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Enhancing Parametric Design Through Non-manifold Topology

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Abstract

This paper aims to build a theoretical foundation for parametric design thinking by exploring its cognitive roots, unfolding its basic tenets, expanding its definition through new concepts, and exemplifying its potential through a use-case scenario. The paper focuses on a specific type of topological parameter, called non-manifold topology as a novel approach to thinking about designing cellular spaces and voids. The approach is illustrated within the context of additive manufacturing of non-conformal cellular structures. The paper concludes that parametric design thinking that omits a definition of topological relationships risks brittleness and failure in later design stages while a consideration of topology can create enhanced and smarter solutions as it can modify parameters based on an accommodation of the design context.

Parametric design is both misunderstood and over-used. Many who hear or read the term associate it with complex and curved works of architecture. Others may even associate it with a style of architecture or work produced by an architectural office. While many have used the concepts of parametric design thinking to create a certain style of architecture, from a research point of view, parametric design thinking is separate from the outcome that we are witnessing in built works. One can build simple and subtle geometries that have complex parametric relationships among their parts or indeed build very complex solutions based on very simple parametric relationships. Furthermore, one can build works that appear to use parametric design methods, but do not. Given this state of confusion, the larger aim of this

paper is to establish a solid theoretical foundation for parametric design thinking and enhance our understanding of it by exploring its cognitive roots, unfolding its basic tenets, expanding its definition through new concepts, and exemplifying its potential through a use-case scenario. To achieve this aim, we offer our definition of parametric design as a rigorous and mostly systematic method that requires a fundamentally different approach to design thinking. The paper starts by providing a background on the cognitive roots of parametric design based on the work of the Swiss clinical psychologist Jean Piaget and proceeds to introduce a taxonomy of parametric design elements based on previous published work (Jabi, 2013). We then focus on one element of this hierarchical taxonomy: topology (the study of properties of entities that are not normally affected by changes due to transformations) for its potential to enhance and expand parametric design thinking. To explore the implications of integrating topology into parametric design thinking, we explore the concept of non-manifold topology (NMT) (Aish & Pratap, 2013; Jabi, 2015). While most current Building Information Modelling (BIM) approaches are successful in representing and parametrizing the physical components of the building's fabric through 3D solid boundary representations, the mathematical concept of NMT is proposed as a different approach to thinking about space/void. Solids within BIM systems strictly divide the world into the void of the exterior and the solid material of the interior of the solid itself. In contrast, NMT representations allow consistent internal division of complex volumes into cellular spaces using zero-thickness internal surfaces. In addition, NMT maintains topological consistency so that a user can query cellular spaces and surfaces regarding their topological data (e.g. adjacency information).

While computational methods are not essential to parametric design thinking, they are the most effective tools for exploring the complex relationships within a design solution space. Thus, the paper reports on a use-case scenario of a software system using NMT for the design and additive manufacturing of conformal cellular structures. The paper concludes with a reflection on the role of topology in influencing parametric design thinking, the limitations and advantages of the proposed approach and the future potential of additive manufacturing of conformal cellular structures using non-manifold topologies. One of the major findings in this paper is that the ability to consistently define topological structures and query the system for topological data enhances parametric investigations and creates more efficient solutions that take better consideration of the design context.

1. Background - Cognitive roots of parametric design

“Parametric design is about change” (Woodbury, Gün, Peters, & Sheikholeslami, 2010). This simple and fundamental idea is the most compelling and seductive attribute of parametric systems. The largely static system of design that involved drawing or building analogue representations can now be amplified, enhanced, and extended with fluid and interactive representations that change (almost) instantly as the designer operates a set of controls. As our hands and fingers move sliders, type new numbers, or press buttons, our eyes see the design morph and evolve. We begin to recognize schemas and patterns and our hands and fingers either proceed or retreat to morph the design configuration into the desired solution. The coupling of action and *reflection-in-action* (Schön, 1984) is a fundamental part of our cognitive system. Jean Piaget called this coupling *accommodation* and *assimilation* (Piaget, 1951). To illustrate these concepts simply, imagine a person (perhaps from some years ago before the digital age) searching for his favourite radio station on his car radio. As the needle moves and as the sounds coming from the radio change, his fingers, ears and eyes work in unison to operate the radio knob and achieve the desired goal of finding the radio station. As the external situation is fluidly changing, his mind and body are trying to *accommodate* this new situation. At a certain point, this person hears a faded, noisy and crackling sound of a favourite song from his teenage years. Although the sound is not a perfect match to what he remembers, he recognises the song and *assimilates* it into his internal experience and continues to fine-tune the location of the radio needle to improve the reception. Assimilation is what allows us to understand external situations in terms of internal schemas that we have constructed based on experience. Reverting to parametric design, we can see accommodation and assimilation in the continuous manipulation and fine tuning of parametric controls to achieve design configurations that we assimilate into internal schemas (e.g. of what constitutes an elegant design or a successful or optimal solution to a problem). New aspects of the configuration are accommodated and learnt from and the remainder is assimilated within a constellation of internalised abstracted patterns that we consider desirable.

The reader may look back at the previous passage and rightly criticise it as an incomplete definition of parametric design systems. After all, the above fits the definition of a general computer-aided design system (CAD) just as well. A three-dimensional object in CAD such as a prism would have parameters such as width, length, and height. The user can manipulate user interface elements, such as sliders, to modify these parameters and observe the change in real-time. What was not fully explained above is the fact that parametric design systems can

establish higher-level abstracted design concepts through the linking of parameters. For example, the user can establish a parametric relationship between the height of a prism and its length and its width such that all three dimensions are identical; if one parameter changes then the other two change accordingly. This will ensure that the prism will always be a cube. It is at this precise moment that the designer has created a consistent higher-level concept (cubic form) that is derived through the establishment of (or constraint of) parametric relationships. In other words, the designer is *thinking with abstraction* (R. Oxman & Gu, 2015). This is not a concept specific to parametric design: Le Corbusier famously argued that great works of architecture are derived by the use of *regulating lines* (Le Corbusier, 1931). These regulators abstract the design and influence, if not dictate, the placement of features in buildings and their overall proportions and geometry. Other higher-level or *abstracted* concepts such as the concept of circumscription (e.g. a minimum bounding object) can be affected by relating the parameters of that object (e.g. its extents and location) to the parameters of other objects (e.g. their extents and location). Essentially, parametric design systems allow the definition of a language of design based on vocabularies (e.g. shapes, forms) and grammars (rules and relationships). More precisely, “Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response” (Jabi, 2013). Thus, parametric design is first and foremost a *design* process based on algorithmic thinking which calls for a shift of focus from achieving a high fidelity in the representation of the appearance of a design to that of achieving a high fidelity in the representation of its internal logic (Figure 1).

operate independently on inputs to produce desired outputs. We are getting closer to an era where, as Hugh Whitehead writes, a generation will emerge who can “sketch with code”(Woodbury et al., 2010). If this is about to or indeed has already happened, it becomes essential that we set a clear theoretical foundation to what we call parametric design. One of the first questions we need to answer is “What are the different types of parameters we can encode in a parametric design system?” The remainder of the paper will attempt to answer that question as well as focus on a few types of parameters and explore their role in parametric design systems using a constructive and experimental research methodology.

2. Taxonomy of parameters

One method to understand and categorise design parameters is to organise them into a hierarchical taxonomy (Jabi, 2013) (Figure 2). The word *taxonomy* originates from the Greek τάξις, (*taxis*) meaning order or arrangement and νόμος (*nomos*) meaning law or science. Thus, a hierarchical taxonomy uses a scientific method to classify a set of concepts in a certain hierarchical order. In the case of design parameters, the hierarchy of the proposed taxonomy is based on the inter-dependency of the parameters with the more independent parameters located at the bottom of the taxonomy and the more dependent parameters located at the top of the taxonomy. A general rule of this taxonomy is that parameters at the lower levels of the taxonomy form the foundation of the more complex parameters at the higher levels of the taxonomy.

At the most basic level within this taxonomy, mathematical parameters establish numeric relationships and use mathematical concepts to compute other parameters. A spreadsheet is a prime example of a mathematical parametric system where a cell can contain not only data, but a mathematical expression that can refer to, and thus establish a mathematical relationship with, other cells in the spreadsheet. Based on these mathematical parameters, we can build geometric parameters that use the concepts of geometry to relate 2D shapes and 3D forms to each other. The church of Hagia Sophia, for example, is precisely designed and constructed (not surprisingly by two accomplished mathematicians: Isidore of Miletus and Anthemius of Tralles) according to the geometric concepts of *squaring the circle* (Jabi & Potamianos, 2007) (Figure 3).

The next level of abstraction addresses topology (or how parts are related to each other). One of the early criticisms of CAD is the fact that an object can intersect another as if the other object does not exist. This created conceptual as well as pragmatic problems. Modern

parametric systems can (or should be able to) express topological relationships such as “always place a window in the centre of its host wall”. Topological relationships can be generalised into parametric ones through a process of parametrization. For example, one can set a rule that a window is always placed on the right-side of a wall by limiting its position (generally) to less than half the width of the wall by measuring from the right-side. The fact that it is placed on the right side established a *topological* relationship between the window and the wall, while the multiple possibilities for its exact location creates a *parametric* relationship. As the next sections explain, this paper explores how topology, and specifically non-manifold topology, can be used to enhance and expand parametric design thinking, but we will get to that later.

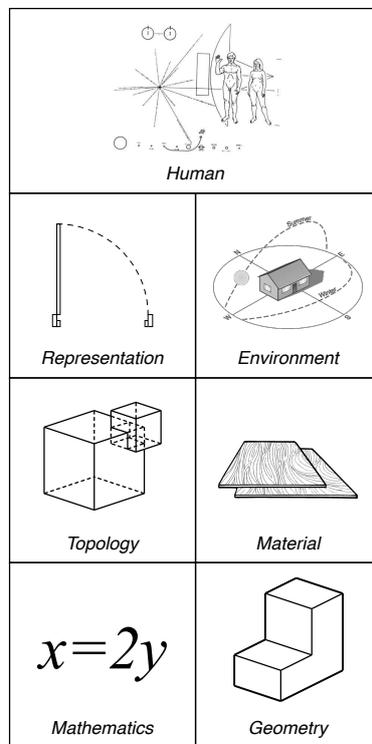


Figure 2. A taxonomy of parameters.

attempts at understanding and encoding our behaviour and decision-making processes. This is an essential area of research for the future.

Each element in this taxonomy deserves one if not multiple papers to analyse fully. Within the scope of this paper, we are focussing on the role of topology in parametric design systems by exploring how topological queries can enhance a parametric investigation.

3. Topology in parametric design systems

Within the above conceptual framework and parametric taxonomy, this paper focuses on the role of topological data structures with the aim to enhance computational parametric design processes. Topology in mathematics is defined as “the mathematical study of the properties that are preserved through deformations, twistings, and stretchings of objects. Tearing, however, is not allowed” (“Wolfram,” 2016). One can think of topology as an abstract construct that allows us to think spatially about, order, and navigate our environment (e.g. the lecture hall is directly one floor below us, or his office is the door just after the staff lounge). Alternatively, one can think of topology as a conceptual regulating skeleton that allows the development of more complex and detailed design solutions. Many new students of parametric design make the mistake of creating *the thing itself* (e.g. the building fabric) skipping over the importance of creating the conceptual framework for their design. Vitruvius distinguishes between the physicality of making architecture (*fabrica*) and the rational and theoretical *setting out* of its principles (*ratiocination*) (Pont, 2005). Similarly, Woodbury uses the patterns *controller* (something that controls something else) and *proxy* (something that stands in for something else) to emphasise the importance of thinking more abstractly and strategically about one’s design (Woodbury et al., 2010). Ellen Do and Mark Gross arrive at the same conclusion by studying diagrams in architecture: “The graphical elements and spatial relations of the diagram map to elements and relations in the domain and the spatial representation of the design offers insights and inferences that would be more difficult to see and work with in other representations.” (Do & Gross, 2001). When a design system omits *ratiocination* and the definition of topological relationships, it risks brittleness and failure in later design stages.

On a more pragmatic level, a consideration of topology can create enhanced and smarter solutions as it can modify parameters based on an accommodation of the situation as explained below. The chosen example implementation in this paper falls within the area of additive digital manufacturing of conformal cellular structures. This was borne out of a

perceived research gap in the literature regarding the role that topology can play to improve the design and manufacturing of cellular structures as well as observed inefficiencies and manufacturing problems that exist due to a lack of consideration of topology.

4. Topology in conformal cellular structures

A cellular solid material is composed of two phases. The first is a continuous solid phase (usually called the matrix) while the second is either a continuous or discontinuous gaseous phase (Gibson & Ashby, 1990). Examples of cellular material found in nature include bones, cork, and wood while there exists a plethora of manufactured cellular material such as polystyrene and foam. Cellular material is usually classified either as closed cell or open cell based on whether the gaseous phase is continuous or discontinuous (Busse, Herrmann, Kayvantash, & Lehmus, 2013). Cellular material, such as honeycombs, lattices and foam, offer several potential advantages over solid material including increases in thermal insulation, acoustic insulation, compressibility (e.g. for transportation), strength-to-weight ratio, volume-to-weight ratio, and energy absorption (Nguyen, Park, & Rosen, 2012; S. Soe, Ryan, McShane, & Theobald, 2015). Parametric conformal cellular structures enhance the use of cellular material by replicating a cellular unit whilst parametrically distorting it locally to conform to a potentially complex and curved design envelope (S. Soe, Jabi, & Theobald, 2016) (Figure 4).

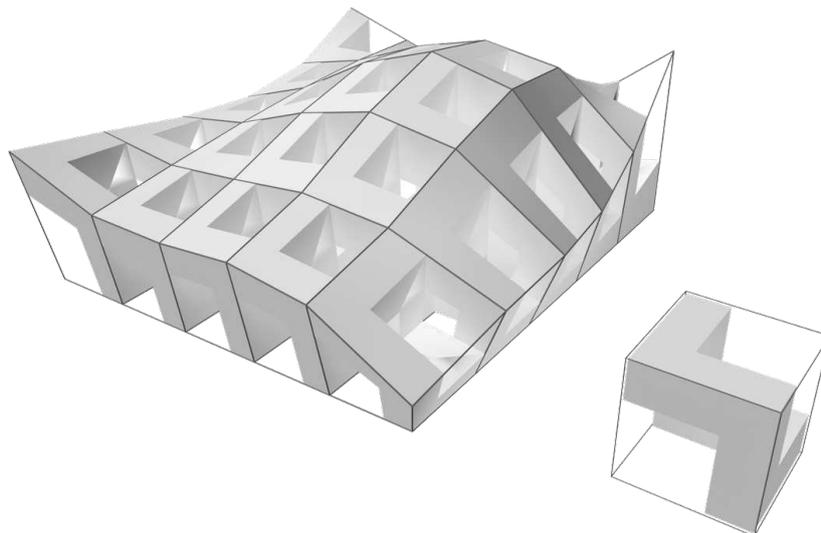


Figure 4. A conformal cellular structure regulated by an undulating design envelope.

With the ever-increasing availability of new engineering materials, additive manufacturing of conformal cellular structures offers great potential for producing functional products. The

additive manufacturing process has the advantage of depositing material only where it is needed thus further enhancing its efficiency and sustainability. Material computation and performance requirements can drive the parametric functional grading of conformal cellular structures to affect shape, wall thickness and other attributes.

While the additive manufacturing process is particularly suited to computationally-generated forms, traditional commercial CAD packages have struggled with the design and generation of conformal cellular structures due to their complexity (Gu & Yau, 2002). Advanced parametric and generative techniques have enhanced and partially helped overcome the limitations of traditional CAD software (Jabi, 2013; R. Oxman & Gu, 2015; Woodbury et al., 2010). Through combining the concepts of deformation (or morphing) and panelling, visual programming software such as Grasshopper, provide a “procedure for dividing a *freeform* surface (modelled in Rhino or generated in Grasshopper) into destination boxes for morphing. The result of this operation is the distribution of deformed geometries on a complex surface.” (Tedeschi, 2011). With additional scripting, the software can also vary the sizes of these unit object as well as their shapes and densities to achieve functional grading based on design performance requirements such as impact absorption or structural strength (Figure 5).

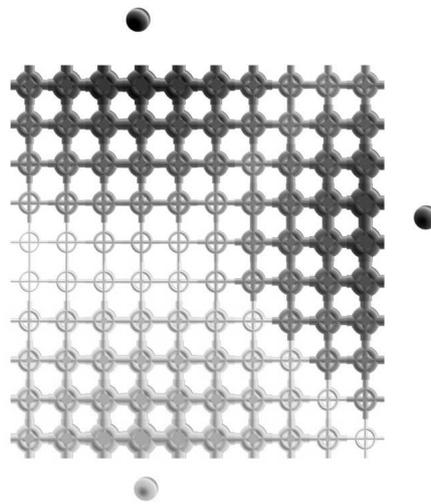


Figure 5. Functional grading of cellular structures based on parametric attractors.

However, these parametric variation techniques made available in software such as Grasshopper and Dynamo are not yet sophisticated enough to take into consideration topological information (e.g. adjacencies between cellular units, boundary conditions) to inform the additive manufacturing process. One possible solution is to use a mathematical

concept called non-manifold topology (NMT) that, among other features, allows the subdivision of a complex design envelope into multiple cellular spaces within a unified data structure while maintaining topological information among these cellular spaces. As we will see below, using NMT allows for the customisation of deposited material in each cellular unit so that it takes into consideration the configuration of neighbouring cells and surface boundary conditions.

5. Definition of Non-manifold topology

In a traditional 3D modelling environment, solid objects (e.g. polyhedral) are said to have a 2-manifold boundary. If one imagines the boundary to be flattened and made infinite, then each point on this boundary is completely surrounded by other points on that 2-dimensional boundary. Examples of 2-manifolds include the surface of a torus, a sphere, or a prism. More importantly, each point on the boundary of a 2-manifold solid divides the modelling space into two regions, the solid material inside the boundary and the void of the outside world. The implementation in this paper aims to enhance the computational parametric design of conformal cellular structures using a novel technique based on the mathematics of non-manifold topologies (NMT) (Aish & Pratap, 2013; Jabi, 2015). A non-manifold topology is defined as the condition at which a point on the boundary does not divide the modelling space into two regions. Practically, non-manifold geometric models can be defined as combinations of vertices, edges, surfaces and volumes (Figure 6). Contrary to traditional solid geometry boundary representation, NMT allows for and consistently represents any combination of these elements within a single entity. Conversely, traditional boundary representation struggles with representations where a surface divides the interior of a polyhedron, an edge is shared by more than two surfaces or ones that combine an isolated vertex, edge, surface and a solid in one representation.

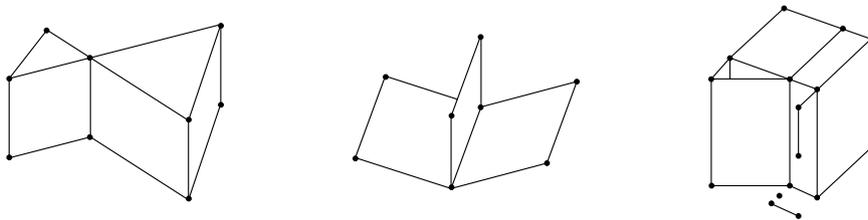


Figure 6. Examples of objects with non-manifold topology.

Elements within NMT structures are hierarchically inter-connected (Figure 7). The bottom-most element is a vertex (point). Vertices can exist in isolation or they can be the end-points

of an edge (line). The similarity with traditional surface boundary representation ends here because isolated and inter-connected vertices and edges can form open and closed wires. Closed wires with ordered edges form the basis of a face (surface). Faces, in turn, can be combined to create shells, but those can also contain isolated vertices, edges, and faces. Next, the concept of a cell is introduced which can be made from a series of closed and connected faces (i.e. a closed shell). A group of inter-connected cells create a CellComplex which can also include lower-dimensional entities through secondary relationships. Finally, any number of entities of different dimensionalities can be grouped together in a Cluster. These expanded data structures and topological relationships allow for a richer representation of loci, centrelines, elements, surfaces, volumes, and hierarchical groupings.

In regular constructive solid geometry (CSG), Boolean operations are used to combine, subtract or find the intersecting volume of two or more solids. NMT allows for a re-defined set of Boolean operations that includes the notion of merging and extraction (Figure 8). In traditional Boolean operations, the original operands disappear and are replaced with the resultant shape based on the chosen operation. In NMT, however, the two shapes are merged and can overlap and consistently share vertices, edges, surfaces, and volumes without redundancy.

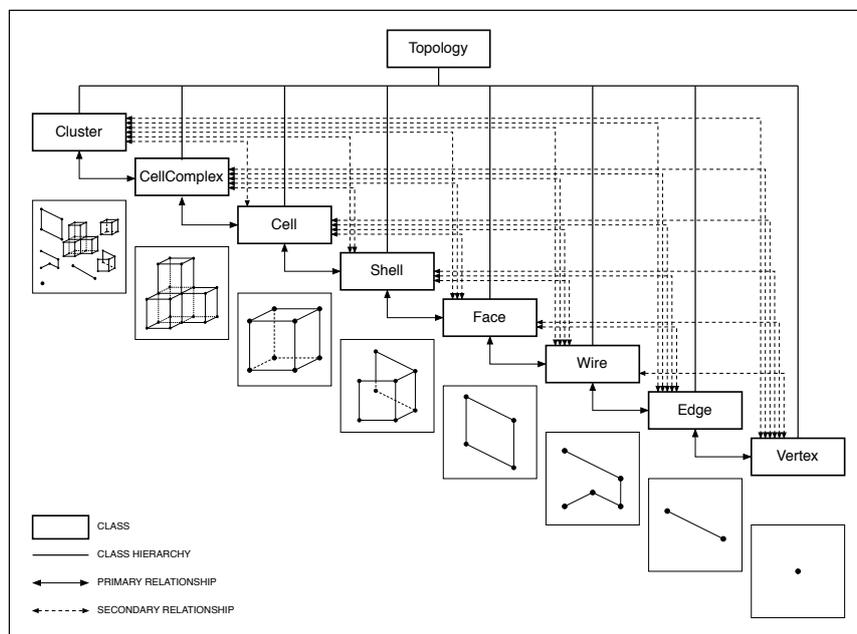


Figure 7. Non-manifold topology class hierarchy.

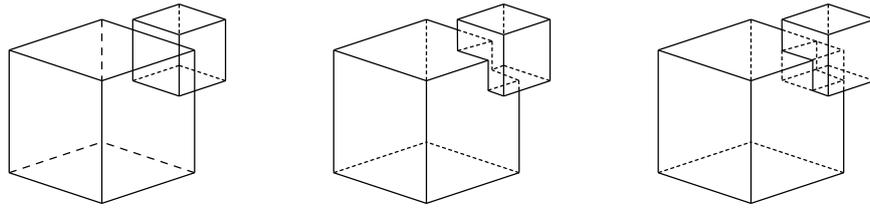


Figure 8. Traditional vs. non-manifold topology Boolean operations.

Analysing and reflecting on previous work by the authors has instigated the combination of separate but intersecting research threads and using NMT and associated parametric algorithms as a regulating framework for designing and manufacturing functionally graded conformal cellular structures. In the first instance, NMT was used successfully to design and regulate the geometry of a building façade and informing customisation operations (e.g. trimming, parametric variation) by computing the average vertex normals and edge bisectors made available through adjacency queries (Fagerström, Verboon, & Aish, 2014). In the second instance, NMT was used successfully to enhance the representation of architectural spaces within buildings by using planes to segment an overall structure into cellular spaces (Figure 9) and directly converting these spaces in the NMT model to thermal zones and producing energy models that are highly compatible with the input requirements of building performance simulation engines (Jabi, 2015).

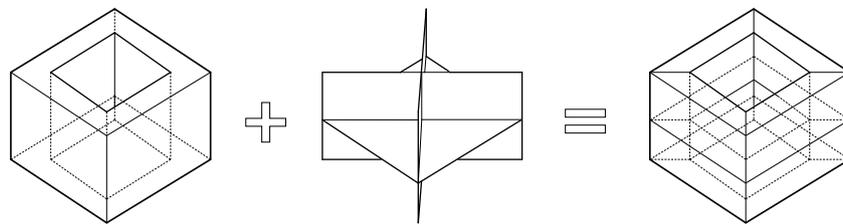


Figure 9. A polyhedron (left) is segmented using a set of planes (middle) to create an object with internal cellular spaces (right).

In the third instance, new and novel cellular structures for impact protection (e.g. helmets) were contoured predictably to conform to curved and complex design envelopes whilst maintaining mechanical performance through the retention of the relative alignment of individual cellular units (S. Soe et al., 2016, 2015; S. P. Soe, Martin, Jones, Robinson, & Theobald, 2015). Similar to the work by (Rosen, 2007), the mechanical performance of these structures was tuned by parametrically varying cellular shapes, wall thicknesses and relative densities and optimised through finite elements analysis (FEA) that measured impact forces and reactions.

6. Experimental investigation

A previous experimental investigation by the authors included developing a custom parametric and generative script that was developed within a commercial 3D modelling environment to create non-manifold topological models that are then used to regulate the geometry of cellular units to create conformal cellular structures (S. Soe et al., 2016). Several case studies were generated and analysed from the point of view of performance along several dimensions including manufacturability. These case studies were further optimised through a feedback loop that combined generative parametric variation with FEA analysis.

For this paper, the experimental investigation focused on the incorporation of topology queries within conformal cellular models to evaluate their usefulness for fabrication planning. Cells in a topological model can act as containers for other unit objects and regulate their geometry. For example, a cellular unit can contain a solid, a gas, or a void. A topological model allows its constituent components to make topological and geometric queries to the adjacent components. For example, the surfaces of a unit cell can be queried if they separate the unit from the outside world (i.e. exterior surfaces) or if they separate the unit from another unit (i.e. internal dividing surfaces). Adjacency information is important for building simulation models since "... most boundary conditions and loads tend to be applied to these interface regions." (Nolan, Tierney, Armstrong, & Robinson, 2015). The results of these simulations can then be used to enforce rules for depositing material (e.g. connect across internal dividing surfaces, but offset away from external surfaces). This geometric and topological information can be used to customise the inter-cellular connections across shared surfaces (e.g. to maintain structural or flow continuity) and to address edge boundary conditions to deposit material only where needed (Figure 10).

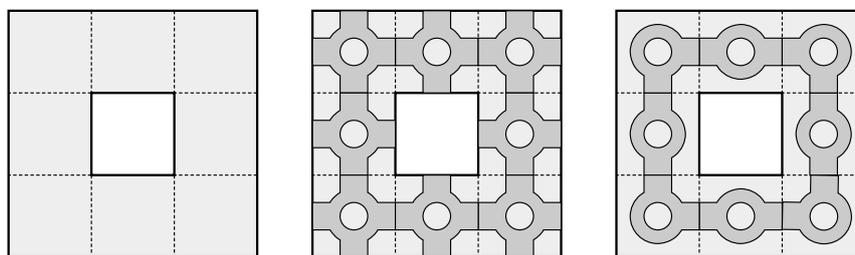


Figure 10. Conceptual diagram illustrating a non-manifold design envelope (left), a regular repetitive insertion of a cellular unit in each cell (middle), and an optimised rule-based trimming of cellular units based on topological information (right).

To exercise the script, a design envelope was segmented into a 20x10 grid of cellular units (Figure 11). The script was run twice under two different conditions. In the first test, only one cross-shaped unit was repeated throughout the design envelope regardless of boundary conditions. The resultant form mimics many manufactured cellular structures such as foam that need to be trimmed or augmented at their outer boundary (Figure 12). In the second test of the script, rules were implemented regarding what unit to place based on topological boundary rules. In this case, the rules are kept simple to test for an edge, a corner, or a middle condition as per Figure 10 above. The resulting conformal cellular structure adopted in the second test, an architecture described elsewhere as a ‘triply periodic minimal surface’ (TPMS), was more geometrically controlled in terms of its outer boundary and corner conditions while maintaining the same interior connectivity as the one produced in the first test (Figure 13). Both structures are parametric in their nature, but only the second structure takes advantage of topological queries to enhance the design solution.

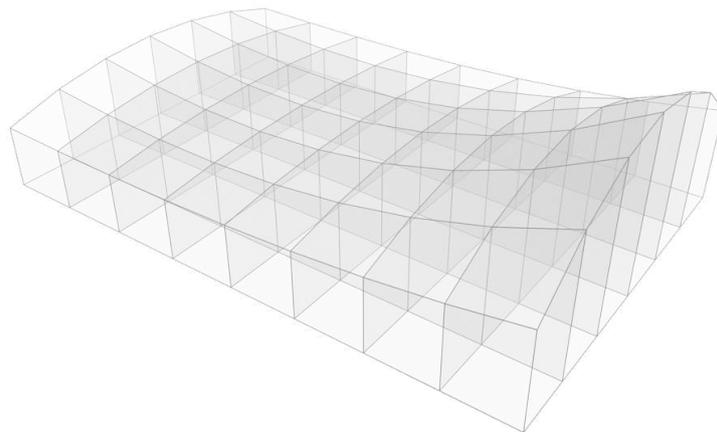


Figure 11. Non-manifold design envelope with 6x8 cellular unit divisions.

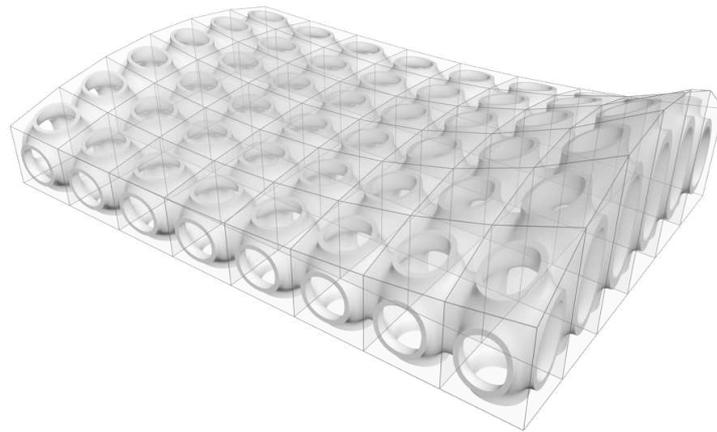


Figure 12. Conformal cellular structure with same repetitive unit regardless of boundary conditions.



Figure 13. Rule definition of cellular units for corner, edge, and interior conditions.

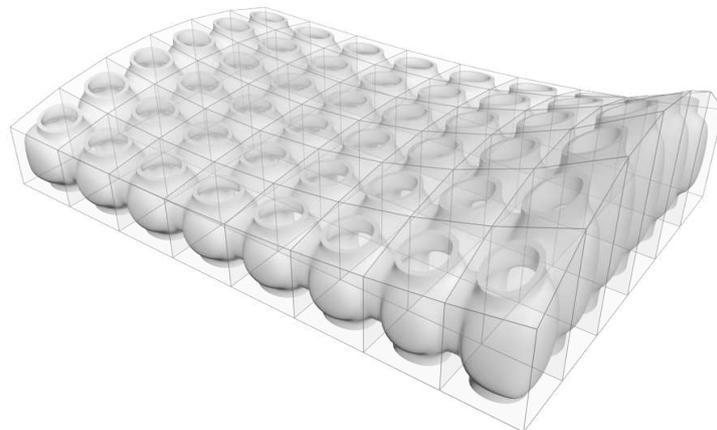


Figure 14. Conformal cellular structure with topological rules applied for corner, edge, and interior condition.

FEA simulation was then performed on the TPMS, demonstrating the capability to assess structural and mechanical performance. This process could ultimately be useful for evaluating the effectiveness of such structures for industrial applications that require attributes including enhanced energy absorption, or superior strength-weight ratios. Two exemplar scenarios are presented here, to indicate future potential that can be achieved through the integration of design and simulation software. Using Abaqus/CAE 6.14-1 simulation software, the first application simulated a high-speed ‘impact’ load on the entire upper surface of the TPMS, achieved by sandwiching the structure between the two rigid plates. Impact of the upper plate causes the sequential TPMS deformation and buckling (Figure 15). For clarity, this figure illustrates only the main part and bottom surface which absorbs energy. Further analysis would provide detailed criteria such as maximum impact load, stress levels and an acceleration-time profile, parameters that would enable the structure to be further optimised to achieve a specific mechanical performance. In the second case, a planar portion of the structure is isolated and impacted, allowing the functional evaluation of the region of interest. Planned future work will complete the feedback loop from simulation results back to the rule-based generative software to enact measures to further optimise the design of the structure.

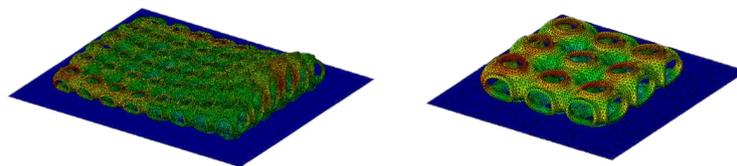


Figure 15. FEA impact simulations of the TPMS conformal cellular structures.

7. Conclusion

This paper set out to enhance and expand our understanding of parametric design thinking by exploring the role of topology. Parametric design thinking was found to be closely linked to our primordial cognitive tendency to accommodate and assimilate new information. This cognitive basis was then used as the foundation to explain the tenets of parametric design and its basic vocabulary of parameters. Borrowing the Vitruvian concept of *fabrica* vs. *ratiocination*, this paper outlined the limitations in the current implementations of parametric building information modelling systems that focus heavily on the design of the thing itself with little attention to the rational and theoretical *setting out* of its principles. Establishing

topological relationships was found to be an essential component of the setting out of the conceptual principles of a design project. One type of topology (non-manifold topology) was found to be a richer representation of entities that have internal cellular structures that can be thought of as spaces, voids, or containers of other material. While this concept was previously explored by the authors in the context of energy analysis, and building façade design, it was explored in this paper in the context of additive manufacturing of conformal cellular structures and was found to enhance the efficiency of their design through topological queries. One of the major limitations facing this work is the lack of a rich editing environment that allows for the creation and modification of non-manifold topologies in a consistent manner. While some commercial systems, such as ACIS, CATIA, and Pro/E support NMT internally, they do not expose that functionality consistently and richly to the end user. In most current commercial 3D environments for architecture and design (e.g. Rhino, Revit, Maya, 3ds Max, C4D), NMT is considered a fault in modelling and an error that needs to be eliminated, especially when the modelled object is destined for 3D printing that requires *water-tight* (i.e. manifold) objects. Thus, given a recent research grant from the Leverhulme Trust, a major ambition of the authors is the development of a more appropriate representation of architectural space so that it is available both for immediate use in conceptual design and as a partner technology in a future unified computational design system. This new modelling approach will be supported by an expanded set of tools that allow architects to create models that are consistent, flexible, and extensible while maintaining design creativity and desired spatial complexity.

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