Material-Based Design Computation: Tiling Behavior

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ABSTRACT
From natural objects to man-made artifacts, tiling is all around us: it is the act of rationalizing highly complex form by breaking it up into smaller, continuous components. If well pursued, tiled objects can be easily designed and assembled. However, a geometric-centric view of tiling, whereby a predefined form determines the shape, size, and organization of tiles, has victimized the field of digital design. This paper questions the role of tiling as rationalizing method and offers an alternative theoretical framework and technical grounding for tiling behavior: the act of generation-through-tessellation informed by material behavior. The tools developed are implemented in the design of a 3D-printed chaise lounge, using multiple materials. The technical objective is to introduce a quantitative characterization and analysis of property mapping, as it is applied to a tiling algorithm using Voronoi cell tessellation. The network of tessellated Voronoi cells is used as an element in the Voronoi Finite Element Method (V-FEM) that the author developed. Various characterization functions and geometric parameters are generated, and V-FEM is executed for plane-strain analysis of doubly curved surfaces, from which global and local responses are evaluated.

1 INTRODUCTION
Patterns in nature often inspire textures and patterns in architectural design. However, in the synthetic world, geometrical considerations traditionally define tiling choices, followed, after the fact, by behavioral constraints and material choices. This paper proposes a material-based approach to tiling, whereby each tile,or group of tiles, represents different mechanical and, potentially, environmental properties as an integral part of the form-generation process.

1.1 MATERIAL-BASED DESIGN COMPUTATION
Current CAD applications, including associative modeling software packages, appear frequently to promote generative approaches to design (Shea 2003). Rather than treating the computational media as merely representational, the designer is now able to establish parametric relationships between features, methods, and functions in a way that supports design processes of a generative nature. However, geometrical considerations, mainly, currently drive this liberation, which seems to be manifesting itself across the board throughout the continuous phases of the design process. Generative performative modeling approaches have been introduced that engage principles of engineering with form finding. Yet, even when integrating performance factors and tools that are significant in determining architectural form, material organization and behavior are already predetermined design constraints and predefined factors. Form finding, in the digital realm, is thus restricted to the relationship between structure and geometry (and/or fabrication); it does not generally incorporate, and support, the expression of material properties, organization, and behavior (Oxman 2008).

Defined by the author as the process of computationally enabled form-finding, informed by material properties, Material-based Design Computation promotes an integrated approach to design, whereby material properties inform the geometrical generation of highly complex 3-D surface structures (Oxman 2007).

This approach allows the designer to incorporate the mechanical (along with other types of) properties in the process of form generation. Early work has demonstrated the theoretical and technical potential of this approach through design experimentation and tool generation for stretchable fabrics and light-omitting surfaces (Oxman 2007).

1.2 TESSELLATION: PRECEDENTS

Tessellation—defined as the process of subdividing a surface into continuous, smaller elements that are geometrically congruent to their neighbors—appears to be a problem of great significance in Material-based Design Computation. This is due, namely, to its basic formulation as a geometric manipulation informed by formal constraints rather than behavioral data.

The work presented aims to establish the actions of surface tessellation as a process rudimentary to form generation by claiming that tessellation algorithms could and should include physical data that is expressed geometrically. By considering parameters such as variable stiffness and tactility as functions informing the design of complex form, the work offers a theoretical and technical approach to tiling behavior.

Precedents pointing towards Material-based Tiling exist mostly as procedural protocols written for the analysis and optimization of form after it has been generated. Such computational research is generally found in the areas of optimization and visualization (DeHaemer and Zyda 1991) and focuses on issues of shape interpolation, namely, on the development of robust methods for connecting new vertices over given surface representations, and on methods for smoothly interpolating between models that represent the same object at different levels of detail (Turk 1992). The key notion is that of a re-tiling procedure that involves the creation of intermediate models, called the mutual tessellation of a surface, that contain both the vertices from the original model and the new points that are to become vertices in the re-tiled surface (Turk 1992).

Related work in computer science and visualization includes vector-field visualization and segmentation using centroidal Voronoi tessellation (Du and Wang 2004). In this method, the generators of the Voronoi regions in the tessellation are also the centers of mass with respect to a prescribed density. A distance function in spatial and vector spaces is developed to measure the similarity of spatially distributed vector fields. In this case, the tessellation assists in the analysis, simplification, and visualization of an existing material substance and its related vector fields. The method offers the generation of tessellated patterns a-priori or in parallel to form generation, such that geometrical properties inform physical attributes and vice versa.

Specialists in the field of computer science had previously reviewed a large body of literature on automatic mesh generation for use in Finite Element techniques (Ho-Le 1988). In most of the cases examined, the aim was to subdivide the surface area or volume of a given object to provide a mesh, over which some physical properties of the material, such as heat dissipation, stresses, and strains, could be simulated. Here, once more, the application of physical properties is applied for the purpose of analysis rather than the synthesis of form.

The field of computational geometry has also seen a good amount of work dedicated to tiling problems (Du and Wang 2004). Specifically, the properties of Voronoi regions and the associated Delaunay triangulation are relevant to establishing heterogeneous sizing hierarchies between triangular elements in the depiction of highly complex 3-D form (De Floriani et al., 1985).

Digital design as a whole has experienced a renaissance in tiling through advancements in computational geometry and implementation of associative modeling strategies in design (Kajima and Michalatos 2008). However, the question of how to extend the function of tiling beyond its role as a post-rationalizing strategy in the geometrical domain remains ill-developed.

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2 TILING BEHAVIOR: MATERIAL-BASED TESSELLATION

The work presented here introduces the notion of tiling behavior as a theoretical framework, a methodological setup, and a technical approach that extends its role as rationalizing technique beyond geometrical representation. This work demonstrates tiling behavior through the development of computational tools that include material properties and their assignment to corresponding structural and environmental performance data.

2.1 CLASSES OF SURFACE TESSELLATION

The breaking up of self-intersecting polygons into simple polygons is called tessellation, or more properly, polygon tessellation. There are exactly three regular tessellations composed of regular polygons that symmetrically tile the plane. Tessellations of the plane by two or more convex regular polygons, such that the same polygons in the same order surround each polygon vertex, are called semi-regular tessellations, or sometimes, Archimedean tessellations. In the plane, there are eight such tessellations. Simple and relatively known examples of surface tessellation are square and hexagonal tiling. Examples that are more complex include Penrose tiling; randomly colored, uniform polygon tiles; or hexagons and pentagons that compose a Buckminster sphere. I distinguish between tiling of regular polygons (in 2D), polyhedrals (in 3D) and polytopes (for n dimensions).

I propose four discrete approaches to surface tessellation, defined by the guiding content for the tessellation. Such classification includes curvature-based tessellation, performance-based tessellation, assembly-based tessellation, and material-based tessellation.

2.2 CURVATURE-BASED TESSELLATION

Curvature-based tessellations are tessellations informed by the geometrical features of the surface. Examples include the transformation of polygonal-size variation as a function of the type and degree of curvature: smaller polygons are allocated in regions of sharp curvature, whereas larger cells are allocated in regions of low curvature.

2.3 PERFORMANCE-BASED TESSELLATION

Performance-based tessellations are tessellations informed by a set of governing performance criteria such as the type and magnitude of mechanical loads or heat flux. In this case, the variation of cell size and density is a function of force vectors that emulate the magnitude and direction of the structural load. Geometrical features on the hosting surface demonstrate such functions. For instance, smaller polygons are allocated in regions of higher stress in order to increase the surface area that connects the elements, and larger polygons are allocated in regions of lower stress.

2.4 ASSEMBLY-BASED TESSELLATION

Fabrication constraints define assembly-based tessellation: in the case of repetitive fabrication, in which the size of each polygon edge is equal to all others, the polygonal tiling would be symmetrical across all directions. In other cases, the number of discrete measurements defined by the logic of assembly informs cell size and distribution.

2.5 MATERIAL-BASED TESSELLATION

Material-based tessellation assigns physical features to geometrical entities such as stress, strain, temperature flux, etc. In this case, mechanical material properties govern the relative form, size, and density of the cells. This class is different from all other classes as it relates to the substance of the surface as a heterogeneous curvature domain. The location of a finite set of heterogeneities, defined by mechanical behavior, informs the tessellation. Each heterogeneity has a polygon, or a group of polygons, associated with it. The mechanical properties ,as defined by the user, inform the spatial distribution of heterogeneities.

Naturally, there could also be combinations of the classifications above, whereby a polygonal map, for instance, is defined by both the surface's curvature degree and its assembly logic.

3 METHODOLOGY

The research demonstrates the notion of behavior tiling through the design, analysis, and fabrication of a chaise lounge, created by the incorporation of physical parameters into digital form-generation protocols.

A single continuous surface acting both as structure and as skin is locally modulated to cater for structural support on the one hand and sensual relief on the other. The chaise combines structural, environmental, and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility, and translucency to load, curvature, and skin-pressured areas respectively. Multiple algorithms are generated that correspond to these variables, such that stability is mediated with the sense of pleasure upon surface contact, and structural integrity, with visual and sensual experience. In this light, the chaise celebrates the negotiation between engineering and experiential performance. It is a method as much as an object of pleasure that promotes material and structural integrity with the physical act of sitting and lying down against a hard-soft surface.

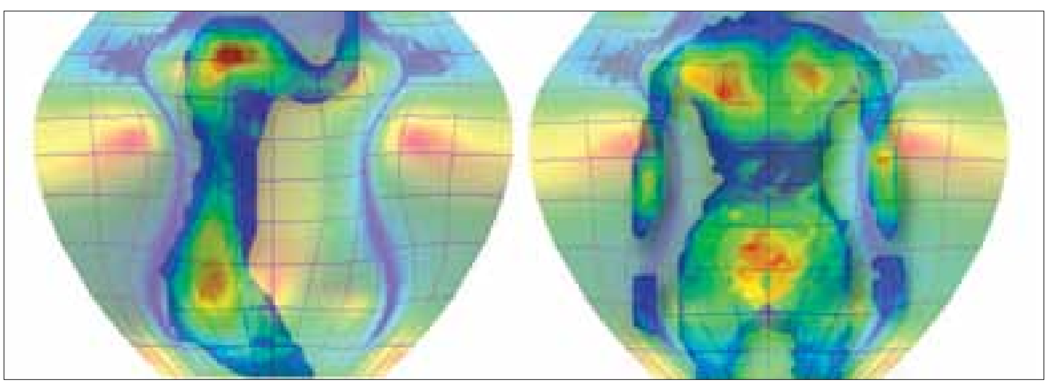

Figure 1 Chaise design informed by material properties assigned to pressure map registration, body form, and body weight

4 TILING BEHAVIOR: IMPLEMENTATION IN THE DESIGN OF A CHAISE LOUNGE

4.1 INTRODUCTION

The project presented here represents a case study for the design of a chaise lounge that demonstrates the notion of tiling behavior. The traditional chaise is transformed to promote lounging of a different kind. The cellular pattern applied to its entirety is designed to increase the ratio of surface area to volume in areas where the body potentially rests. A pressure map study is conducted that matches the softness and hardness of the cells to cushion and support sensitive and high-pressured areas.

By analyzing anatomical structures that cause concentrated pressures, the chaise becomes softer and flexible where pressure needs to be relieved (fig. 1). The relative volume of each cellular cushion is locally informed by pressure data averaged with values that represent structural support and flexibility. Global and local mean curvature values inform its density, such that denser, smaller cells are organized in areas of steep curvature, whereas larger cells are found in areas of shallow curvature.

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The chaise's natural relation of structural and sense datum is propagated in variable polymer composites, offering a wide range of physical properties. Through these algorithms, force conditions naturally propagate functionality. Stiffer materials are positioned in surface areas under compression, and softer, more flexible materials are placed in surface areas under tension. State-of-the-art technologies are applied here for the first time to cater for a large range of physical properties and behaviors. The surface patches are printed in 3-D, using a new multi-jet matrix technology, which simultaneously deposits materials of different properties, in correspondence to structural and skin-pressure mappings.

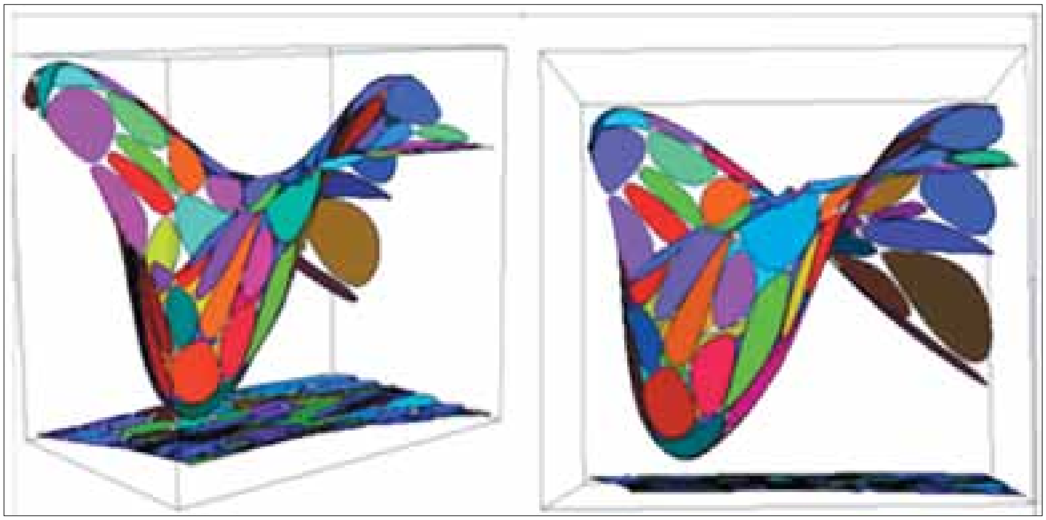

Figure 2 Example of Voronoi construction with a vertical projection. The tile squeezing correlates to the angle between the surface normal and the projection vector.

4.2 VORONOI TESSELLATION: INTRODUCTION

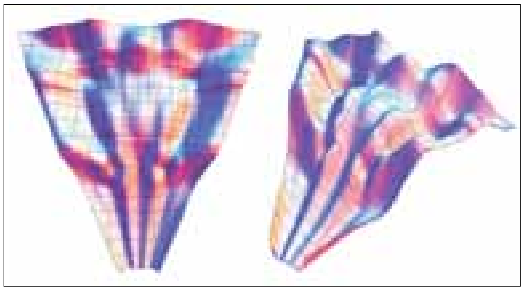

Figure 3 Point cloud density representation mapped from curvature

Voronoi tiling appears in disparate fields (Turk 1992). In this method, each tile is defined by the set of points that lie closest to each generated point (i.e., a hexagonal tiling derives from a hexagonal lattice of generating points). Many algorithms exist that produce simple versions of Voronoi tessellations from point clouds. Fast Voronoi algorithms have been developed with computational geometry techniques, but the computations are generally time-consuming.

A Voronoi tessellation is an example of a tiling generated by a random point process, in which the tiling develops algorithmically from points that appear on a surface by some random or informed process. In most cases, a homogeneous, uniform, random distribution (also called a Poisson process) generates the points. In such a uniform process, no position is favored over another: the Voronoi tiling segments the object at the length scale of the average distance between points. As a result, the tiling is homogeneous when averaged over larger distances. However, the Voronoi tessellation need not derive from such a uniform, random process.

The object in fig. 2 is an example: the individual texture components (i.e., the SPline loops) derive from a Voronoi tessellation, but the point cloud density is a function of the object's local geometric curvature, demonstrating the concept of curvature-based tessellation. In this case, because local stiffness and tactility depend on local tile size, the object's geometry is intrinsically coupled to its material behavior, and as we shall explain, the converse is also true.

4.3 VORONOI TESSELLATION IN CURVED SURFACES

Because the Voronoi definition includes a distance function (i.e., "closeness" is a comparison of distances), the Voronoi construction depends on what is meant by distance. In the simple case of a Voronoi construction on a two-dimensional plane, the common choice is the Euclidean distance √ (d = x2 + y2, also called the L2-norm), but there are an infinite number of ways to define a distance. For the Euclidean distance, the Voronoi tiles are all polygons, for which each shared polygon edge is (a segment of) the perpendicular bisector of the ray that joins the generating point centers of the two tiles. The set of all rays connecting neighboring Voronoi centers is a skeletal structure that is "dual" to the Voronoi construction, and is called a Delaunay triangulation. However, the resulting polygonal structure is particular to the definition of distance.

On curved surfaces, such as the uniformly curved sphere, the definition of distance is generally complicated as the tile edges have out-of-surface curvature. For non-uniformly curved objects, the distance definition, and the algorithms to find their corresponding tessellations are complex and typically undeveloped. In these cases, tile edges have non-uniform in-plane and out-of-plane curvatures.

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There are methods to use a simplified distance metric to produce a Voronoi tessellation on a curved surface. An example follows (fig. 3). A point cloud can be generated on the vertical projection of a surface, or a point cloud on a curved surface can be projected vertically to a plane. In the first case, a uniform cloud distribution on the plane produces a non-uniform point cloud on the surface; in the second case, a uniform point cloud on the surface produces a non-uniform cloud on the plane. In either case, the Euclidean algorithm can be used to produce a Voronoi tessellation on the projected plane, and that tessellation can be projected back onto the surface. Such methods are possible on limited surface types (i.e., graphs of the form z = f(x, y)). The surface's angle of inclination from the vertical produces the non-uniformity of the point cloud: points become arbitrarily close in regions where the surface approaches verticality.

The choice of algorithm may potentially have property-related consequences. Figure 4 illustrates the effects of this algorithm. A full implementation of an L2-norm on a U and V coordinate system embedded in a surface of the form {x(u, v),y(u, v),z(u, v)} would be computationally prohibitive. An algorithm that approximates this norm produced the final object.

In figure 4, note the density increase at regions of large squeezing. The illustrated solution: a uniform point cloud on the 3-D surface is a non-uniform cloud on the UV plane. The Voronoi construction in the UV plane produces odd-looking cells on the UV-plane but uniform Voronoi on the 3-D surface.

Figure 4 Example point cloud producing UV-squeezing

V-FEM: WEIGHTED MATERIAL SELECTION

During the initial stages of the design, the texture inherits the geometrical features of the design as defined by the user. Such geometrical features, in the case of the chaise, are customized to fit body curvature criteria. The initial distribution of cells corresponds to the type and degree of curvature: smaller, denser cells are located in regions of high curvature, and larger, sparser cells are located in regions of low curvature. Material properties correspond to both structural requirements (self-stability with no additional enforcement members) and environmental requirements (assigned to the body pressure mappings). For the structural performance, a stochastic computational process was developed, in which stiffer materials are assigned to vertical regions, which work for buckling, and softer materials are assigned to horizontal regions, which work for bending (fig. 5). The probability of a material being stiffer or smoother depends on the angle defining the level of horizontality in the chaise.

Regarding the environmental requirements, the degree of pressure mapped onto the chaise defines the relative height of each cell, such that softer and bigger silicon bumps are located in regions of higher pressure (fig. 6).

FABRICATION

The chaise was fabricated using a multi-material 3-D printing technology. Thirty-two sections were assembled, each comprised of five material combinations ranging in stiffness from hard to soft.

EVALUATION

Fabricated as a scaled prototype, this project is potentially under way for mass manufacturing. In considering assembly in full scale, some rigorous evaluation processes must be accommodated for. In the case of the current scaled build, the model was fabricated from photopolymers, which mimic the properties of polypropylene. It simulates toughness (Izod notched impact of 44.22 J/M), flexibility (elongation at break of 44.2 percent) and strength (elastic modulus of 1,135 MPa) of polypropylene. Such materials appear to be incredibly robust for the generation of small-scale models and some implementations in product, and industrial design. However, since most of these technologies are developed for prototyping purposes, material fatigue may prohibit full-scale development. In which case, there appears to be significant need for the development of robust materials that can pass for structural loading cases that match FEA simulations and functional testing.

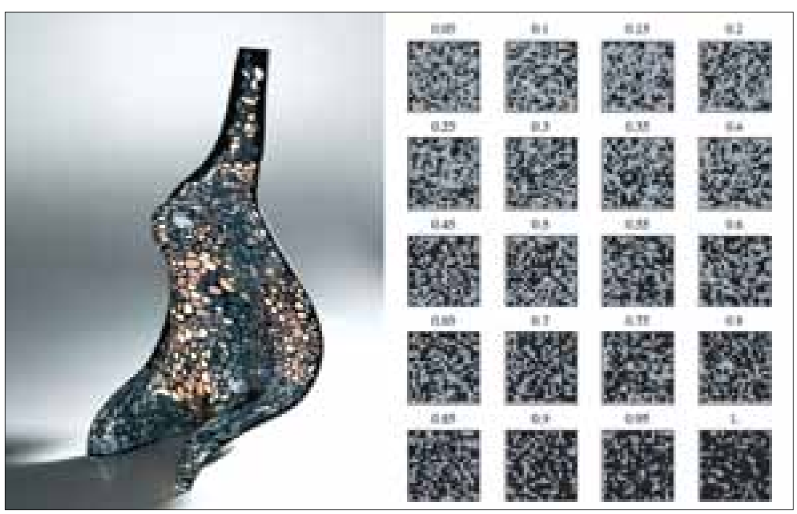

Figure 5 Weighted material selection: a stochastic computational process assigns a stiffness ratio corresponding to structural performance

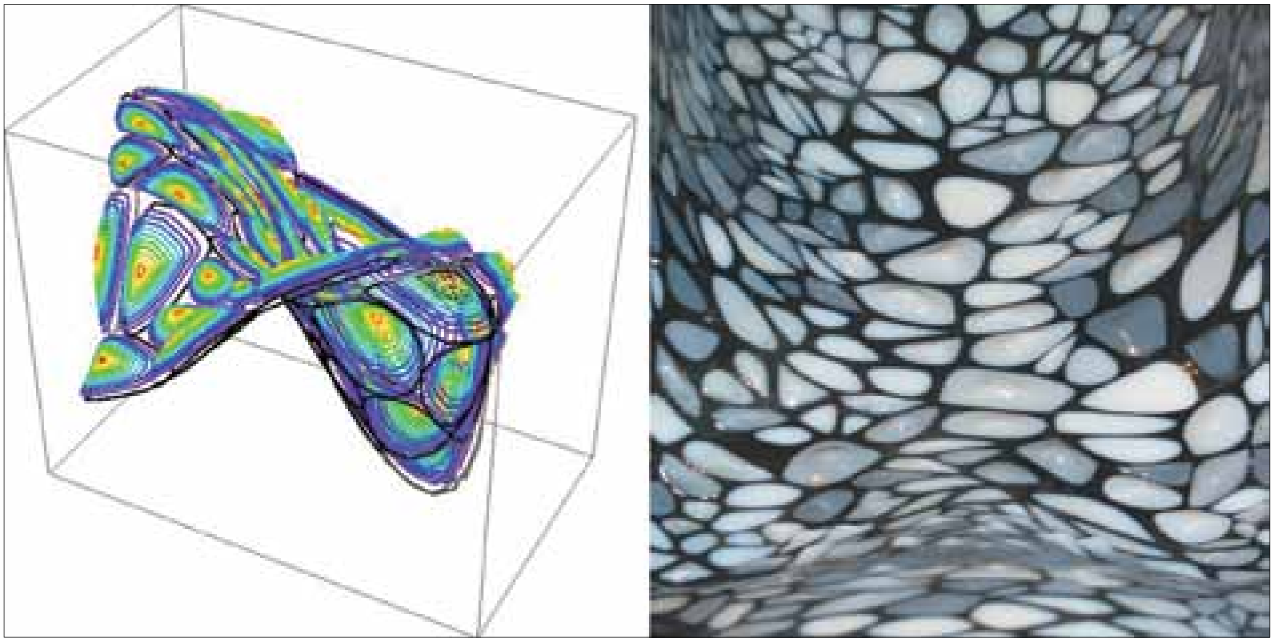

Figure 6 Weighted material selection: a stochastic computational process assigns a stiffness ratio corresponding to environmental performance. The relative height of the soft silicon bumps corresponds to the body pressure mappings.

Figure 7 3-D assembly model comprised of 32 sections for multi-material printing

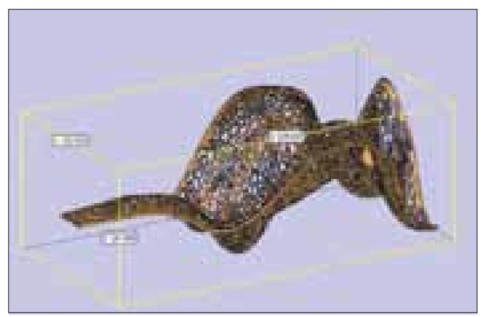

Figure 8 3-D printed parts illustrating assembly logic