Mindful Spaces: Computational Geometry and the Conceptual Spaces in which Designers Operate

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Combinatorial computational geometry, while dealing with geometric objects as discrete entities, provides the means both to analyse and to construct relationships between these objects and relate them to other non-geometrical entities. This paper explores some ways in which this may be used in design through a review of six, one-semester-long design explorations by undergraduate and postgraduate students in the Flexible Modeling for Design and Prototyping course between 2004 and 2007. The course focuses on using computational geometry firstly to construct topologically defined design models based on graphs of relationships between objects (parametric design,) and concurrently to output physical prototypes from these “flexible models” (an application of numerical computational geometry). It supports students to make early design explorations. Many have built flexible models to explore design iterations for a static spatial outcome. Some have built models of real time responsive dynamic systems. In this educational context, computational geometry has enabled a range of design iterations that would have been challenging to uncover through physical analogue means alone. It has, perhaps more significantly, extended the students’ own concept of the space in which they design.
1. INTRODUCTION: TOPOLOGICAL ARCHITECTURE

Guiseppa Di Cristina writes in 2001 of “the topological approach in architecture” which she shows has developed progressively throughout the previous decade [1]. Bound up in these “pliant and fluid new architectures”[1] there are at least two fundamental underlying ideas. One is the expression of homeomorphism or continuous transformation of one form to another. This essentially dynamic idea is hard to express in the static medium of architectural design [2, 3] but easier to represent through computational geometry than through most material analogue modeling media in the physical world. The second is the mixing of “forces”[1], spatial and formal arrangements that are directly responsive to extrinsic and intrinsic influences from site, program, environmental change that relate directly (smoothly/continuously) to the formal (geometrical/spatial) system of the architecture. Through computational modeling, the architecture can be wired, connected in a multidimensional network, potentially extending beyond the immediate physical space of the site, a concept for which Michael Speaks coined the term “design intelligence” [4].

Computational geometry has been very successful in hiding the (geometrical) joins. Solid modeling programs provide surface algorithms that marry heterogeneous conditions into a single surface or series of cotangential surfaces and there is no demand placed on the modeler to engage closely with the abstract symbolic geometrical description of that surface. In this way designers can move conceptually to the more general geometrical world of topology, foregrounding connectivity and continuity, a familiar starting point for space planning but not a traditional metaphorical starting point in design of form. To what extent is the manipulation of continuous surfaces, even driven by external “forces”, really a topological approach to architecture? In the first place, designers are generally intensely concerned with the formal (shape) output of such dynamic systems so that while the topological system is a powerful conceptual tool or metaphor to describe a whole design space (field of potential designs) the system variables are generally manipulated in ways to steer the shape outcomes (spaces and built form) by subjective aesthetic and performance criteria. Secondly, while the model itself may be subject to topological constraints (meaning that it is topologically stable, while being metrically and geometrically variable in other geometries), its structure is always subject to, what could be framed subsidiary, geometrical description using Euclidean, projective and descriptive geometry. This is regardless of how the geometry is revealed to, or concealed from the designer within the internal algorithms of the program. Topological transformations that are trivial in physical analogue modeling are hard to simulate directly within a solid modeling environment, cutting a slit without removing part of a surface is one example of this.
The linking to external parameters and to the work of fellow designers to collectivise the work in a broader context (expanded physical site or social context for instance) through linking parameters of the design has been explored specifically in earlier design studios and in the recent work of others [5, 6]. This paper will describe work in a multidisciplinary elective that provides special license to focus specifically on design modeling.

2. CONCEPT TO COMPUTATIONAL GEOMETRY

Parametric design, defining a hierarchy of geometrical associations and relationships, necessarily makes computational geometry more explicit than within general solid modeling and CAD software interfaces. If all the geometry is to be predicated on, (descended from), a first parametric point, that point must itself be defined by a method and appropriate parameter values: a 3D coordinate system and three coordinate values; or a curve, starting point and the distance along a curve; or a surface and u and v parameters for the point on the surface, as instances. The magic of concealed algorithms remains but the relationships between one geometrical object and others has to be stated and constructed as a directed graph and this creates a more genuinely topological space. This raises the question of whether this reifies the abstract geometrical content of the activity at the expense of a more intuitive engagement, calling directly on innate spatial intelligence in the early conceptual and sketch stage of design.

In the process of engaging with these modeling techniques, students become aware of a series of overlapping spaces: the space of the Euclidean, descriptive and projective geometry, understood primarily through the visualization, the topological space of the relations between geometrical objects (and between external values and these objects), a very hierarchical directed graph, and thirdly, the bounded space of (infinite) possible spatial variations or iterations within the system, for which the boundaries are generally only discovered empirically. The modeling itself is an iterative process, sometimes leading to several generations of new models each involving radical restructuring of the computational graph. Is this a useful activity in coming to know the design system that is being designed, or; a distraction from the engagement with the projected characteristics and qualities of the ultimate object of design? Or does engaging with geometry through computation in this context distance the designer from a Platonic idealistic view of what architecture might be, art mimetic of the world of ideas, and place them in an Aristotelian world where design is a practice not an essence and where to be a masterful designer is to master computational geometry? [7]. There is perhaps, within this way of working, room for the Platonic idealist realisation of ideas where the ideas are not so much stable, universal forms as stable systems of variation: an organic Platonism. To privilege the “constraints” in this approach to modeling, is to reinforce the idea of typological or performance boundaries which strengthens this concept of idealized systems [8].
3. TOPOLOGICAL THINKING

Spatial conceptualization is difficult to separate from media of representation. Engaged thinking rather than contemplation is generally the useful conception [9]. For design this translates to a reciprocal relationship between ideas and their representation, whether through sketching, natural language, formal language, or modeling. The space in which sensory visual perception is interpreted as the conceptual space we inhabit bodily, the visual cortex, seems to be topologically organized. Experimental biology identifies complex continuous mappings onto the visual cortex that include edge orientation and direction of motion [10]. For instance, neurons are found to be selectively responsive to the orientation of an edge stimulus (in the image we see) which varies with position in the cortex. Nearby regions in the cortex have similar preferred orientations and preferences generally change smoothly with position. Different orientation preference domains meet in points known as singularities. In this context it is ironical that the topological space of geometrical relations, constructed computationally, in associative geometrical modeling is so hard to visualize except as an abstracted family tree of nodes and edges which gives little conception of its space-making characteristics. It becomes better known and more predictable through familiarity but it seems to be an abstract, analytical, logical, rather than sensory knowing. Observation indicates that a sensory or intuitive spatial engagement comes through empirical experiment — varying the parameter values and formula relations in the model to observe the results. Smooth variation is usually only local in a model with many variables. The geometry itself quickly becomes a complex system as the size of the graph of relations grows, so that while its variability may be predictable for changes in a single variable over a limited range of values, that range varies with changes to other parameter values.

Designers are familiar with starting from the end. Nothing is known at the start but conjectures are made about the characteristics of the outcome. In this context Lawson talks about ‘primary generators’ and quotes (Darke 1978) who asserts that designers often tend to latch on a simple idea very early in the design process to narrow down the range of possible solutions [11, 12]. The most useful initial sketch for the associative geometry model is not a shape or a map but a description of what it should ‘do’, how it should be driven and to what end. It is not a direct way to achieve a single design outcome but a machine to generate design outcomes within a particular design domain. It is the definition of the domain which is at the very front of the design process. It is an open starting point, a point that permits both commitment and deferral for the same attribute simultaneously. It does not leave the field open. But it allows, in a small way, the harnessing of the dynamics that are integral to our own perceptual understanding of space and objects within it, while extending this to morphology. Evolutionary decisions are made at each step but the broad (parametric) variations in the population lead to diverse hereditary
As in any design decision path, a 'flawed' early ancestor leads to 'flawed' descendants but the computational genealogy in this mode of geometrical modeling allows for posthumous replacement by a topologically consistent but more benign alternative ancestor: moderate genetic engineering of preceding generations.

The examples briefly examined in this paper feed reflection on firstly, at what stage in the overall design process it is possible, or appropriate, to define this domain and secondly, whether the progressive definition of this domain through successive models is a useful early design approach.

4. EXAMPLES

In questioning the value of this mode of engaging computational geometry for early design I will list examples of generic investigations that students have undertaken in the flexible modeling elective. It is a one semester long course for one quarter of a fulltime student’s work load. It is open access to all disciplines across the University and includes a significant skills acquisition component. The majority of participants are from architecture, landscape architecture, industrial design, interior design and structural, mechanical or aeronautical engineering. Others have come from urban design and fine arts. I include this information to stress the generic nature of the course objectives: literally to find techniques for making flexible models for design. The projects are generally either at the early stage of design or re-workings of the students own design projects or of published works. Projects are reworked in the spirit of musical variations. The explorations and questions that the students have sought answers to through the medium has ranged from a very open “what could the design become” to “how can the spatial/formal characteristics respond to external environmental drivers in optimal or interesting ways” to “how can I emulate the finite dimensions of objects in the physical world” to “mass customization: when is this object no longer this object.”

Everyone has been encouraged to extend their “system” to a level of detail where they can explore how macro changes to the design update the detail and in some cases this has been the primary focus of their investigation, particularly for individuals who have directly experienced the on-site challenges of describing and constructing junctions in architecture using non standard, non-orthogonal geometry.

I have included examples of five generic categories of design investigation using relational computational geometry. For most, if not all, students there is a steep learning curve in migrating from a background in using explicit geometrical modeling software, or in some cases from no experience of digital modeling at all to a parametric environment.

4.1. What Could My Design Become?

This very basic question has been fruitful. The students will take a very abstract sketch proposal, the blob in Figure 1, for example, and remodel it...
using associative geometry, progressively introducing greater degrees of refinement and articulation into the original and exploring the formal and environmental opportunities through varying the parameter values, as shown in Figure 2. In this instance, while the objectives are simple and not overly theoretical or ambitious, it has been possible to arrive at a variety of formal proposals that could not have been easily modeled explicitly in the first instance. By modeling the proposal with a variable relationship to the existing structures in the site and its structure in relation to a central guide curve of variable shape and position, the author gains control at a macro level of design. Within those variations, the designer can also vary the number and distribution of the structural divisions, their sectional shapes, the horizontal inclination of the glazed walls between structural divisions in response to orientation and sunlight. This particular proposal fits into Di Cristina’s category of ‘topological architecture’. While it has scale, it is not bound by modularity, everything can vary smoothly in the space of real numbers rather than integers. The shapes are created within the black box of the program’s B-Spline algorithms, controlled only by points on normal planes distributed along the central curving spine.

Figure 2. Parametric variations in the associative geometrical model David Hislop, 2007.

Figure 3. Adam Jackson, 2005: Nature vs Nurture – poster for a tool for rapid testing of conceptual design for residential or commercial towers (developed in response to experience in LAB office of working on rapidly changing proposals for large building projects in China).
4.2. Responding to Environmental Drivers

There have been a variety of projects that investigate architectural design responsive to directional sunlight with the aim to minimize glare and increase comfort and energy efficiency. Wind and wildfire spread are also drivers that have been linked to geometrical parameters. These projects fall into two categories: those that work on systems of dynamic shading or art/architecture response that mean that calling up a particular day of the year and latitude results in a particular arrangement of shading, and those that seek optimal static geometry. In each case these require some basic programming, for instance linking input data to geometrical parameter values using formulae within a spreadsheet linked to the model. In this example the sun shading device is sculpted according to the orientation of the building façade on which it is placed. In this way the generic description of the sunshade could be applied to many different buildings and would vary according to the building geometry. For a rectangular building the shades on one particular façade took on a common shape, varying only subtly with the floor level in the building. For a hypothetical building of circular plan they varied continually around the building. In this project the student linked the sunshade geometry to output fabrication information. This is both an early design project – the sunshade model itself is a form finding model that takes on different forms when instantiated in different orientations and building geometry, it can be modified at the master prototype level – and a late design project – the student's interest was in creating a simple affordable component that could be retrofitted to public housing blocks to improve the solar performance of the units and add aesthetic variation and interest to the buildings.
A second example of this category of project was the remodeling of the unbuilt competition winning design for the Victoria and Albert museum extension by Daniel Libeskind with Cecil Balmond. Drawing on Balmond’s sketch of the scripting process to build the spiral form in his book Informal [12] the student worked to construct a model based on the same geometry but introducing variability to investigate ways in which the design might have developed. This led to a series of studies including the use of optimization software to ‘adjust’ the angles between the spiraling walls of the building to maximize the potential for natural lighting and passive solar gain. In the course of the optimizer searching the space of possible solutions, impossible geometrical relationships would be created, for instance certain intersections (on which other geometry was built) would no longer occur in space. Reactive changes to the model geometry had to be scripted to make all cases within the range viable. This is an example of the use of computational geometry for design development from a pre existing schema.

![Figure 5. Optimizing the spiral form of Daniel Libeskind’s proposal for the Victoria and Albert museum for natural light, Paul Nicholas, 2005.](image)

### 4.3. Emulating Physical Materials

It is a surprisingly challenging problem to try and constrain the precise overall dimensions and proportions of a surface regardless of the deformation you subject it to in a computational geometrical environment. Generally as you lift a point in the centre of a flat handkerchief in a 3D modeling environment, the handkerchief grows or stretches to accommodate the change rather than drawing in its boundaries as the physical article would. Neither folding a planar surface, nor unfolding a developable surface presents the same difficulty but the fluidity of topologically driven architecture is another question. A surface representing a two dimensional manifold in 3-space, metaphorically a length of draped silk, is difficult to constrain to its original dimensions as it is moved and reformed, draped over different objects within the parametric modeling environment. The problem, once identified, invokes a certain tenacity that will not admit the download of a draping algorithm. The outcome of one project led to a close approximation to the physical analogy and applied it in architectural design. The process was revelatory in uncovering the complexities of introducing even a second dimension in some constraint systems and the intriguing hybridity of computational geometric space which includes topological tendencies that are not as manifest in handkerchiefs.
4.4. Mass Customization

Mass customization is a prime objective for parametric modelers. In this case the big question is what remains the same and what can change? The cultural objective is to be able to produce many similar but individualised objects from one production process or in the design domain one single, parametrically adjustable model. In apparel we are accustomed to the mass production of a limited range of sizes of similar garment where once clothing was custom tailored and shoes made by the cobbler. One student took his Prada sunglasses and started to consider how they could be adapted to face shapes and style needs: *Personally Prada*. The taxing ontological question was at what point the characteristic Prada Aviator glasses shape, the vitality of the brand identity, was lost in making the shape adjustments. In designing this model it was the consideration of what was essential to keep that steered the choice of parameters and relationships.

Another example of early design in this category was the design of a suite of furniture – a model that could generate a chair or a chaise long and adjust each ergonomically to the body measurements of user.

4.5. Dynamic Systems

Many students have investigated modeling dynamic systems: a laneway installation of unrolling flapper boards, responsive brise soleil, and a recent proposal for a wall in which oculi open and close in response to the stimulus of people walking by. Such things can be demonstrated through animation from still images of the model in various states but being able to demonstrate live interaction within the model is a better way to interact with the system and learn how to build the rules. This is early design setting up simple prototypes using scripts and rules to answer the questions ‘what if’. 

![Figure 6: Clothlike from a project by Mark Di Bartolo, Flexible 3D Modeling student, 2004.](image)

![Figure 7: Parametrising Prada sunglasses from a project by Mark Wong 2007.](image)
‘is it possible to’, and ‘what would it be like?’ Such projects are often explored through alternating computational geometry and physical prototypes to explore different aspects of the design, gradually building up the size and complexity of the systems.

This concludes the examples of student work taken to exemplify certain generic questions investigated through this approach to modeling.

5. DISCUSSION: GEOMETRICAL SPACES

These flexible modeling exercises engage the designer in three distinct computational geometrical spaces: the overtly geometrical space of the visualization, in which it feels we are constructing the geometrical forms; the topological space of the relations, which defines the design domain and which for simplicity we will call the database (regardless of its representation); and the space of the parameters, the innumerable variations possible within each state of the geometrical relations, for which we might adopt for clarity the epithet the spreadsheet (regardless of their representation).

The visualization is an immediate space that engages at least one of the five senses in ways closely analogous to movement in physical space – it is more literally three dimensional than natural space and framed, pictorial, isometric rather than perspectival but importantly kinetic – the viewpoint can move in real time. This is the space that links to the innately topological space of our visual cortex but possibly the one that reveals least about the true topology of the model. This space is the most intuitive to read but also for this reason the most potentially deceptive – we may read patterns that are counter to underlying relations and miss those that are there.

The database is the space with the most significant content and the hardest to read or conceptualise. Relations are invisible, like parameters, they are represented symbolically, syntactically. They become apparent only through change (changing parameter values, changing the relations themselves.) We cannot read them through the visualization when it is in one particular state. They are the formalization of design intentions. Their hierarchy can be graphically represented. It is, arguably, in this space that the design can most meaningfully be described as topological.

The spreadsheet is a natural- and formal- language space were we see values in a table, a collection, we can sort it and order it various ways, and we can map its symbols to the visual geometrical objects (sometimes they
are helpfully represented as annotations within the visualization). This can be regarded as the combinatorial space – a space for interrogation and for creating algorithms relating geometrical objects.

There is a sense in which this tripartite computational geometric space is expansive of conceptual space. It is a generative, exploratory space. New understandings of the design are born of designing and constructing a particular computational space in which to design: a specific design domain, a sort of machine that designs. When the system is first in place and a student watches their model update (in response to varying the parameters) to a geometrical composition that they do not feel they have literally built, the expression of delight and satisfaction is universal. The frustration upon quickly finding the limits of their design machine and having to return to the metaphorical drawing board to edit the relational graph or remodel completely is also commonplace. A lot of the project subjects chosen are models for developed design and fabrication. The course encourages this through requiring the students to select an existing project for their first starting point. In acknowledgement of the steep skills acquisition curve and the conceptual adjustment to constructing the parametric schema (the topological model of relations) a concrete starting point is offered. The new demands in conjunction with the openness of early design can submerge the less confident. It is harder to model design intentions when the intentions are very fuzzy. This could be interpreted as an indictment of parametric design for design exploration and early design. Does this mean that parametric design is primarily a tool for a more advanced stage of design when is more is known about the parameters and the domain?

6. CONCLUSIONS

In addressing the question of what “a topological approach to architecture” might be, there are ways of applying computational geometry that provide answers at several levels. Through generic examples of student projects, five different ways of applying topological approaches are catalogued. The most important way in which these applications are topological is not in the nature of the descriptions of form, or even in the formal morphology as such, but in the underlying model structure. The greatest value of this for pedagogy lies in its capacity to expand the cognitive spaces in which students design. Relational computational geometrical modeling is a way to build exploratory design spaces. The activity is expansive of the conceptual space in which we work and potentially uncovers iterations that might not be accessed by other means. This leads to the question of whether the process is a distraction from a more intuitive spatial engagement, focused on the characteristics of the design. It does appear inhibitory to rapid investigation of ideas at the very earliest sketch design stage, simply through the time taken to commit to parametric definitions and relations while modeling. Practitioners speak of the first conceptual stage ‘when I need to show ten schemes in a day.’ For this level of brainstorming activity, if
computational geometry is to play a part it needs a very immediate interface in which the reflective construction of a graph of relations may play no part. But, simple associative geometrical models are quickly useful for testing early ideas as soon as it is possible to posit a few definitive characteristics of the domain to test and they can provide a relatively intuitive interface for empirical formal exploration, once constructed. This supports the idea of a 'Platonic' realization of ideas as defined systems of variation rather than stable forms. It is also clearly a useful means of deferral for design refinement through design development and for adjusting many geometrical aspects simultaneously through the same model. The student project examples demonstrate a broad range of contexts and design stages. I believe that formulating this brief and non-exhaustive list of generic ways in which associative computational geometry has been applied in this particular academic context provides a useful basis for further discussion and experimentation in design research, teaching and practice. It has the potential to broaden the perception of the potential application of these ways of working in practice in a time of relatively early uptake.

My future research building on these findings will include:

- conceptual design exploration using associative geometrical modeling by groups that already have pre-developed skills and experience of working in this way;
- observing the use of sketch design using 3 dimensional sketch modeling tools that permit subsequent parameterization;
- investigating other ways to understand and communicate the topological space of relations in the design space.

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Definitions

Topological is used here in the mathematical sense to indicate form or spatial definition that is independent of quantitative geometrical relations that might be governed, for example, by length or angle parameters. In architecture, this has come to be loosely associated with curved smooth shapes that are free from angles and edges and hence from quantitative geometrical definition but can change smoothly in shape within a single topological description. Spatial design modeling, while it might theoretically refer to topology and include transformations that leave the topology unchanged cannot generally conform to the world of pure topology, where, by example a drinking cup is equivalent to a torus of any scale. Certain non-topological geometrical properties of the way the cup has been defined in the model not to mention performative constraints (holding liquid in a gravity field) tend to intervene. Parametric models are topological in
another sense also. The network of relationships between geometrical entities is a topological space in a sense first introduced by Leonard Euler’s ‘Seven Bridges of Königsberg’ paper in 1736.

Combinatorial Computational Geometry is used loosely here to distinguish computational geometry used to structure geometrical models from the numerical computational geometry used to measure real world objects and translate objects for physical prototyping.

Relational modeling refers to geometrical models in which geometric objects are constructed in parametric relationships to others rather than all given independent explicit description in relation to a coordinate system. When a parameter of one object is updated the change will affect all child objects that have a relationship to this one. This is also referred to as associative geometry where association is equivalent to relation.

References

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