Tableware Shape Grammar

Towards mass customization of ceramic tableware

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Abstract. *Mass customization is pointed as a means of improving a company's competitiveness, which is an essential trait in Europe's economic situation of today. This paper reports a mockup implementation of the mass customization paradigm to ceramic tableware design, through the use of shape grammars, parametric modelling and rapid prototyping. Focus is emphasized on the initial development of a parametric shape grammar as a design system, operating on curved surfaces and solids. Mapping operations are suggested for dealing with the formal complexity of these shapes. This initial academic experiment poses as a first step into the development of a mass customization system that is expected to meet industry standards.*
Keywords. *Mass customization; ceramic tableware; generative design; shape grammars; rapid prototyping.*

INTRODUCTION

Research is currently being developed towards the application of the mass customization paradigm to the design and production of ceramic tableware. The experience documented in this paper represents a first mockup of the framework necessary for the implementation of such paradigm. The ultimate objective is that end users can create their own, highly customized, tableware set.

According to Duarte (2008), the implementation of a mass customization system implies development on three fronts: a design system that encapsulates the stylistic rules of tableware elements, generating the corresponding digital models; a production system that allows to automatically materialize those models into usable tableware elements; and a computational system that implements the design system and articulates it with the production system.

According to Pine (1993), mass customization can improve a company's competitiveness, allowing it to offer differentiated products to its customers. This research is thus intended to be applied to an industrial context, through collaboration with a local ceramics company.

Methodology

A small scale implementation of the mass customization paradigm was tested as an exercise, in a semester long course about shape grammars. In this exercise, the shape grammar apparatus, invented by Stiny and Gips (1972), was used as a design system, encoding the rules for the shape generation of ta-

bleware elements into a parametric shape grammar. This paper will focus mainly on this design system.

Subsequently, parametric models corresponding to derivations of the shape grammar were implemented using the visual programming interface Grasshopper. The implemented system allows the user to combine shape rules and manipulate its parameters, generating derivations of the tableware elements and the corresponding digital models.

Finally, these digital models could then be automatically produced using powder-based 3D printing equipment.

Application of shape grammars to three-dimensional curved shapes

Although the original shape grammar has been developed for straight line shapes (Stiny, 1980), some authors have used this tool to work with curved shapes, which are predominant in tableware design.

Knight (1980) developed a shape grammar on Hepplewhite-style chair-back designs. While deriving the chair-back shape mostly in terms of rectilinear elements, in the final designs they are replaced by the typical curved shapes in a descriptive procedural fashion.

McCormack and Cagan developed work on branding of automobiles, namely a shape grammar for generating the front-end view of a Buick (McCormack et al., 2004). In this two-dimensional shape grammar, curved lines are used extensively. The curved lines are controlled by parametrically positioned control points. Although it is not explicit, these curves seem to be Bézier curves. A similar strategy will be used in the definition of the profile curve of the base shape of the tableware elements.

Around the same time a shape grammar is developed that features curved shapes, using both straight lines and circular arcs to generate the bottles of Coca-Cola and Head & Shoulders (Chau et al., 2004). Despite mentioning research towards the generalization for NURBS curves, it is not present in this research.

This issue was addressed by Jowers and Earl (2011), who have developed and implemented a curved shape grammar for generating Celtic knots, using quadratic Bézier curves. Their research focuses mainly on the problem of shape recognition and emergence, which is a typical research problem when implementing a shape grammar into a computer program.

Although an implementation was developed in this exercise in order to test formal aspects of the shape grammar rules, it is not the grammar itself that has been implemented, but rather parametric models that correspond to specific derivations of the grammar. Different derivations can be generated, but it is the user who must directly manipulate the rules, selecting the ones to be applied. Therefore, issues like shape recognition and emergence, which are typical of shape grammar implementation, will not be addressed for now.

So, although some work has been developed on shape grammars of curved shapes, these shapes are mostly linear. Research on shape grammars applied to surfaces is still sparse. We hope that this research can contribute to fill in this shortcoming.

DEVELOPMENT OF THE SHAPE GRAMMAR

One of the objectives of this research is to develop a shape grammar that is able to encode the styles, regarding both shape and decoration, of different collections of tableware sets. However, for this first exercise, the goal was set to develop a shape grammar that would encapsulate the style of one collection (Figure 1). The shape grammar should automatically generate the different elements of the selected collection, taking into account that it would be subsequently extended to other collections.

Element types

Even before focusing on any specific collection, a reflection was made on the different types of tableware elements. A first observation on the dimensions of these elements led to establishing a distinction between deep and shallow types. The shallow type category includes the charger plate, the dinner plate and the soup plate, while the deep type cat-

Figure 1
Shape grammar corpus.

egory includes the bowl, the mug and the cup.

Types in the same category were considered formally similar among each other, differing only in terms of dimensions. In the deep type category, if we disregard the handle in the mug and the cup, these types are formally similar to the bowl.

Different types are thus characterized by different sizes, measured both in height and radius. Table 1 illustrates the dimensional relations between the six chosen types within the selected collection, as well as the mentioned distinction between deep and shallow types: in shallow types, radius is larger than height, and so the ratio between these dimensions is higher than 1, whereas in deep types, it is lower than 1.

The shape similarity among types within the same category is interpreted as a parametric variation of the same entity, justifying the development of a parametric shape grammar.

Functional parts

This first observation has also brought attention to the distinction between functional parts within tableware elements. Let's take the example of the soup plate. Three functions can be identified in its shape: the broad border is used to *hold* the plate; the soup needs to be *contained*, and so the dish must have a deeper part for this purpose; and finally, it needs a broad and flat bottom, so it *lays* steady on the table. So the three functions are: holding, containing and laying on the table.

The functional parts were analyzed in terms of dimensions, namely height and radius. The relations between dimensions of the different functional parts are described by a functional configuration. The functional configuration for the soup plate, systematizing the example given above, is shown in Table 2.

Different types feature different functional configurations. For example, to be able to contain liquids, the soup plate and the deep types feature a taller containing part than the dinner plate.

Generally, all three functions are present in each type. However, in some types they are assigned to parts other than the main body of the tableware element. For example, in the mug or the cup, the hold-

Table 1
Classification and dimensions of the different types in one collection

Type	Charger	Dinner	Soup	Bowl	Mug	Cup
Radius (cm)	15,50	13,50	11,50	7,00	4,50	3,75
Height (cm)	3,00	2,50	4,00	8,50	10,00	5,00
Radius/Height	5,16	5,40	2,88	0,82	0,45	0,75
Category	**Shallow types (plates)**			**Deep types**		

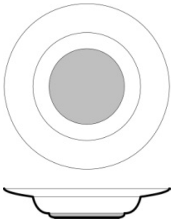
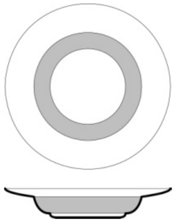
Function	to lay on (ps*)		to contain (ct*)		to hold (pg*)	
						
radius		46%		20%		35%
height		14%		58%		29%

Table 2
Functional configuration of the soup plate (from the portuguese "pousar", "conter" e "pegar", respectively).*

ing function is assigned to the handle. In its current state, this shape grammar is only encoding shape for the main body of the elements. Parts like the handles in the cups and mugs will be addressed in the future.

Further development of the shape grammar will focus its extension to other collections. It is expected that for the same types within other collections, functional configurations, despite featuring some dimensional variation, are somewhat similar, and therefore characteristic of the type. Variations on this configuration are to be registered as other collections are analyzed, and will be properly integrated into the design system.

Initial shape and first derivation steps

This first analysis is incorporated into the first two rules of the shape grammar, which are applied in the beginning of each derivation of a tableware element (Figure 2).

Derivation begins with the initial shape, which is a referential determining the center of the tableware element, as well as the upward direction (h, from *height*) and the outward direction (w, from *width*). The general dimensions of the tableware element are introduced as input parameters of rule 1, which creates an object in which the element is inscribed. This object is called the *envelope* (Figure 3, en). In the two-dimensional view of the profile, the envelope is represented by a rectangle, or more generally speaking, a quadrilateral - since the rectangle will be subsequently distorted, the general term quadrilateral, or quad, is more appropriate.

The initial envelope is subsequently subdivided into the element's functional parts by rule 2, which is parameterized according to the correspondent functional configuration (Figure 3). Rule 2a subdivides the envelope into three functional parts, and can be applied to the shallow types. For the deep types, rule 2b should be applied, which disregards the holding part (pg).

Derivation of the tableware elements can be split into three phases: initialization - which applies rules 1 and 2 as seen above -, base shape definition

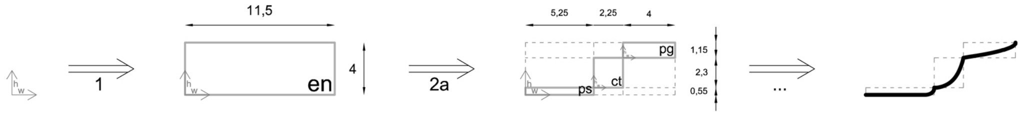


Figure 2
First steps of derivation for the soup plate: envelope creation and functional partitioning.

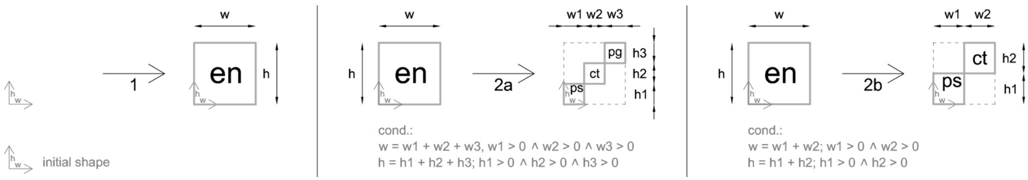


Figure 3
Shape grammar rules for envelope creation and functional partitioning.

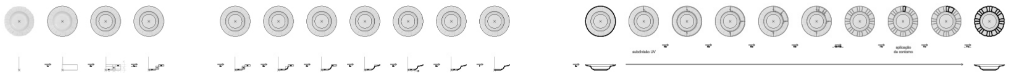


Figure 4
Overview of the soup plate derivation.

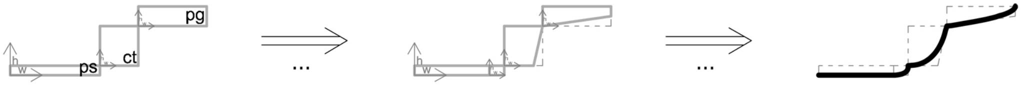


Figure 5
Resumed derivation for base shape of soup plate.

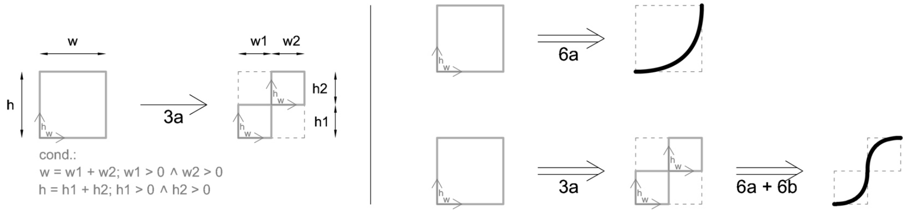


Figure 6
Subdivision rule and example of application: subdivision allows for more complex shapes.

and decoration - which applies subsequent rules (Figure 4). To each phase corresponds a bi-dimensional view, which best illustrates the three-dimensional geometry of tableware elements, as well as the operations applied to them.

Base shape definition

Since the selected collection features circular elements, their base shape can be described as a solid of revolution. Therefore, rules and derivation steps regarding base shape generation are represented by a bi-dimensional profile. For this first approach, the profile thickness is not being considered, and therefore the resulting shape is more accurately described as a surface, rather than as a solid.

The base shape is defined by formal manipulation of the functional parts that result from the initialization phase. In the end, the base shape profile is the product of a combination of quadratic Bézier curves, controlled by their corresponding envelopes (Figure 5). The quadrilateral envelopes are used as auxiliary shapes for defining the Bézier curves inscribed in them.

Therefore, in the base shape definition phase, three types of rules can be applied: subdivision, distortion and substitution.

Subdivision rules in the base shape definition phase (rule 3) are similar to the functional subdivision rules seen previously, the difference being that the resulting envelopes keep the type of the preceding envelope. These rules allow for more complex shapes, through subsequent combination of more than one Bézier curve (Figure 6).

Distortion rules allow to manipulate the quads that correspond to the envelopes, and therefore manipulate the control points of the Bézier curves that will substitute them. Distortion rules can be applied recursively, allowing to generate additional distortions not coded into rules through a compound effect. Figure 7 shows how to obtain this through applying rule 4 recursively and with different transformations - which are shown under the rule application arrow. Parameters are used both for the distortion effect as for the shape matching, and were

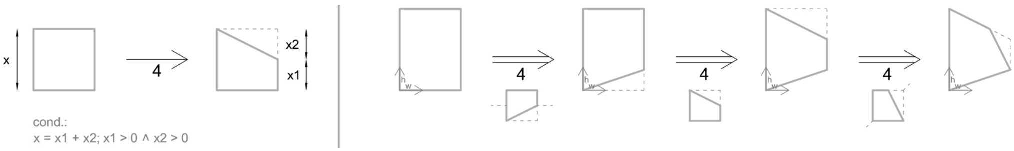


Figure 7
Distortion rule and example of recursive application.

omitted for clarity.

Substitution rules replace the envelopes by their corresponding Bézier curves. For each curve, three of the vertices of the corresponding quad correspond to the curve's control points, whereas the directions of the curve's start and end tangents are defined by the quad's edges (Figure 8).

The rules are allowed to be applied in different order. For example, we can subdivide an already distorted envelope. This is possible because of the parametric nature of the grammar, which allows for perspective transformations (Stiny, 1980). However, the result of applying the rules in a different order is not necessarily the same (Figure 9). In this way, some flexibility is added to the grammar.

Figure 10 shows all the derivation steps for defining the base shape of the soup plate, including the initialization phase. The final step corresponds to the revolution of the profile into a set of surfaces, the actual base shape upon which decoration rules will be subsequently applied.

Decoration

Decoration is achieved through the application of shape grammar rules to the resulting base shape surface set.

Rules for defining the base shape of the tableware element operated on its profile, which is a two-dimensional representation. In the decoration phase, however, and because we are dealing with three-dimensional surfaces, representation of rules and derivations in two dimensions is not straightforward - in fact, neither is imagining them. For this purpose, we make use of the parametric representation of surfaces. In this representation, the Cartesian coordinates of a surface point depend on two different parameters *u* and *v*, allowing for a continuous mapping of a two-dimensional region into space (Pottmann et al., 2007).

A typical example of a parametric representation is a world map. The map's horizontal lines represent coordinates on the surface of the Earth with the same latitude, while the vertical lines correspond to points with the same longitude (Figure 11). Therefore, latitude and longitude can be considered the uv parameters of the Earth's surface. A point with given parameters in the map can be easily and accurately identified using a GPS device. Similarly, lines and shapes can be mapped from the map into the

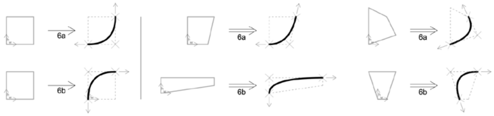


Figure 8
Replacing envelopes for corresponding Bézier curve: substitution rules and examples of its application.

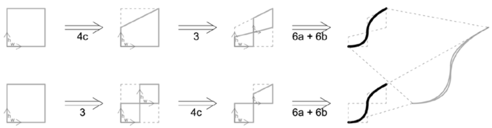


Figure 9
Different sequence order generates different results.

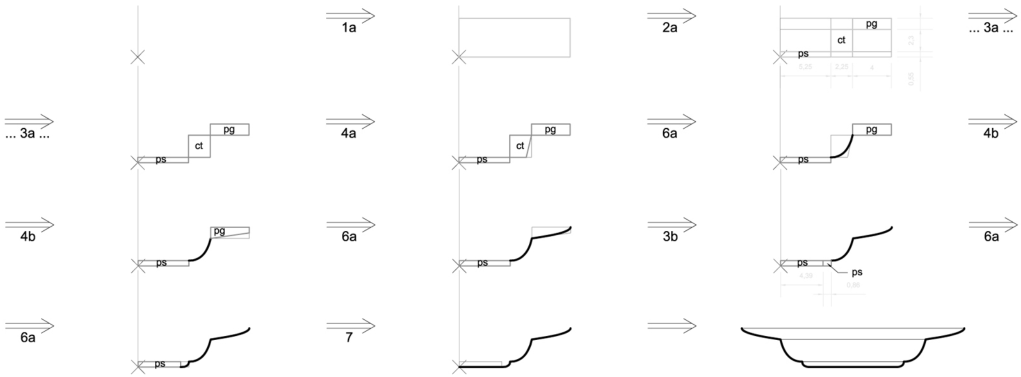


Figure 10
Derivation for base shape of the soup plate.

globe and vice-versa.

These mapping operations are used in the decoration phase. In this phase's derivation steps, the tableware elements are represented in two-dimensional space as top views. In the case of the selected collection, these elements correspond to circular objects, and inherently their parts feature circular arcs. In rule description however, such as in the base shape definition rules, surfaces are represented by squares, a generic shape which evokes the two-dimensional nature of the uv parametric representation (Figure 12).

Therefore, rules are mapped into the design in the same way a shape in a map is mapped back and forth into the surface of the Earth. These mapping operations imply the use of non-linear transformations - transformations that map straight lines into curves (Pottmann et al., 2007) - , which are not usually addressed in the shape grammar formalism. In fact, Stiny (1980) states that "a shape rule **a** → **b** applies to a labeled shape **c** when there is a transformation **t** such that **t(a)** is a subshape of **c**" (p. 347), limiting these transformations to translation, rotation, scale and reflection, which he refers to as Euclidean transformations (p. 344). However, the author points out that for transformations other than Euclidean, such as affine or perspective transformations, a parametric grammar should be used (p. 351).

For the development of this grammar, we are assuming that, similarly to affine and perspective transformations, non-linear transformations can be also be used in parametric grammars. This hypothesis should be later proven in order to validate this grammar.

In the selected collection, decoration is based on a) subdivision of surfaces, and b) application of a relief- and contour-based motif onto the resulting subsurfaces (Figure 13).

Subdivision rules are similar to the subdivision operations mentioned previously, except they op-

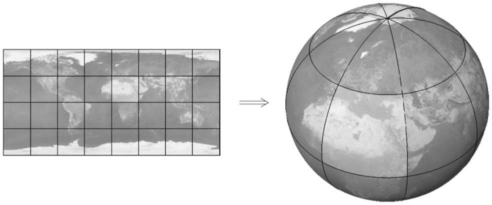


Figure 11
World map as parametric representation of the surface of the Earth (world map from www.free-world-maps.com).

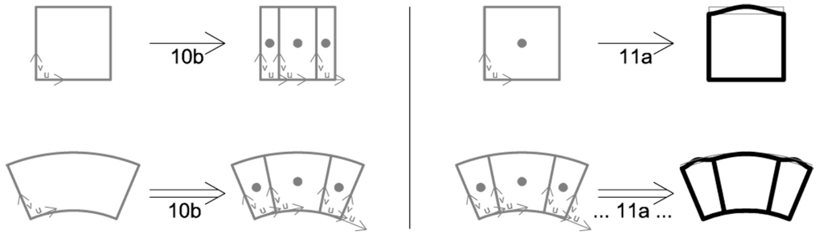


Figure 12
Example of UV mapping: rules are mapped onto surfaces.

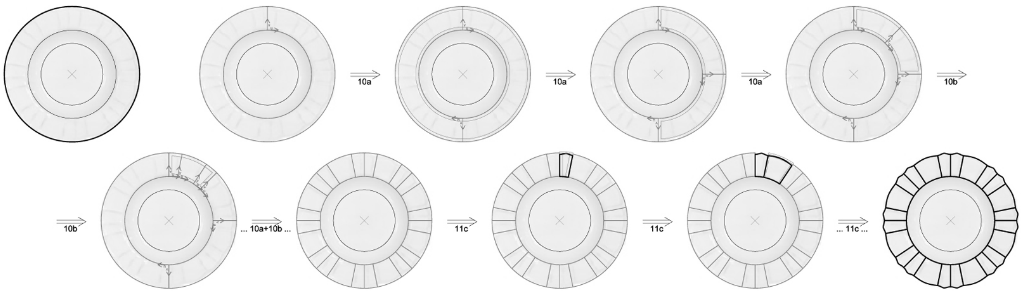


Figure 13
Derivation for decoration of soup plate.

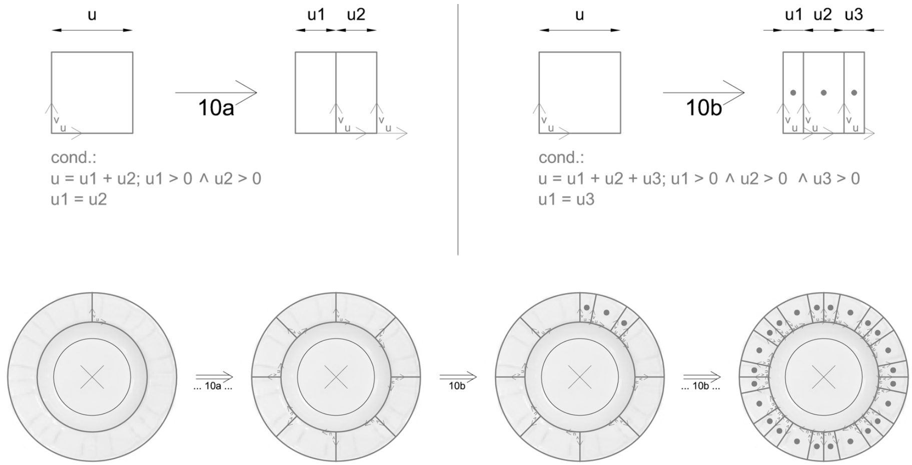


Figure 14
Decoration subdivision rules and application in the soup plate derivation.

erate on the surface's parametric, or UV, space. Rule 10a subdivides the surface into two parts with the same U parameter differential (Figure 14). In the derivation for the selected collection, rule 10a is used recursively to subdivide the plate into eight parametrically equal parts.

Rule 10b subdivides it into three parts, also along U, but in this case the first and third part have the same U parameter differential, which is different for the second independent part. The parametric relations among the parts are variable. In the selected collection, the second part is larger (Figure 14). However, in the corresponding rule this constraint is not set, so to allow for a wider range of variation.

Rule 10b uses a label to mark the subsurfaces to which subsequent decoration rules can be applied. Since the use of labels is still under development and lacking consistency, it has not been addressed in this paper.

Similarly to the base shape definition phase, surfaces resulting from the subdivision operations are to be replaced by more elaborate ones featuring relief-based motifs. For the selected collection, two rules are defined, 11a and 11b, which are to be applied exclusively onto shallow and deep types respectively. Both rules apply a slight depression to the target labelled subsurface, a motif which is typical for the selected collection. However, contrary to rule 11b, rule 11a also changes the subsurface's contour (Figure 15).

Recursive application of motif replacement rules to all labelled subsurfaces is the final stage of the derivation, resulting in a design that belongs to the collection's language (Figure 15).

APPLICATIONS OF THE SHAPE GRAMMAR

Parametric modelling

A three-dimensional parametric grammar is difficult to test without some kind of implementation. On the one hand, the combination of several parameters corresponds to a large number of solutions.

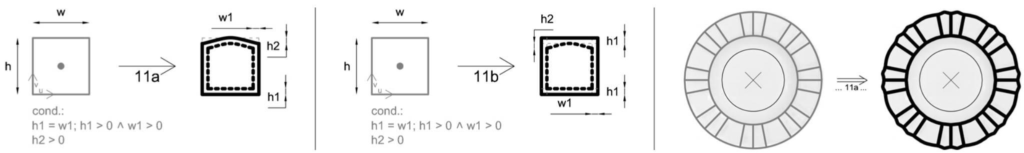


Figure 15
Motif replacement rules and application in the soup plate derivation.

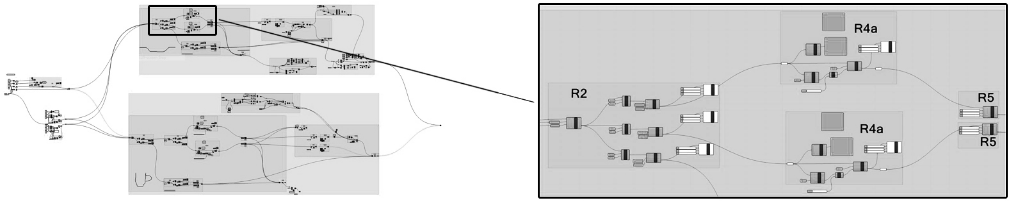


Figure 16
Parametric model developed in Grasshopper: using rules as groups of components.

On the other hand, some three-dimensional geometric operations are difficult to represent in two-dimensional drawing, such as the surface mapping operations.

Therefore a computational model was developed in Grasshopper, a visual programming interface that interacts with geometrical modelling software Rhinoceros, and allows implementing, and therefore evaluating, parametric models. It should be noted that the Grasshopper model is not considered an implementation of the shape grammar. However, if we consider that the result of the derivation of a parametric shape grammar is a parametric model, than we can argue that we are implementing a derivation. Actually, the Grasshopper model was developed so that rules can be identified as groups of components, in a modular fashion (Figure 16).

With this tool, two derivations of the soup plate were implemented as parametric models. The two derivations differ slightly, having different rules applied in the base shape. Then, for each derivation, two models were generated using different parameter configurations. Therefore, a total of four digital models were generated in Grasshopper (Table 3). These models were to be later produced through rapid prototyping.

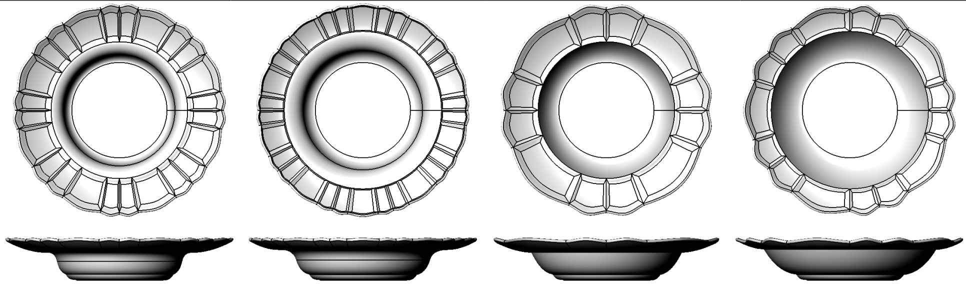
3D printing

The digital models generated in the Grasshopper program were materialized through available 3D Printing technology. For saving purposes, four quarters of dishes were produced, instead of four complete dishes (Figure 17). This was also useful to evaluate the results in terms of their section.

Prototyping the models provided for a general first impression about the models being generated, namely in terms of scale and weight. The 3D printed models are especially useful for communication purposes, allowing to better illustrate the project design, either to faculty members as well as to potential partners in the industry.

Further research will aim at determining if these

Table 3
Digital models of derivations of the shape grammar.



Derivation 1 Parameters 1A	Derivation 1 Parameters 1B	Derivation 2 Parameters 2A	Derivation 2 Parameters 2B

3D printed models are suitable for mold making, and if it is possible to use 3D printing for digital fabrication, i.e., for producing final products.

CONCLUSIONS

This exercise brought the attention to the many questions that should be answered in order for the mass customization paradigm to be applied to ceramic tableware. Focusing particularly on the development of the shape grammar, the manipulation of three-dimensional and predominantly curved shapes poses as the main challenge, which needs to be mastered in order to serve as an effective design system.

However, the success of this first mockup poses as a good indicator for further research, which is planned to develop along the three systems.

Future developments

Some aspects of the Shape Grammar formalism are to be further addressed, stabilizing the design system so it can be extended to other collections and element types, namely the validation of mapping operations, as well as control mechanisms such as labels and parameter intervals. Concerning implementation, although Grasshopper was used in this first mockup, a study must be conducted on the available programming technologies for implementing the design system. Concerning the production system, a thorough research on production techniques is to be developed, both for handcrafted and industrial ceramics manufacturing. Last but not least, establishing a partnership with a manufacturer is a key factor for the success of this research.

Figure 17
3D printed prototypes.

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