A Grammar-Based System for Chair Design

From Generic to Specific Shape Grammars

Sara Garcia¹, Mário Barros²
¹,²Faculty of Architecture of the University of Lisbon
¹sgarcia@fa.ulisboa.pt ²milbarros@gmail.com

A shape grammar-based computational system for chair design is presented. The paper focuses on the development of a methodology for modelling the definition stage of the design process. It is achieved by incorporating a specific grammar into a generic grammar to assist the designer in the convergence activities during the definition stage. Both grammars and their respective implementations were previously developed by different authors. The purpose is to enable the generation of a generic design solution that encompasses characteristics of a specific style, thus permitting subsequent exploration in the development stage.

Keywords: Multipurpose Chair, Shape grammars, CAD, Design methods, Collaborative design

INTRODUCTION
The general activities in each stage of the design process can be summarized in cycles of divergence for exploration and convergence for selection. The Double Diamond model (Design Council, 2005) considers the referred cycles and systematizes them into four constituent stages of the design process: discovery, definition, development and delivery. The ultimate goal of the present research is the development of a shape grammar-based computational system to assist the furniture designer in the design process of multipurpose chairs, from conceptual design to manufacturing (Figure 1).

The system is based on the association between two types of computer implementations of shape grammars: a generic shape grammar, to support design activities in the discovery and definition stages; and specific shape grammars, to assist the development and delivery stages. The current phase of the research focuses on the methodology for modelling the definition stage of the design process. It is achieved by coupling a specific grammar into the generic grammar to assist the convergence activities during the definition stage. The purpose is to enable the generation of a generic design solution that encompasses characteristics of a specific style, thus permitting subsequent exploration in the development stage. The methodology is presented by merging two shape grammars implemented in computer-aided design independently developed by different authors (Barros, Duarte, and Chaparro 2011; Garcia and Romão 2015).

The paper is structured as follows. Section 2 discusses the theory of shape grammars, considering different approaches to open up or constrain the domain of solutions. Section 3 presents the structure of the shape grammar-based computational system. In addition, it overviews the generic and the specific
shape grammars which constitute the basis of the present case study. Section 4 details the methodology for the incorporation procedure. Finally section 5 discusses the suitability of the proposed methodology and the presented computational system in the envisaged design process.

Figure 1
Grammar-based system for chair design (based on the double diamond model).

RELATED WORK
Shape grammars (Stiny and Gips 1972) have been used to translate aspects of tacit knowledge observable in a design style into explicit knowledge capable of creating different design solutions which belong to a design language. Rules permit a step-by-step formation of the designs and may encompass different algebras to enable the representation of additional layers of information (Stiny 1991).

The arrangement of shape grammar's properties establish the domain of solutions. During the process of encoding a shape grammar, there are distinct strategies to open up or close the domain. The use of these strategies is dependent on the particular goal of the shape grammar, the complexity of the represented object and its use in the design process.

During the development of a shape grammar, strategies to open up the domain of solutions include the application of parametric shape grammars (Stiny 1980), which enable the generation of different designs sharing a similar topological structure by varying the dimensional parameters; or embedding (Stiny 1991), which permits different interpretation of designs sharing the same structure, by the recognition of distinct emergent subshapes. Conversely, labels can be used to constraint the generative procedure through the representation of particular features.

After a shape grammar is established, the domain of solutions can be augmented or new languages can be created by the means of a transformation (Knight 1981). The transformation can be devised by analyzing either internal properties of the shape grammar or external information. The first premise may focus on a different interpretation of the shape grammar representation, refinement of labels or describing new spatial relations. The second premise may comprise the addition of new objects to the corpus to create new solutions within the same style or from different styles.

A different approach on transformation has been developed by Benrós et al. (2012). The goal was the development of a more generic grammar capable of generating designs in different styles. The methodology encompassed the analysis of three shape grammars independently developed by different authors, each one characterizing a unique design style. The analysis included a comparison between the corpuses, the strategies for encoding the shape grammars and their respective rule sets. The authors concluded that specific styles can be generated by different shape grammars formulations.

Analytic grammars reproduce one design style and are context-dependent, as the classification is made through a set of qualities typical from one designer, or observable in a place or a period of time. A different approach is the one of generic grammars, defined by Beirão et al. (2011). Generic grammars express abstract, recurrent design patterns. These are
context-independent and reproduce different design types, as they are based on ontological classification of sets of objects that share similar functions or morphologies. Generic grammars can be customized in order to achieve specific languages, by the restriction of sets of rules and their parameters.

**Shape grammars in product design**

Shape grammars have been successfully applied as the generative mechanism in different product design classes. Analytical shape grammars, which systematize a particular design style, is the prevalent approach. Its methodology is based on the analysis of a corpus, definition and iterative refinement of the shape grammar’s properties, and testing of the rules to generate the corpus and similar designs in the language to validate the grammar (Stiny and Mitchell 1978). The first application in the product design field is the Hepplewhite chair-back shape grammar, developed by Knight (1980). It captures the characteristics of the style by simplifying the representation into higher levels of abstraction. In particular, the geometry is simplified into lines, and curvilinear representation is abstracted into rectilinear representation. The result is a straightforward set of rules that operates within the boundaries of the chair-back designs, the key feature of the style.

Beside the generation of objects in a specific style, more general applications have been developed. They address the subject of additional flexibility in the design process, by inferring rules common to a class of objects. In certain cases, sets of rules are constrained to permit the generation of designs within a subset of the class, or within a particular style. The coffeemakers grammar (Agarwal and Cagan 1998) analyses a corpus comprising four similar objects belonging to four brands. Moreover, each pair targets a specific market niche. The grammar separates the overall shape of the coffeemakers into three subparts and sets of rules detail each part independently. The strategy permits the reproduction of the corpus and generates new design concepts. The motorcycle grammar (Pugliese and Cagan 2002) extends the former approach, aiming to a more general domain of solutions within the selected class. The grammar comprises a constrained set of rules that supports the exploration to occur within the Harley-Davidson style. More general grammars can also address additional creative realms, enabling the generation of designs in new classes which are not observable in the analyzed corpus. The cross-over vehicles grammar (Orsborn et al. 2006) embodies this concept. It analyzes vehicles in three different classes and allows for the generation of hybrids vehicles displaying characteristics from multiple classes.

**THE GENERIC AND THE SPECIFIC SHAPE GRAMMARS**

The underlying concept of the present research differs from the above-mentioned examples from the literature. It formulates the hypothesis that shape grammars can be used to assist all the stages of the design process. As a result, shape grammars must comprise properties to support the two cycles of divergence/convergence, thereby permitting both exploration and synthesis of the designs. The goal is achieved by coupling a generic grammar for multipurpose chair design with a specific grammar.

The multipurpose chair grammar supports the discovery and the definition stages. The main goal of the discovery stage is the exploration and establishment of the working principles. The shape grammar implementation enables the user to add/delete components and edit parameters of individual components on a 3D model. In the definition stage, the designer compares different concepts and begins the convergence path. Convergence is the exploration within a smaller domain of possible solutions until achieving a generic solution of the envisaged chair (Pahl et al. 2007:131). The generic solution may comprise characteristics of a specific style.

The development and delivery stages are supported by a specific grammar. The grammar details components according to shape- and material-related issues, and limits the domain of solutions to a set of features which characterize the design style.
The Generic Grammar for Multipurpose chair design

The generic multipurpose chair grammar (Garcia and Romão 2015) is able to generate general solution of chairs from the multipurpose class, supporting different types of components. It is implemented as a digital tool, intended to be used by designers at the early conceptual steps of a chair design process. The methodology for its development encompassed with five main stages: (1) sample, (2) ontology, (3) shape grammar, (4) digital tool, and (5) evaluation. (1) The multipurpose chair population was defined according to the following criteria: no moving parts, no upholstery, minimum decoration, industrially produced, featuring bilaterally symmetric shape, and to be a modern chair classic. From the analyzed population, a corpus of 26 chairs from 24 different designers was selected, aiming to represent many different types. (2) The corpus selection and the grammar development were based on an ontology classification of the parts of the chair as follows: the chair parts class is decomposed into the structure subclass - which contains the legs, the stretchers, the base, the seat rails, the back rails, and the arms; and into the support subclass - that includes the seat and the backrest. (3) The corpus was reduced to a high level of abstraction - the structure is represented by lines and the support by planes. About 50 rules generate the parts of the chair through a process of step-by-step addition, each part being controlled by parametric variation. (4) The shape grammar is implemented on a GUI encoded in Racket programming language, that works along with AutoCAD or Rhinoceros 3D. It is a straightforward implementation of the grammar, because it allows the addition/subtraction of components (by activating/deactivating checkboxes), and the control of its parameters (by manipulating sliders). While manipulating the components in the interface, one can see the result on a 3D model in CAD software. (5) Finally, the system was tested and evaluated by undergraduate design students.

The Specific Grammar for Thonet chair design

Thonet grammar is the specific grammar used in the study (Barros, Duarte, and Chaparro 2011). It is focused on the generation of the backrest structure of the chair, the key area to the definition of the design language, and it was developed considering a corpus of six different Thonet chairs. The schemata for rule application is a simplified representation, similar to the one used by Terry Knight for Hepplewhite chairs (1980). It was obtained by abstracting curves into rectilinear lines and representing just half of the backrest structure due to its symmetry properties. This grammar accounts different algebras to control the position of elements and the description of their material proprieties. When the generation process is complete designs are reflected and the representation is translated into curves. Rule application results were converted into parametric models to assist the interactive exploration of the designs. The shape grammar is implemented in CATIA as a set of parametric design models, each one representing one topological solution created by rule application. Simulation and optimization (Barros, Duarte, and Chaparro 2014) guarantees that a customized variant that belongs to the design language can proceed to the production system.

INCORPORATING THE SPECIFIC INTO THE GENERIC GRAMMAR

The expansion of the generic grammar can be defined by two major purposes, and these relate to the usage of the grammar in the respective stage of the design process. The first purpose is to enable additional design exploration. This condition relates to the discovery stage and can be met by applying known methods from the literature. The second purpose is the incorporation of specific grammars into the generic grammar. The goal is to support the definition of a generic solution that can display features of a specific design language. This section details the methodology to achieve this intent, considering the particular conditions of the case study.
The first stage is characterized by a comparison between the Generic Grammar for Multipurpose Chair design (GGM) and the Specific Grammar for Thonet Chair design (SGT). Both are functional generative design systems, sharing a similar structure encompassing a shape grammar for characterization of the generative procedures and its corresponding implementation for exploration in the design process. The goal of mapping the similarities and differences determines the set of requirements for the incorporation procedure. Table 1 summarizes the properties of both shape grammars and respective implementations.

Thonet chair no.14 is common to both corpuses, which means that there are some similarities a priori.

Shape abstraction comprises the same principles in both grammars and implementations: in shape grammars the shape is abstracted into its wireframe skeleton; and displayed solid in the respective digital tools. Curve abstraction follows different approaches. In GGM spline curves are simplified into lines and arcs, whose curvature is controlled by the radius. This condition is applied both in shape grammars and its implementation. In SGT spline curves are represented by rectilinear lines between its fit points in the shape grammar. In the parametric design models spline curves are NURBS controlled by the tension values and the tangent lines. In regard to visualization GGM uses a 2D axonometric representation of the whole chair; while the SGT uses a 2D front view of the backrest area. Both implementations are based on a complete 3D model.

<table>
<thead>
<tr>
<th>Corpus</th>
<th>Shape Abstraction</th>
<th>Curve abstraction</th>
<th>Visualization</th>
<th>Initial Shape</th>
<th>Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGM</td>
<td>Wireframe skeleton</td>
<td>Lines &amp; arcs</td>
<td>2D axonometric</td>
<td>Bounding box</td>
<td>Additive Back, Seat, Legs, Base, Stretcher, Arms</td>
</tr>
<tr>
<td>SGT</td>
<td>Wireframe skeleton</td>
<td>Lines</td>
<td>2D front</td>
<td>Bounding box &amp; Back outer frame</td>
<td>Additive Back inner frame parts</td>
</tr>
<tr>
<td>GGM</td>
<td>Wireframe skeleton &amp; Solid</td>
<td>Lines &amp; arcs</td>
<td>3D</td>
<td>Bounding box</td>
<td>Additive Back, Seat, Legs, Base, Stretcher, Arms</td>
</tr>
<tr>
<td>SGT</td>
<td>Wireframe skeleton &amp; Solid</td>
<td>NURBS</td>
<td>3D</td>
<td>-</td>
<td>- Back, Seat, Legs, Stretcher</td>
</tr>
</tbody>
</table>
the initial shape can either be visualized or not. SGT implementation does not have an initial shape since it does not support rule application.

Both shape grammars are based on addition rules and do not allow embedding. Each rule systematically adds an element of the chair to a design until the final solution is reached. Moreover, the generation process is concerned to only half of the chair, as the other half is generated by bilateral symmetry. The implementations follow different approaches. The GGM implementation follows directly the conditions verified in the shape grammar, allowing both topology and parametric variation. The SGT implementation only allows parametric variation within a topological solution. As mentioned above, rules in GGM are concerned to all chair parts, while in SGT these focus on the backrest part. The rules of the SGT generate the backrest inner frame shapes, from the connections between the four outer frame parts - side, top, symmetry axis, and bottom - and from the arisen connections. The 34 rules of the SGT can be divided into four categories, as described below:

(a) **Label rules**: rules 1 to 3. These rules correspond to parameters restriction.
(b) **General connection rules**: rules 4, 27, 28 and 29 (or 30). These rules make connections between opposite outer frame elements: rule 4 corresponds to the GGM rule 'Back Splat', and rules 27 and 28 to the GGM rule 'Back Cross'. The rule 29 (or 30) is equivalent to the GGM rule 'Back Surface' (Figure 3).
(c) **Detailing connection rules**: rules 5 to 7, 11 to 19, 26, 29 and 30. These rules correspond to structure reinforcements or unconnected elements. They produce connections of adjacent outer frame elements, connections between the arisen inner elements, extensions of inner elements, and collinear elements. Besides detailing connection rules, rules 29 and 30 allow for selecting material. These two rules correspond to the 'Back Surface' in GGM.
(d) **Termination rules**: rules 8 to 10, 20 to 25, and 31 to 34. These rules remove the labels.

Rules from group b) are encoded only in GGM implementation, enabling chair parts to be added or deleted. As mentioned, SGT implementation does not support rule application, as it only encodes the final shape grammar solutions. In GGM shape grammar and implementation all chair parts are controlled by parametric variation. In SGT shape grammar labels specify the range for parametric variation of the positioning of the inner frame. In the parametric design models, position, angle, radiuses and dimensions of all chair parts can be adjusted. These parameters are all included in the GGM, except the ones related to the shape grammar labels.

Next we present the method to incorporate the SGT into the digital tool of the GGM. It is based on three main stages: selection, extraction and implementation. Two procedures to implement the specific into the generic are considered. The first one is the implementation of chairs of the SGT corpus, based on the extraction of values. The second is the implementation of the grammar, which expresses the specific Thonet style, based on the extraction of ranges of values.

**Implementation of three Thonet chairs**
The method used to implement the Thonet chairs is similar from the one of transformation, which means that new chairs are added to the corpus and
are checked whether they can be generated by the grammar. This procedure can be generalized to chairs which fit the requirements of the GGM. As mentioned, the method encompasses the stages of (1) corpus selection; (2) parameter extraction, and (3) implementation and use.

(1) Corpus selection. The goal of this stage is to check if the 'candidate' chair fits all the aforementioned requirements of the GGM and therefore can then be implemented in its generic form. From the six chairs of the SGT corpus only chairs No. 14, No. 15, and No. 18 fit every required criterion (Figure 4). Conversely, the chairs No. 1, No. 4 and No 16 do not. Chairs No. 1 and No. 4 were not mass produced, and chair No. 16 comprises unconnected elements.

(2) Parameter extraction. This stage is characterized by the extraction of chair parts and its respective parameters. The first step involves geometry extraction of the skeleton and sections from the 3D Specific model (Figure 5a). Then, spline curves are simplified into lines and arcs, to fit the principles of the 3D Generic model (Figure 5b). In the third step numeric information is retrieved from geometric information. Two sets of chair parts and parameters are extracted: the ones common to all three chairs; and the distinct ones. The common parts are the front and rear legs, the seat rails, the seat surface, the backrest outer frame. The distinct parts are the ones of the inner frame (Figure 3). For the chair No. 14 the Back Cross (height) is extracted; for chair No. 15 the Back Cross (height), Back Cross bottom (height), and Backrest surface (height in top and in bottom); and for chair No. 18 the Back Splat (spacing crosswise in top and in bottom).

(3) Implementation and use. While extracting the parts and parameters, we noticed that not all existed in the GGM. The new part implemented in the GGM is the Back Cross Bottom; and the new and parameter is the Spacing crosswise Top of the Back Splat. The Back Cross Bottom was not observable in the original GGM corpus but its inclusion follows the requirements of GGM. Spacing crosswise Top of the Back Splat was not included in the original formulation although it is similar to an existing parameter in the seat area. The GGM does not support collinear parts as it addresses the main activities during discovery and definition stages of the design process. During these stages the goal is to define the constituent chair parts and their basic shape. Detailing and full specification of these threads are related to the development and delivery stages.

The usage of the mentioned encoded information in the GGM digital tool is made by accessing the 'Guides' tab. This tab enables the user to visualize the initial shape during the generation procedure. It was added a check-box called 'Chair Templates', where the user of the tool can select amongst one of the three Thonet chairs (Figure 6a). When a specific chair is selected, the system processes the parameters stored in an Excel spreadsheet, and changes all the interface parameters in order to reproduce the 3D model of the selected chair. In such a case, the parameters are not blocked allowing the user to change the parameters. 'Chair Templates' is a library of chairs that can be accessed at any time during the gener-
plementation process. The selection of a chair template enables the user to start upon or even reverse the generation procedure to a predefined option and then proceed in exploration of the design, by selecting the remaining features of the digital tool.

**Implementation of the Thonet style**

The implementation of the Thonet style is based on the analysis of the SGT labels. The labels restrict the inner frame generation to predefined ranges established as proportions of the line segments of the outer frame. Those proportions are expressed in the grid depicted in the initial shape (Figure 2b). The procedure to implement the Thonet style followed the stages of (1) label selection, (2) label extraction, and (3) implementation and use.

(1) **Label selection.** From the seven labels of the SGT we selected four (a', a'', a''' and b'') which refer to the GGM general rules for the inner frame mentioned before.

(2) **Label extraction.** The labels of the SGT are expressed in fractions, and they were converted to the percent notation used by GGM.

(3) **Implementation and use.** The converted values in the previous stage were directly implemented in the GGM digital tool. The usage is made by selecting the option 'Style Templates' in the 'Guides' tab (Figure 6a). When the user selects the option 'Thonet Style', all the variables assume the values imported from an Excel spreadsheet. The inner frame part and respective labels enable the variation in the ranges described in SGT (Figure 6b). The remaining parts and parameters become blocked, not allowing any variation. They become unblocked only if the user deselects the style template.

**New solutions**

Figure 7 shows four solutions generated by the GGM digital tool. The first two belong to Thonet style and the last two are explorations in a broader style. From left to right: (1) one chair from the corpus - the chair Thonet No. 14; (2) one new chair from the Thonet style - generated by manipulating the parameters of the style - which resembles the chair MUJI No.14, designed by James Irvine; (3) one new chair built upon the Thonet style with two parameters slightly outside
Figure 7
New solutions generated by GGM digital tool.

the style range (positions of the inner elements); and
(4) one new chair from a broader style, with one parameter outside the style (square section), different stretcher rails and without an inner back frame.

DISCUSSION
In this case study we intended to provide the guidelines to accommodate one specific grammar (SGT) into one generic grammar (GGM). The developed methodology encompasses three main stages - selection, extraction, and implementation - to enable the encoding of specific chairs and chair styles into the GGM. The methodology suited the initial goals and may be applied to augment the template library of the GGM digital tool with other examples.

The cooperative design proved to be fruitful and should be encouraged in the development of this kind of systems. The methodology tests both the completeness of the generic grammar and the accuracy of the specific grammar. Furthermore, it clarifies the boundaries of each grammar and respective addressed problems.

The Thonet style used in the case study allows for variation in a highly constrained exploration space. The strategy to augment the exploration within the style (using GGM digital tool) could be made either by encoding a transformation of the Thonet shape grammar; or by encoding additional Thonet chairs.

Further work can also occur under two major directions: the first may consider the implementation of other styles, such as the Hepplewhite grammar (Knight 1980); and the second may consider the encoding of further individual chairs.

The Thonet style used in the case study allows for variation in a highly constrained exploration space. The strategy to augment the exploration within the style (using GGM digital tool) could be made either by encoding a transformation of the Thonet shape grammar; or by encoding additional Thonet chairs. Further work can also occur under two major directions: the first may consider the implementation of other styles, such as the Hepplewhite grammar (Knight 1980); and the second may consider the encoding of further individual chairs.

The issues addressed in this paper have implications and analyzes information from distinct stages of the design process. This paper presented the discovery and definition stages in order to achieve a Generic Solution. Parts and parameter constraining are issues from the specific grammar that were incorporated in the GGM digital tool.

The premise presented in the beginning of the paper, that the incorporation of a specific grammar into the GGM digital tool would assist the convergence activities during the definition stage, can be interpreted as a restricted vision of what the system is able to do. We suggest that the user can use specific chairs or styles at any time during the discovery or definition stages according to his/her own particular purposes. Accordingly, specific and generic exploration may not sequential, but parallel. Future work on this topic will concern evaluation tests with professional designers to study the templates usage and utility during the design process.
The extension of the implementation to assist the development and delivery stages of the design process will be addressed in future research, since the interpretation of one Generic Solution can lead to different Specific Solutions. The specific issues to be considered in the mentioned stages are: shape detail; specification of materials and joints; analysis and optimization. These issues can follow the methodology defined in Barros et al. (2014). The challenge of creating such an integrated tool refers to the ability of implementing and managing the complexity across the different stages of the design process, providing proper degrees of flexibility for the designer.

REFERENCES

Knight, TW 1980, 'The generation of Hepplewhite-style chair-back designs', Environment and Planning B: Planning and Design, 7(2), pp. 227-238
Knight, TW 1981, 'Languages of designs: from known to new', Environment and Planning B: Planning and Design, 8(2), pp. 213-238
Stiny, G 1980, 'Introduction to shape and shape grammars', Environment and Planning B: Planning and Design, 7(3), pp. 343-351