This paper presents an innovative approach towards parametric design using point-clouds as design media. Exposing the internal numeric representation of digital models led to the development of parametric point-clouds as design drivers. A parametric point-cloud concept is presented in this paper, exploring its potential application for behavior modeling, generative design and performance-driven design of building envelopes.
1. Introduction: the treason of CAD

In 1929 Rene Magritte painted “The Treason of Images”, an image of a wooden pipe and a text stating that this is not a pipe [1]. Magritte’s discussion can be projected to digital design. Thinking of Magritte’s work in a digital context, one could imagine he might have created a new image discussing digital representation; a 3D CAD model of a pipe with a text saying that this is not a pipe either. Indeed it is just a visual plot of a hidden numeric representation of that pipe (Figure 1). The image of that 3D pipe on our computer screen is a model representing a real pipe – but it is also a representation of a digital pipe made of digits. This duality can be referred to as “The Treason of CAD”.

These thoughts motivated the development of a new digital design tool as part of a quest to reveal the native language of the digital domain. To cope with the suggested treason of CAD, the development process started with revisiting the foundations of the digital domain. We can describe it in a bottom-up fashion starting with the minimal piece of information, the Bit (a Binary Digit). A combination of bits defines a digital word that can be measured by its length. For example, an 8-Bit word defines a color channel on our RGB computer display. Collections of digital words create a digital domain, a container of information cells, arranged in a given order and a fixed size. The most immediate digital domain is our computer display. It has a fixed number of physical pixels ordered in a rectangular matrix, allowing us to control the content of each pixel like an artist approach an empty canvas. The visual image we see on the computer screen is in a fact a map of bits stored in its memory. The interpretation of the binary digits plots 2-dimensional pictures as screen pixels, 3-dimensional objects as voxels (cubic pixels) or vectors, and any N-dimensional entity as a multi-layered matrix. In fact, any visual representation we see on our computer screen is merely an analog interpretation of a digital numeric model hidden from the designer view and referred to as internal representation [2].

The way we practice digital design is mainly defined by our CAD tools. When observing current trends in the development of CAD tools during the past decade, one reveals that not much has changed. The Single-Building-Model approach is now referred to as BIM; architects continue to adopt Mechanical CAD (MCAD) for parametric design and NURBS are still...
around when free-forms are discussed. It is visible that the rapid
development of computer hardware and software satisfies the designers’
growing eagerness for complexity. But there lays the catch; this desired
complexity that provides the visual stimuli (in detailed 3D models and
renderings) proves to be difficult to handle when design changes occur.
Throughout the design process, architects modify and alter the design
models exploring alternatives and optimizing a solution. These procedures
require comprehensive understanding of modeling and navigating in the 3-
dimensional Cartesian space. However, most 3D CAD tools offer a design
interface based on coordinate planes which provide good support for planar
and 2.5D geometry. When the model geometry is non-planar and more
complex, the task of altering the CAD model becomes difficult.

Handling such complexity is made possible by adopting constraints-based
modeling and parametric design techniques from the automotive and
aerospace industries [3]. This approach appears to be adequate when using
the formal dictionary of these industries that typically construct curvilinear
forms and complex geometries. When comparing the design processes in
these industries to the building industry we notice that the number of
engineers designing one square meter of an airplane or a car is much higher
than the number of architects designing one square meter of a building.
Therefore, the level of complexity and the technology used in one industry
should not be transferred directly to the other.

Although parametric modeling has become more accessible to
architects, the task of creating complex parametric design models
introduced the need to acquire new skills, including advanced knowledge of
complex geometry and scripting languages. Hence we notice a bottle neck
in the design process due to the steep learning curve involved. The
development of a new parametric modeling method that simplifies the
complexity of design models is suggested in this paper as a way to
overcome this problem.

2. Points as media

Points are the foundation of every CAD entity. In fact, all our interaction
with CAD models is done with points. We draw by placing points in the
Cartesian space; we define viewpoints and target points to observe and
walk through CAD models and we can manipulate entities such as NURBS
using a control-points interface. A collection of points (point-set) can
describe the geometry of any 3-dimensional object in a Cartesian space [4].
A box, for example, can be described by its 6 faces, which are defined by a
string of points (Figure 2):

Points are actually non-objects. A point is just a location in space; it has
no size, no orientation, and no shape. Yet, we have to cognitive ability to
recognize an object described by a dense array of points, typically referred
to as a point-cloud. Point-clouds, generally used for digitizing and surveying,
are suggested here as a design media. We identify two types of point-clouds; a non-structured point-cloud which contains no spatial information regarding its internal order (generally the product of Coordinate Measuring Machine devices), and a structured point-cloud which can be described as a two dimensional matrix. The matrix dimensions represent the number of points in a point-string (a profile), and the total number of profiles defining a 3-dimensional object.

Using points as a design interface is practical when the number of points is low. A point-based interface, like the control-points of a NURBS surface, will prove inadequate when trying to edit a surface with dozens of points. For that reason, point-clouds that contain thousands of points were not even considered as an interface for design. Handling an extensive amount of points is made possible through computation. Employing generative modeling concepts in a parametric design environment allowed for the development of the Smart Cloud of Points entity [5]. This entity stores a parametric behavior pattern which is coded as a forth coordinate referred to as “i”. Activating the behavior pattern drives the points through a generative modeling sequence that results in a parametrically controlled point-cloud. Changing the value of the “i”-coordinate transforms the point-cloud and regenerates it (Figure 3).

The modeling sequence is stored in a generative DNA matrix (GDNA) containing the parameters of the behavior algorithms and the association to the cloud of points. Figure 4 demonstrates a generative modeling sequence that takes place by altering the original point-string shape, and regenerating the point-cloud model according to the behavior patterns shown above.

Box Faces: 1-2-3-4, 5-6-7-8, 1-2-5-6, 2-3-6-7, 3-4-7-8, 1-4-5-8
This allows for a complex-geometry shaping process resulting in a sinusoidal parametric loft surface. The behavior pattern for each point is defined by the "i"-coordinate value while the transformations magnitude is defined by the values assigned in the GDNA matrix. Modifying the parameters of the behavior algorithms allows shaping the point-cloud in a controlled manner. Using the proposed model, various families of design alternatives can be explored. The GDNA and the "i" coordinate permit to regenerate and alter point-cloud models in a non-linear way, transforming it from one typology to another.

The behavior pattern stored in the GDNA matrix layer together with the i-coordinates, create the map of the Smart Cloud of Points’ model logic (Figure 5). This map visualizes the internal representation of the smart cloud of points and provides the foundation for understanding the innovation behind this modeling approach. Unlike the traditional feature-tree model approach that employs hierarchical logic (where every child has a single mono-logic parent), the proposed model offers a poly-logic relationship array, where at every point two or more parent trees can intersect. The resulted connections are of a rhizomatic nature.
3. The puppeteer metaphor

Working under the constraints and limitations of CAD tools is quite frustrating. The ability to create a CAD model of one’s design ideas is not yet as immediate as a hand drawn sketch. The long quest for digital sketching tools, started in 1963 with the digital napkin project [6], produced many ideas and tools exploring this man-machine interaction. The human-computer interaction in digital design environments can be metaphorically equated to the art of puppeteering. Puppeteers design not only the puppet, but also the control mechanism to operate it (Figure 6). Wiring the two allows the puppeteer to perform the act. This metaphor can be interpreted by designers in several ways according to their computation skills. A designer with basic CAD skills feels like a puppet controlled by the CAD vendor, while a designer with computer programming skills feels like the puppeteer driving his design model with the CAD tool as the control interface. Most CAD systems today are open systems, allowing designers with programming skills to script their own design tools and customize their design environment.

The following sections will discuss the development of parametric point-clouds, a simplified parametric control interface that allows designers to puppeteer CAD models.

4. A novel parametric approach

The development of parametric point-clouds started with observing modeling methodologies in architectural design. Parametric modeling in architectural design typically refers to constraint-based modeling, an approach adopted from the mechanical CAD industry. This approach requires rationalizing the design, which sometimes occur prematurely in the
design process and may result in fixation. Operating constraint-based parametric systems in a 3-dimensional space is a very complex task, and therefore most tools support only planar constraints. In such a system, a spatial form can only be defined by connecting several planes. The level of complexity involved in operating these tools would make it impossible to handle the extensive amount of relationships between the points of a point-cloud. Therefore, developing parametric point-clouds require a new approach.

5. From 3D space to n-dimensional matrix

Points-clouds can be employed as design media at any stage of the design process. We can generate points computationally as described previously, digitize an existing object or capture points from CAD models in an ordered fashion. All these processes provide an ordered point-cloud that has a given resolution and enables us to define relationships between its points according to the location within the resolution matrix (the row and column numbers provides a fixed address for each point just like a pixel in our computer screen). Any given point-cloud can be re-sampled as an ordered point-cloud by simply projecting a grid through it, resulting in a dual-layered matrix describing the altimetry and bathymetry of the original object. In this case, the resolution of the point-cloud matrix is derived from the projection-grid size (Figure 7).

Using low-resolution sampling would ease the control issue but reduce the accuracy. The ability to resample the point-cloud at any given time throughout the design process, allows the designer to choose the resolution that fit the task and design stage.
The result of the sampling operation, visualized as a bar-histogram, provided a simplified representation of the design-model parameters. This led to the development of histogram matrices as an interface for 3D modeling [7]. The histogram provides a simplified unfolded interface which allows creating and managing parametric values and relationships between the points of a point-cloud. Unfolding the parametric values read from the ordered point-cloud into a rectangular matrix of the same dimensions, allows creating mathematical relationships between the values assigned to each point of the cloud. This creates a parametric point-cloud equipped with a simple interface enabling to define and edit relationships between its points. The relationships can be of a mathematical, geometrical or performative nature. The histogram interface includes a numerical and graphical representation of the data, providing a rectangular map where each point in the histogram matrix is positioned according to its order in the point-cloud. The histogram matrix provides an abstract description of various relationships between points' properties in an ordered point-cloud.

6. Generative parametric point-clouds

We refer to D’Arcy Thompson’s study of natural genesis of a form to illustrate the potential in using parametric point-cloud as a design media. Thompson’s study of the Callimima is applied here to generate a parametric spherical tetrahedron [8]. We start with creating a pyramid using a triangular shape sampled with 49 points. This point-string is extruded along its center of gravity generating 13 profiles. Scaling the base shape along the extrusion resulted in a parametric point cloud of 637 points defining a tetrahedron. The generation parameters of the point-cloud allow regenerating various alternatives by changing the extrusion, scaling and twist factors (Figure 8).

Unfolding the Y-coordinate values as a histogram matrix allows introducing parametric deformation to the pyramid extrusion, for example,
applying parametric equation \( Y_n = Y_{n-1}^2 \) to the unfolded matrix (Figure 9). Applying the same rule to the X-coordinate values will result in a skewing effect that correlates with the parametric equation: \( X_n = X_{n-1}^2 \).

We scale the point-cloud relative to its center of gravity and document the distance between the resulted points to their origin. This results in a dual point-cloud structure of paired points. Unfolding the distance values as a histogram matrix reveals the spherical ratio on each face of the pyramid (Figure 10).

When assigning an equal projection distance to the points, the spherical ratio is revealed in the form itself. The graphic representation of the internal geometric relationships is suggested here as a parametric control interface that allows exploring the design model further. The unfolded representation provides an interface for driving transformations to the 3-dimensional model in a controlled fashion. In this case, the matrix-histogram allows...
controlling the offset distance for every point in the model, using an unfolded representation that correlates with the point-cloud order. This provides a simplified graphic interface for a complex parametric-control issue (Figure 11). Using the histogram matrix interface, the data can also be edited numerically in a tabular form.

The parametric point-cloud, presented in this paper, provides unfolded interfaces for driving spatial transformation in a controlled manner, developing various typological alternatives. The ability to explore various typologies and drive topological transformations to the design model provides a powerful design tool, as shown in the next section.

7. Case study: learning from London

One of the latest contributions to the London skyline demonstrates morphogenetic architectural thoughts. The twisted gherkin on 30th St. Mary Axe, by Foster and Partners, exposes a spiraling atrium emphasizing its structural growth pattern [9]. Studying the building envelope growth, we notice the analogy to botanical structures and patterns like the Sunflower and Pine Cone; both contain a bi-directional spiraling pattern that creates a diamond grid notion. Tracing the building section with points and revolving it about a vertical axis resulted in a 3-Dimensional point-cloud representation.

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of the overall form. Driving a secondary rotation factor through the horizontal sections of the form introduces a spiral growth pattern within the point-cloud (Figure 12).

The formal analysis provides a high degree of parametric control over the overall shape and allows exploring various typologies by driving the model points through the behavior algorithms at various magnitudes (Figure 13).

Offsetting the points to form a rib structure allows introducing performative aspects as parametric design drivers. For example, a structural analysis can be mapped as a parametric driver for the structural depth of the envelope structural cage. Summing up the structural depth and the components layout, both represented as matrices, resulted in a performance driven layout for the components distribution along the building envelope. We employ a point-based component population algorithm using the resulted matrix as a layout to generate the structural cage envelope (Figure 14).

Satisfying the structural requirements resulted in an even building envelope. Calculating the solar exposure of the building skin and using it as a performative design driver, introduced a directional transformation to the building envelope. Figure 15 shows a solar exposure study that was used for defining the depth of the triangular cladding section of the structural cage as an integrated shading device. Combining the two performative aspects introduces a calculated distribution of structural members which provides optimized shading for the building skin (Figure 16).
Additional performative aspect can be added by simply mapping the performance results in a tabular matrix of the same dimensions as the unfolded building envelope. The multi-layered matrix interface of the parametric point-clouds allows introducing a performative evolution process, providing the designer with simple tools performing complex modeling tasks. Each performance matrix-layer can be considered as an additional dimension of the design model providing the performance data for any given location specified by a 3-dimensional point.

Figure 14: Applying structural analysis as a design driver using a matrix histogram.

Figure 15: Applying solar exposure analysis as a design driver using a histogram matrix.

Figure 16: Left: 3D generative model, Middle: 4D – structural performance driven envelope, Right: 5D – structural and solar exposure performance driven envelope.
8. Conclusions

This paper presented how parametric point-clouds employ histogram matrices as a parametric control interface that unfolds and simplifies the design complexity. This approach corresponds with the way complexity in general is captured by cognitive science as a multi-layered problem. The parametric relationships embedded within the design model are unfolded into a set of schematic histograms and tabular interfaces which allow handling each layer of the complex model separately. The first layer of the design model contains the point-cloud coordinates ordered in a tabular matrix. This matrix provides an unfolded representation of the design model and provides an identifier to drive direct manipulations to the 3-dimensional design model. Any parametric relationship assigned to the point-cloud model can be represented as an additional control-layer, automatically unfolded into a tabular matrix and a histogram. This representation simplifies the interaction with the design model, making parametric design more accessible and reduces the need to operate the design model in 3D space. The ability to assign and create relationships between various design aspects from spatial coordinates to performative analysis allows designers to adjust their tools as well as the objects they design.

The points of the parametric point-cloud, as presented in this paper, can be used as place holders for populating the design model with pre-defined components. This way the parametric point-cloud acts as a design operator driving the generation of parametric components according to generative and performative parameters. The point-cloud geometry can be extracted from an existing design model embedding parametric relationships at any given time throughout the design process with no set backs. Storing the behavior and performative data within the point-cloud provided a foundation for developing a design environment that supports the n-dimensional complexity as a multi-layered matrix. This embedded logic assures that the alterations of the design model yield design alternatives according the requirements stated within it. The multi-layered matrix, as demonstrated in this paper, provides a simple control interface for the spatial complexity of an architectural design task.

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