DISCRETISATION DESIGN STRATEGIES: DISCRETE DESIGN METHODOLOGICAL CLASSIFICATION

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ABSTRACT

The discretisation process is a digitally emerging effort that aims to rethink and possibly remodel the whole production cycle in the context of an architectural process. This is accomplished by advancing the concept of discretisation in both computational design and actual physical assembly components. In one sense, discretisation can be used to generate a two- or three-dimensional volume, or it can be used to divide an architectural volume or surface into sections that are more easily managed. Discretisation, when viewed from a different aspect, is also known as the science of architectural components. Discretisation is a form of modularity that assumes new architectural possibilities are emerging as a result of digitally driven design processes. These processes are characterised by dynamic, open-ended, unpredictable, adaptable, and consistent networked transformations of three-dimensional structures. Discretisation also confirms that these new architectural potential options are a result of digitally driven design processes.

In this study, we present a categorisation system for discretisation-based design approaches that is based on the technique. Before providing a category for discretisation methods, this work first analyses, evaluates, and constructs case studies for previously published methods from the body of earlier research. In the second step of the process, a broad theoretical framework that is constructed on the categorization analysis is utilised. Because of the specifications and functions, these methods can be synchronised with and combined with various other parametric design strategies, such as panelising, subdivision, or generative design. Within each category, we present an overview of, and conduct an investigation into, the possible associations that exist between our discretisation definitions and the additional parametric parameters. This study concludes by presenting a variety of multiple design possibilities for each category, as well as a logical design technique, and then summarising its findings. This paper does not focus on any specific programme or tool in particular.

Keywords: #Discretisation, #Parametric_Architecture, #Generative_Design, #Digital_Architecture, #Algorithmic_Design

1. INTRODUCTION

Advances in digital technologies and automated systems in the 21st century have caused industries to quickly update their production methods using digital technology; however, it has long been believed that production chain optimisation is what accelerates technical advancement and the creation of newer, more innovative devices (Retsin, 2019a). Immediately after the 2008 financial crisis, which Carpo referred to as the “first digital turn” (Carpo, 2017), digitality in architecture was linked to problematic neoliberal ideology (Retsin, 2019a). Discrete design techniques and algorithms have also been used more recently, during what Carpo refers to as the "Second Digital Turn," by architects working directly with computers (Carpo, 2019). Sometimes, the intention of design, art, and architecture is to create innovative, complicated, or aesthetically beautiful geometries that can be able to meet particular practical requirements (Klemmt, 2019). The use of digital planning techniques has enabled a level of creative freedom that was previously unachievable (Manahl, 2012).

The discretisation process is a digital emerging work that attempts to rethink and maybe remodel the entire production chain in an architectural process by pushing the idea of discretisation in both computational design and physical components of assembly (Retsin, 2019b). Although architectural decisions are occasionally made for aesthetic reasons, which has the obvious disadvantage of limiting the potential for performance enhancement (Wang et al., 2006), discretisation as a functional process can fulfil the requirements for both practical needed functions and aesthetic design (Zawidzki, 2017). In exchange for "scalability," "impact," and "agency," the discretisation is willing to re-evaluate building production while sacrificing a tiny portion of "resolution," "formal distinctiveness," and "excitement" (Retsin, 2019a). Discretisation is also willing to swap out delicate but scholarly material optimisation for huge volumes of inexpensive materials in order to increase accessibility and efficiency (Retsin, 2019a).

Overall, discretisation is the conversion of continuous equations, models, variables, and functions into their discrete equivalents. By breaking down the complicated geometry into manageable roles and relations, discretisation as a step-by-step design process could reduce the geometrical complexity (Jonas, 2014). In one sense, discretisation can be employed to divide an architectural volume or surface into smaller, constructible pieces (Manahl, 2012) or to form a 2D or 3D volume (Kaijima and Michalatos, 2007).

As Restin describes, discretisation can also be referred to as the science of architectural components (Retsin, 2016a). According to this viewpoint, discretisation can introduce new design characteristics. In discretisation, for example, the design process can begin with the module rather than the whole geometry. This feature provides the designer with sufficient flexibility and additional opportunities to explore far deeper into the relationships between building components as flexible, general, and even re-usable modules (Köhler and Hilberseimer, 2016). These two points of view allow for the categorization of discretisation methodologies into two distinct groups: top-down and bottom-up, which are distinguished by the direction in which the design process is carried out and the starting point (Zamani and Dounas, 2022). According to the concept of discretisation, which is a type of modularity, new architectural possibilities are developing as a result of digitally driven design processes that are characterised by dynamic, open-ended, unpredictable, versatile, yet consistent networked transformations of three-dimensional structures (Kolarevic 2000). When we approach at building blocks through the perspective of such specifications, we start to move the emphasis away from thinking of building elements as being unique to their purpose and toward an architecture made up of a defined collection of parts (Claypool, 2019).

2. METHODOLOGY

This paper uses inductive research method which involves drawing conclusions from observations and experiences, rather than starting with a preconceived hypothesis. This includes field studies, case studies, and literature review, where we gather data through develop theories and design principles. The information gathered through inductive research can then be applied to the new designs that are more linkable to the smart fabrication machineries. From this data, this study identifies common themes and patterns in the use of discrete design strategies, such as the specific geometric shapes or forms generated, the design algorithms they are applied to, or the design outcomes they produce, or even tools or specific software. The first part of this paper provides an overview of the development of discretisation methods and provides critical commentary on their relative strengths. These evaluations highlight and identify each case study's parametric logical and algorithmic requirements. The second phase involves categorising the techniques based on the logic of their designs and their conceptual and practical differences.

This study, moving toward a taxonomy for discretisation methods based on their numerous capabilities. This classification provides a full foundation towards a deep methodological understanding of existing discretising approaches in architectural design with the intention of generalising these methods for a wide variety of forms while at the same seeking for digital characteristics and requirements that could potentially be used to integrate digital design and fabrication. The gathered information may then be used to develop more progressive design principles and guidelines for using discrete geometry in architectural design, which can then be used in the development of new design strategies or even more innovative tools.

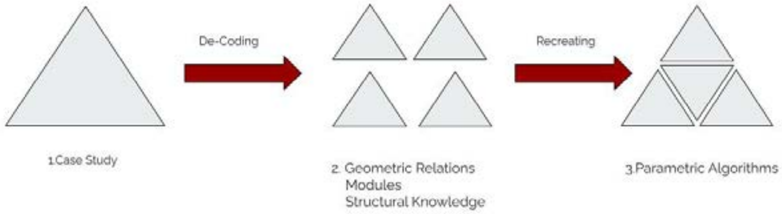

Figure 1 This study first explores a number of discretisation case studies from the literature and constructed structures, and then re-examines their parametric design procedures and arranges their algorithmic steps, credit by Erfan Zamani

3. STRATEGICAL FRAMEWORK

This paper establishes a theoretical framework for digital discretisation in architecture. While many discretisation approaches for architecture have been given at various scales, ranging from building modularity to urban planning, this work gathered digitalised ones to establish a theoretical foundation for digital discretisation. These approaches were classified based on the parametric logic that underpins them. The current work extensively investigated a number of discretisation approaches, whether through literature or prototype structures, in order to determine their parametric procedure. In the process of evaluating each strategy, the related ideas and approaches were also researched. Based on parametric procedural similarities and differences, digital discretisation approaches can be classified as follows. This work is a part of a broader study that aims to establish an integrated construction DfMA (Design for Manufacture and Assembly), from design through production.

3.1. Computational Growth

The computational growth through aggregating discrete parts in design, art, and architecture often strives to produce innovative, extremely complicated, or aesthetically stylish geometries, and even, generated geometries could be able to address particular functional necessities (Klemmt, 2016). The computational growth incorporates artificial intelligence into the design process through the use of exploratory search algorithms (Krish, 2011) and with its iterative progression towards a bigger accumulation of mass, allows for an equally repetitive evaluation of the geometry's current situation (Klemmt, 2019).

Many computer-based growth models, such as Cellular Automata (CA) and Diffusion Limited Aggregation (DLA), have been developed. To simulate growth processes, many part to whole-based mathematical logics have been applied. Although DLA was initially intended to operate in 2D grids, it is now frequently calculated in free form in 3D space (Witten and Sander 1981). There have been numerous attempts to employ them for architecture and urban planning (e.g., Al-Qattan, Yan and Galanter 2017). Also, Differential Growth in architectural design have been discovered comprehensively, in which individual cells can move in 3D space while they are typically structured as the vertices of polylines or of mesh surfaces (Klemmt, 2016). The resulted geometry can be used for digital arts or 3D-priting arts in different scales. Cellular Growth algorithms are utilised by Klemmt and Sugihara (2018), to build an installation out of tessellated sheet material. This research has been updated in (Klemmt, 2019) in which suggested algorithm is based on a 3D point cloud, with each module's centre being a point from the point cloud. modules are analysed and changed iteratively by shifting their positions, and if certain conditions are satisfied, a cell may even be divided (Klemmt, 2019).

Retsin (2016a, 2016b) makes additional arguments in support of serial repetition and assembly of discrete parts, based on volume and disintegration of the figure as opposed to surface and topology characteristic for parametric projects, highlighting the significance of part-to-whole interactions and the usage of elements that contain a certain type of design agency, where elements can respond to data such as stress, vector orientation, etc. Rossi and Tessmann (2017a,b,c & 2019) propose a spatial assembly method for discretised architectural formations. The parametric tool "WASP" underpins their growth-based 3D aggregation model. The final geometry's 3D contour defines a module's density boundary. This reversible approach integrates module shape complexity with geometry relationships and specifications. This method gives designers new manufacturing and assembly options and lets them manage or specify module attribution. Their new plugin WASP connects the discretised digital model to the real world. Tibbits creates an intelligent configuration framework concurrently (Tibbits, 2011). The boundary is aggregated by this self-assembling mechanism using intelligence blocks. Leder (2020) provides a method as coverage for non-standard concrete constructions with modules in the shape of a dodecahedron as another illustration of a modular aggregation configuration. This method can validate aggregation-based techniques and is quite adaptable in terms of overall shape design. The modules can be put together to create a closed form for casting concrete. Modules from this temporary building can be taken apart and reused. Dodecahedrons can be confined among numerous neighbours of the same shape due to their nature and the high number of sides, which provides more interface choices (Leder, 2020).

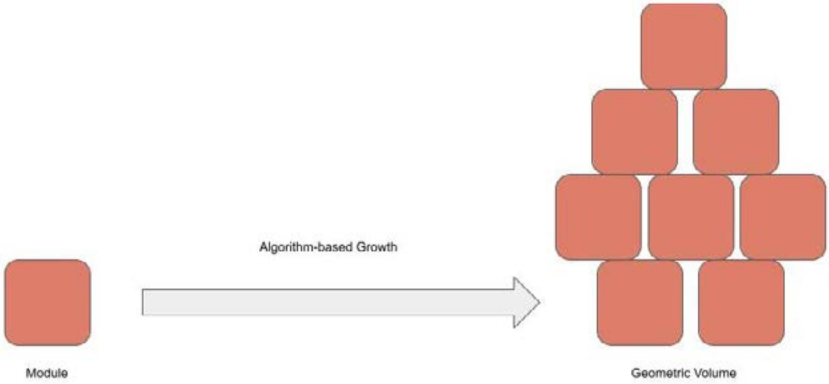

Figure 2 Computer-based growth, credit by Erfan Zamani

3.2. Subdivision Surfaces

The relationship between shape and production brings new challenges and requests for more complex underlying geometry (Pottmann; Helmut; Brell-Cokcan, 2007). Tessellation is the process of covering a surface with one or more geometrical objects without overlapping or gaps (Kizilörenli and Maden, 2021). By using modular shaping and planer surfaces beneath each shape, subdivision, as a parametrical tactic of tessellation, can be employed to approximate and discretise a geometry (Pottmann and Wallner, 2008). Pre-determined, repetitive defining and shaping of a discrete surface mesh defines subdivision surfaces (Liu et al., 2021). It also provides a parametric approach to modeling with developable and generative surfaces. Initially, this discretisation strategy, was targeted on discrete differential geometry, where R. Sauer (1970) demonstrated how discrete modules could be utilized to construct conjugate curve networks on surfaces. Theoretically, there is a strong connection between the limit surfaces of subdivision surfaces and conventional splines. The two phases in typical approaches are: dividing edges and adding vertices to make each input mesh element into multiple elements (one triangle becomes three, for example). Then, the locations of the mesh vertices are smoothed by averaging the positions of their neighbours using a weighting system that is only based on the local mesh connection.

According to (Hertzmann and Zorin, 2000), the fundamental principle of subdivision is to “define a smooth curve or surface as the limit of sequence of successive refinements.” The earliest study on irregular polygon meshes had done by (Doo and Sabin, 1978) in which subdivision generates quad meshes. Quad meshes were the first attempts to approximate the modular shape to a surface. Authors in (Alliez *et al.*, 2003) describe how to compute quad-dominant meshes from smoothed primary curvature lines. Even though these meshes’ faces aren’t perfectly planar, one should assume that they are at least roughly so. According to (Cohen-Steiner and Morvan, 2003), variational shape approximation seeks to position a certain number of planar faces—which are typically not quadrilaterals—in the best possible location. The paper (Pottmann; Helmut; Brell-Cokcan, 2007) uses the same logic for conical meshes.

It demonstrates how to refine a quad mesh so that the mesh can even become conical or have its faces become planar.

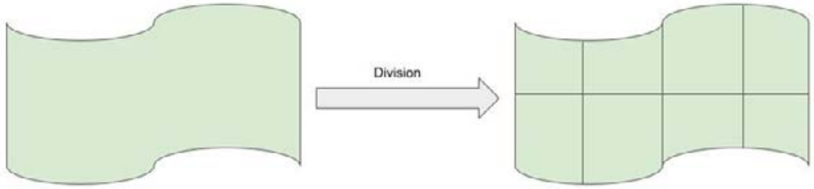

Figure 3 Subdivision logic, credit by Erfan Zamani

The study, (Liu *et al.*, 2020) proposed a non-linear neural subdivision system, based on the linear method of Loop (1987) for triangle meshes, which has attained a comparable level of popularity. A combinatorial update (split faces, adding points, and/or twisting edges (Kobbelt, 2000) and a vertex flattening (repositioning step) based on local average of surrounding vertex positions describe traditional linear subdivision algorithms. The availability, direct analysis, and continuity of the limit surface are thoroughly investigated from the standpoint of subdivision methods (Karciauskas and Peters 2018). A subdivision surface is often worked on by modellers in a controllable manner. The limit surface is typically visualised by most modelling tools, or at least a rough approximation of it, while the operator seeks to control the upper level (Liu *et al.*, 2020). Users can control the surface in addition to changing the vertices by including points or bent edges (Hoppe *et al.* 1994). Although noninterpolating techniques like Catmull-Clark or Loop seem to be the most common, interpolating techniques do exist and have similar smoothing guarantees (Dyn *et al.* 1990). However, fairness is more difficult to establish. In order to ensure smoothness, linear approaches are simpler to analyse and construct. As a result, the modeller or a predictable procedural function is charged with collecting details (Velho et al. 2002).

3.3. Cross Section

Polyhedral forms act as the foundation for the Moving Cross-Section Procedure approach (Kanel-Belov *et al.*, 2010). This systematic modular model consists of a network of planner square grids and polyhedron modules, where each square grid edge plays a key role in determining where the modules are placed. By specifying the side angle of the modules, this procedure can convert the plans into the modules (Pfeiffer *et al.*, 2020). Each square grid's pair the parallel sides defines the positions of the module's sides. This approach allows for the creation of polyhedron modules that are not predefined and work harmoniously with panner grids. Although the modules produced by cross-section are based on angle and pattern, they are still under parametric control. The dimensions and shape of the modules' sides can provide additional possibilities for interlocking joints (Pfeiffer *et al.*, 2020). Based on a planner network, the discretised sections can be topologically aggregated through cross-section.

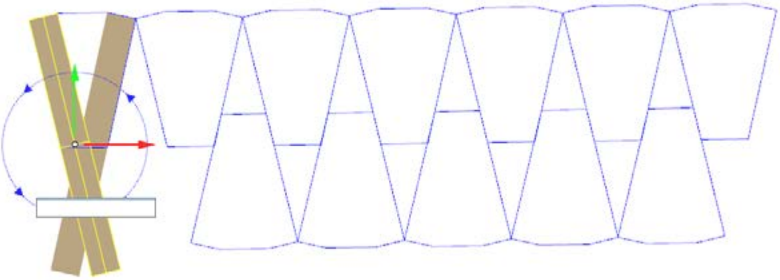

Figure 4 Cross-section, credit by Erfan Zamani

The Cross-Section approach creates a topological structure in which each module is surrounded by several neighbours, depending on the number of sides of the modules (Wang and Liu, 2009). X and Y motions should be avoided in the modules. Through the utilisation of computational design, analysis, and production techniques, the cross-section system can be re-defined inside a topological framework [e.g. (Tessmann, 2012)].

For instance, Bejarano and Hoffmann (2019) used a topological interlocking arrangement to expand Moving Cross-Section. Their configuration includes a repeatable assembly mechanism based on tasselling surfaces or mesh. The angular surfaces still contribute significantly, but Bejarano and Hoffmann add central point and height values that make the modular parametric control more flexible by analysing the structural behaviour of the modules. Rotation, motions, and slide to the front, rear, and sides are examples of these behaviours (Bejarano and Hoffmann, 2019). This method can be applied not just to regular curvature networks but also to develop geometrical shaping. For instance, Manahl (2012) presented a method for rapidly creating discrete meshes with planar faces that are specifically designed to approximate the intersection of tangent planes to the surface. The purpose of this geometric technique was to combine the processes of design rationalisation and form-finding. It was based on the intersection of tangent planes to the surface (Manahl, 2012).

4. CHARACTERISTICS FRAMEWORKS

This classification is based on the common procedural aspects of each technique. The current work attempts to encompass every relevant approach and to lay a solid theoretical foundation for discretisation.

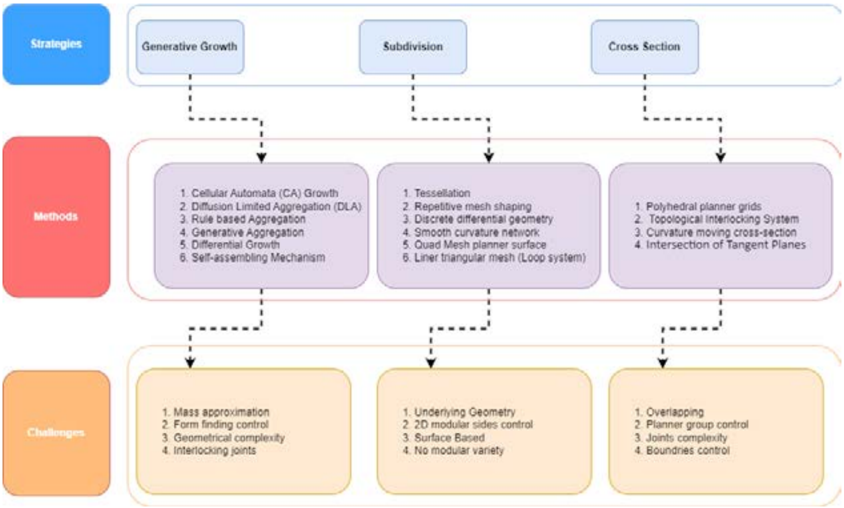

Figure 5 Discretisation strategical classification system, considering the methodological similarities and differences. credit by Erfan Zamani

4.1. Common Characteristics: Computational Growth

The emphasis in biology and medicine is on constructing models that precisely mirror real-life conditions, but the goal in computer science, particularly Artificial Life, is to design and comprehend processes that display life-like behaviours (Klemmt, 2019). A large number of modules are generated by algorithm-based growth. Depending on the method used, geometry approximation is still possible, but accurate geometry design is not. In addition, form recognition and 3D modelling are no longer different. Algorithms can influence the shape that is formed throughout the 3D modelling process. A growth simulation, with its iterative development towards a greater accumulation of mass, provides the opportunity for an equally iterative evaluation of the geometry's current state, which can then have an impact on the behaviours that direct the growth to develop towards a desired outcome, both globally and locally (Klemmt, 2019). Furthermore, this aggregation worked by combining the geometric representations and location data of a certain module, as well as by providing different algorithmic criteria for module data aggregation (Klavins *et al.*, 2004).

Figure 6 Growth-based discretisation is able to generate volumetric geometries. The generated shapes can have no boundaries (right), but setting the boundaries provides the designer better control over the aggregation process. credit by Erfan Zamani

4.2. Common Characteristics: Subdivision Surfaces

Subdivision Surfacing has a wide range of applications because subdivision combines discrete differential geometry, shape processing, and computational design (Pottmann; Helmut; Brell-Cokcan, 2007) to provide developable surfaces that can be projected onto the plane without distortion (Liu *et al.*, 2006). When combined with other parametric features, subdivision techniques can create volumetric geometry, which is extremely beneficial for free form design. Depending on the approach, sub-surfaces can be triangular, rectangular, or other shapes with more or isochronous slides. Certain approaches yield unique 3D modules because the sub-surfaces do not have the same shape and may or may not be regular.

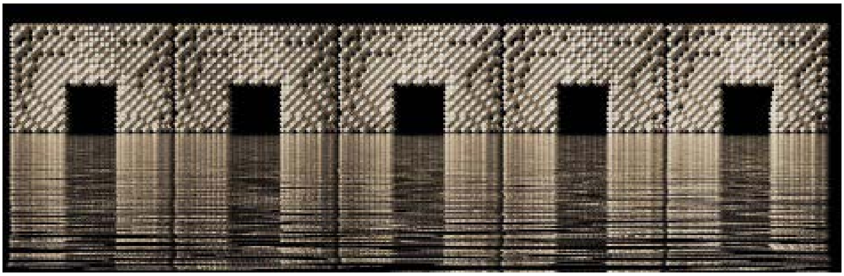

Figure 7 Subdivision technique by applying the voxel-shape modules to the surface. credit by Erfan Zamani

4.3. Common Characteristics: Cross Section

Cross Section develops a systematic modular structure that is organised and touches each neighbouring surface along a straight line by using planes. When subjected to appropriate boundary conditions, the assemblies are capable of withstanding higher bending loads and even tension without the use of an extra binder such as cement (Tessmann, 2012).

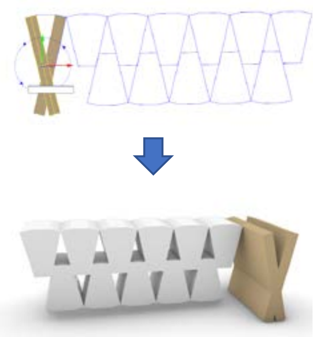

Figure 8 Cross section approaches can generate a repetitive network of modules, weather in one axis, two axis or even possibly in three axes, credit by Erfan Zamani

Moving Cross Section commonly known as the square grid with perpendicular planes on each edge. Picking an angle α, one of every two planes rotates around its particular edge by α, and the next one by -α. Thus, each square generates a tetrahedron, arranged so that it forms an interlocked grid. The square grid with orthogonal planes on each edge is commonly referred to "Moving Cross Section". One of every two planes spins about its specific edge by an angle α, and the following plane rotates by angle -α and as a result, each square becomes a tetrahedron, which is then placed into an interconnected grid (Weizmann *et al.*, 2015). However, this basic paving can be laid out in a variety of patterns, such as a hexagonal pattern that forms an interlocking grid of cubes or octahedrons (Pfeiffer *et al.*, 2020). But in methods like planner surface, even the grid network is not essential [e.g. (Manahl, 2012)] and sub-surfaces approximate on the main surface through a point or line.

Figure 9 Use of discretisation techniques for decoration design. credit by Erfan Zamani

5. FURTHER STUDY

The study that is being given is unique in that it deals with a classification for logical parametric discretisation. The research is important in that it establishes the necessity, limitations, and practical features of Discretisation and offers the toolset and a solid framework upon which production and assembly can be expanded. This study offers systematic categorization of Discretisation methods and emphasises parametric design technique as an effective tool for creative and intelligent creation. Different interlocking alternatives can be constructed for each suggested category of parametric logic. This possibility opens them fresh opportunities to present cutting-edge assembly techniques. A circular and dynamic process in which pre-programmed, computer-controlled machinery work alongside digital models and implementation simultaneously includes design and assembly. This research can be expanded to create structures that are particularly advantageous for robotic assembly. The assembly system can be validated by the proposed logical classification by looking at the joints and structural stability beneath the scale.

6. CONCLUSION

Discretised designs are made up of individual elements that can be modified, rearranged, or scaled independently of one another. This allows for greater flexibility in adapting the design to different site conditions or design requirements, such as changes in building code or zoning requirements, or accommodating topography. This can be especially useful in cases where the design needs to be adapted to fit the specific needs of a particular site or client. Discretisation allows for the use of computational algorithms to design and optimise architectural forms based on specific design criteria, such as structural performance or modularity. This allows for the exploration of a wide range of design options in a relatively short amount of time, which in perspective can greatly increase the efficiency of the construction process.

Automated fabrication processes, such as CNC milling, 3D printing, or robotic fabrication, can also greatly increase the efficiency of the production chain. These techniques can be used to fabricate discrete elements with high precision and accuracy and can be easily integrated with parametric design tools. This can greatly reduce the amount of time required to fabricate the final structure and can also reduce the cost of fabrication by minimising the need for manual labour. Additionally, this can lead to improved performance and durability of the final structure because the discrete elements can be fabricated to precise tolerances and assembled with greater accuracy.

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