slight change in the surface could result in an irregularity, thus keeping control is effortful to achieve. For regular wrapping patterns and designs, a different approach might be better. Another way to get a more regular pattern would be to extend the script to run the wrapping of the multiple strips simultaneously. In this way the strips could take each other into account, while they are moving through the initial geometry. In this way the strips could be smart in a sense that they could try to keep an even distance to each other, resulting in a more evened out design.

This is describing something similar to flocking behaviour, where the strips move around as a coherent whole. With the strips aware of each other, concepts of separation, alignment and cohesion could be applied, thus making their wrapping pattern more regular as a whole. A natural part of the digital design process is to pursue ideas of modifying and developing the script, yet in this thesis the intent was to keep the wrapping logic untouched and it was left as it is. More creative insights on how to use the script could have been invented. It took some time to break free from the mindset of only using the script in the surface level of the initial geometries. Especially in the third speculative design proposal the use of the wrapping algorithm is more out of the box, as the full shape of the initial geometry used is disconnected from the shape of the resulting design.

Further research could focus on the connections between the strips. As some of the main points of the serpentine pavilion are the intricate connections and mono-materiality of the holistic design, this level of clarity is more difficult to achieve in more complicated designs where the connections are not always exact. The approach in this thesis was more general towards the design process as a whole, but when pursuing the excellence of connections, a specific design should be set as the goal, as there are many distinct paths to choose from. The way the strips entangle and interlock, can itself be used to make solid structures without secondary structures. On the high-rise case design this is the purpose, but it is not more strongly developed and tested. A natural follow up would be to add structural simulations and optimization of the structure. This could be implemented in the wrapping generation phase, to evaluate the quality of the overall wrapping cover. Another further development is to research making the strips developable and go more into the direction of fabrication. Fabricating the strips can be a somewhat simple process if it mostly just means unwrapping the design. But another interesting part would be to focus on the connections between the strips so the fabrication could involve for example interlocking these strips or creating a connector piece.
Figure reference

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