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STRATEGIES FOR CONSUMER CONTROL OF COMPLEX PRODUCT FORMS IN GENERATIVE DESIGN SYSTEMS

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ABSTRACT

In recent years, the number of products that can be tailored to consumers' needs and desires has increased dramatically; there are many opportunities to individualize the colors, materials or options of products. However, current trends indicate that the future consumer will not be satisfied with mere material and color choices, but will desire control over form as well. While it is technically feasible to allow consumers to partially mass-customize the form of products subject to functional and production constraints through the use of a generative design system, the question of how the control of form should be presented to the user arises. The issue becomes especially important when the product form is based on complex morphologies, which require in-depth knowledge of their parameters to be able to control them fully. In this paper, we discuss this issue and present and test two strategies for controlling complex forms in consumer-oriented generative design systems, one offering the user full control over the design ("total control" strategy), while the other automatically generates designs for the user ("no control" strategy). The implementation of those two control strategies in a generative design system for two categories of products (bookshelf and table) and five types of morphologies are described and tested with a number of design interested

participants to estimate their level of satisfaction with the two control strategies. The empirical study shows that the participants enjoyed both the total control and no control strategies. The development of the full control modes for the five morphologies was on the other hand not straightforward, and in general, making the controls meaningful to the consumer can be difficult with complex morphologies. It seems that a consumer-oriented generative design system with two different control strategies, as the ones presented in this article, would offer the most satisfaction.

INTRODUCTION

In recent years, the number of products that can be tailored to consumers' needs and desires (known as mass-customization) has increased dramatically; there are many opportunities to individualize the colors, materials or options of products. Sooner than later, the future 'prosumer' [1] will not be satisfied with mere material and color choices, but will desire control over form as well. This is illustrated by the interest showed for companies such as Shapeways (<http://www.shapeways.com/>) and Materialise (<http://www.materialise.com/>) that offers their customers products such as customizable decorative items or user-designed add-ons for existing products manufactured with rapid prototyping techniques which enable one-off production and very intricate forms. Such techniques, however, can currently only be used for certain types of consumer products as it has high costs in comparison with traditional production methods and is limited regarding materials, and product size.

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Traditional production methods, on the other hand, require the product form to comply with technical constraints specific to the production equipment and thus limit the possibilities for form customization.

In the case where the technical and functional constraints are well-defined, it is however possible to partially mass-customize the shape of products that are produced with traditional production systems, through the use of so-called "generative design systems". A generative design system is basically structured around a graphical user interface with which the user can modify and evaluate product forms, and an interactive optimization system or an interactive constraint satisfaction system that handles user and technical preferences and constraints. Most generative design systems have been intended for professional designers, for example to help the designer preserve the "form" identity of a brand [2-5]. Only a few have been developed for consumers, e.g. Kram/Weisshaar developed the Breeding Tables program, which generates variations of a table design using a genetic algorithm that modifies a set of parameters ruling the support structure [6].

For this category of generative design systems intended to be used by consumers comes the question of the control of form, especially when complex morphologies such as natural-mathematical forms are used. These morphologies are for example the minimal surfaces or cellular automata (Figure 1). Many morphologies require advanced knowledge of their parameters to be able to control them fully, which is out of range of virtually all consumers. How can such morphologies then be used when the user has limited or no knowledge in programming or mathematics? The problem becomes even more complex when he or she has to take into account technical and functional constraints.

In this paper, we discuss this issue and present and test two control strategies for controlling complex forms in consumer-oriented generative design systems. The issue of control is first discussed and the two control strategies are presented. The implementation of those control strategies in a generative design system is then described for two categories of products (bookshelf and table) with different manufacturing techniques and five types of morphologies. The empirical study of those control strategies is then presented, and consequences in relation to mass customization are discussed.

CONTROLLING COMPLEX FORMS

There are several possible ways to control complex forms, some requiring a lot of manipulations from the users, some requiring virtually none. The work from Piasecki and Hanna [7] is useful here to provide some guidance. Piasecki and Hanna [7] address the issue of control in relation to complexity and consumer satisfaction. They build on the research done by Schwartz [8] who defined the so-called "paradox of choice": a large amount of choice among product alternatives is positively correlated with consumer satisfaction, but too much choice can lead to dissatisfaction and confusion. They showed that there exists an optimal amount of choice, but that it is not only the amount of choice but also the amount of meaningful choice that

influences consumer satisfaction. Expressed in another way, the consumer may want to have a lot of control of the morphologies but only if the way the morphologies are controlled helps him or her achieving his or her goals (such as sufficient spaces for books in the case of a bookshelf, furniture volume that fits the room it is intended for, etc.).

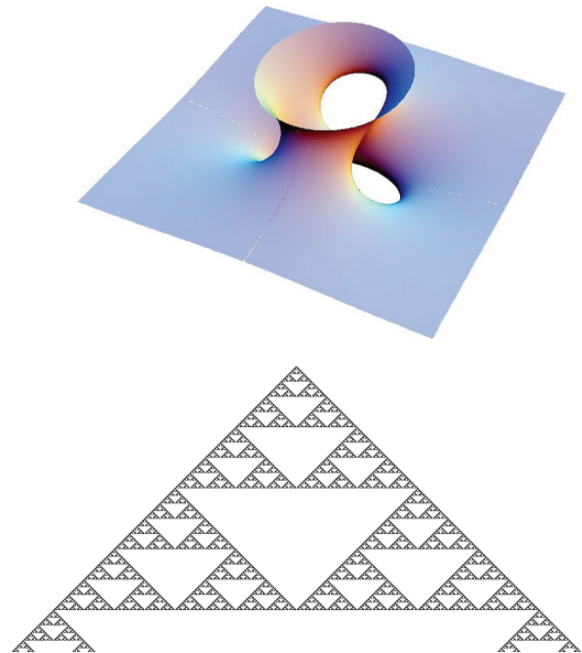


Figure 1. Examples of mathematical morphologies. Top: minimal surface [9], bottom: cellular automata [10]

Therefore, having complete freedom of creation, such as in traditional parametric CAD or surface modeling tools such as Autodesk Alias, is not particularly adapted to consumer-oriented generative design systems. Such software have a steep learning curve and can imply a large workload for relatively simple tasks.

Another possibility is to have a partial control strategy. The user is allowed to design a rough form for the product with a simplified interface. When the user is satisfied with his or her preliminary design, the system tries to satisfy the technical and functional constraints and objectives while remaining as close as possible to the user's original design. A study of this strategy was performed with professional designers [11]. The results showed that this control strategy was not particularly appreciated for several reasons. Some pointed out that it was frustrating that the generative design system altered, even a little bit, their design. For complex forms (probably even simple ones) the least changes can give a completely different visual expression to the product. This study indicated also that one part of the respondents would prefer maximum control of the form creation process (which would include dealing manually with the constraints), the other part — rather surprisingly for professional designers — wanted a generative design system that would generate the product completely

automatically before they could choose their preferred design. Although these two different potential control strategies come from professional designers, they should still be relevant as a starting point for devising the morphology control strategies for consumers. Moreover, these two control strategies present strengths and weaknesses that could be beneficial for further investigation.

The aim of this paper is consequently to investigate these two alternative strategies, hereafter called the "total control" and "no control" strategies. These control strategies are discussed below.

The total control strategy

The total control strategy is based on leaving as much of the control of the morphology to the user as possible, while the generative design system can assist him or her with information about the evaluation of the form in terms of manufacturability and functionality. It is therefore not full control in the sense of traditional CAD software, but rather that the user is free to manipulate the form within the limits of the morphology. This presents several benefits. This strategy removes the need for implementing an optimization system as it is done manually by the consumer. Moreover, it has been shown that allowing consumers to personalize their products in some manner increases their attachment to the product, and increases the perceived value of the product [12].

The concept of total control raises also several issues. First, as mentioned earlier, most users do not possess the skill to manipulate the morphologies directly through their mathematical definition, which prevents *de facto* complete control. It is necessary to have a specific interface for each type of morphology. It also presents the challenge to implement an interface for the consumer that has enough freedom of creation to satisfy the consumer, while hiding irrelevant aspects, and giving instant feedback of important properties such as producibility, stability and weight. It is difficult to assess to what extent the consumer wants or needs to be active (cf. the paradox of choice above). Moreover, users may want to use the morphology as a starting point and then alter it by defying the original definition of the morphology to suit their own preferences, for example by adding and removing curves, lines and vertices in the structure. This presents complex computational problems: if the elements of the morphologies are linked by specific equations, how then should changes introduced by the user be handled? We have consequently interpreted the total control requirement as the possibility to manipulate in a detailed way the elements of a morphology while remaining true to its underlying natural-mathematical structure.

The no control strategy

In the no control strategy, the user lets the design generation system generate solutions that fulfill engineering and production constraints without intervening in the process. The user is still able to define certain design parameters such as the outline of the product (shelf or table), or height or depth,

but the detailed control over the morphology is left entirely to the design generation system. This strategy hides the complexity of handling the morphology from the user, and does not require an interface for handling the morphologies to be implemented, but the automated handling of constraints and optimization must be implemented. It may also be necessary to generate several candidate solutions so that the user is able to make a choice. The constraint satisfaction process might require a noticeable amount of time for the system to give valid solution proposals, and thus might be a cause of frustration for the user. In works such as those of Sims [13] and Secretan [14] the user is active in the selection and evaluation of the solution candidates while the optimization is running in order to guide the optimization in terms of hard-to-quantify criteria such as aesthetics. In order to reduce frustration and user fatigue, techniques such as those developed by Ren [15] implement an active learning algorithm to propose only promising designs to the user. These techniques however require the user to interact several times with the generative design system, which is problematic for design problems that require many iterations or have long evaluation times. Such techniques may be appropriate for professional designers, but is felt too demanding for average consumers. Because of this, the technique used in this paper is based on generating the solutions without user input, and instead lets the user make a design selection only among the final feasible solutions.

Nevertheless, if the no control strategy experience is as much appreciated as the total control strategy, this would be an attractive control alternative in the development of consumer-oriented generative design systems as it removes the need for the development of potentially complex interfaces for the manipulation of different morphologies.

IMPLEMENTATION OF THE TWO CONTROL STRATEGIES IN A GENERATIVE DESIGN SYSTEM

To be able to test the two control strategies with consumers, they need to be implemented into a generative design system. This section describes the system and its implementation.

The design problem

The generative design system allowed the user to develop either a bookshelf or a support structure of a table in sheet steel or plywood. He or she could also define the contour of the product and the depth of the bookshelf or height of the table. The design problem is such that any design-interested consumer can relate to it, while it is still tied to a set of constraints and objectives that are common to most consumer products. The possible morphologies that the user could choose from (Voronoi diagram, Chinese lattice and isohedral tessellations) are described in depth in the next section. Images of the products based on Voronoi diagrams are represented in Figure 2. The design of the support structure of the table and the form of the bookshelf had to comply with different technical constraints.

The table needed to be able to support a weight of at least 50 kg and no part of the table can have a vertical displacement larger than 2.5 mm. The shelves had to be able to support a weight of 10 kg in each compartment. For the shelves there was also a functional objective consisting in the lowest angle of each compartment being in the range of 80° to 90° to aid better stacking of books. The production methods available for sheet metal were bending and laser cutting. The limitations of the bending machine introduced two production constraints. The geometry of the machine limits the flange lengths of the cells of the support structure never to be shorter than 30 mm, and the bending angles never to be less than 35°. The production constraints for plywood were based on the limitations of the saw, which required the pieces to be equal to or longer than 100 mm, and have no cuts less than 35°, as seen in Figure 3.

Note that prototypes could successfully be built according to the production instructions output by the generative design system, verifying that the system was properly functioning [11;16].

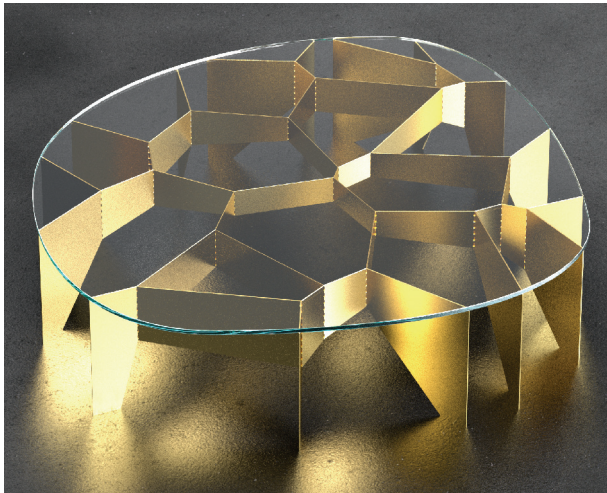


Figure 2. Images of generated table and bookshelf proposals

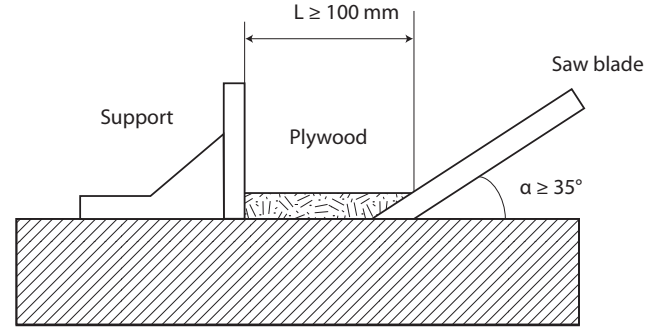


Figure 3. An illustration of the manufacturing constraints

Implementation of the whole generative design system

The generative design system was devised as follows. The interface was divided into five separate steps between which the user could navigate. The first step consisted in choosing which product category to design. This choice affects the later selection steps and evaluation functions. The second step consisted in defining a number of user requirements, such as the height of the table, or depth of the shelf, as well as being able to define the contour of the shelf or table. The contour was defined by drawing a rectangular or polygonal two-dimensional outline (see Figure 4). The third step allowed the user to select what material the product should be made from. The material chosen, and production method linked to it, also affects the evaluation functions, especially the producibility evaluation. The fourth step allowed the user to select a morphology he or she was interested in, and the last step allowed the user to manually manipulate the structure (total control strategy), or launch an optimization (no control strategy).

The morphologies and the manners in which they can be controlled (hereafter, manipulation modes) are presented in the next section.

The whole generative design system and the control strategies have been developed in Matlab and the structural evaluation was performed with the finite element toolbox CALFEM [17].

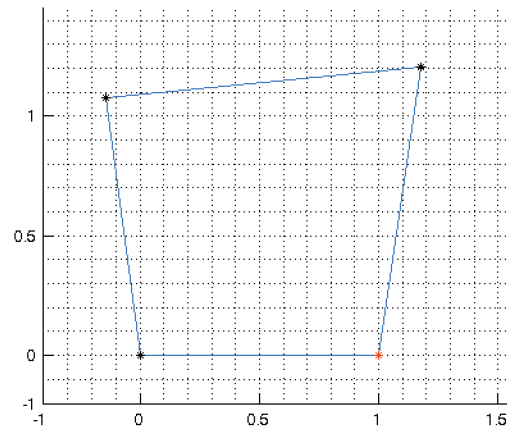


Figure 4. The contour definition interface

Implementation of the total control strategy

The total control strategy allowed the user to move the control points of the morphology while viewing the resulting structure in two or three dimensions. It also allowed for visual feedback of the level of constraint satisfaction in terms of production issues, such as too sharp angles or too short lengths, shown in red, or the amount of deformation of the structure when subject to the loads described earlier. The user could also view detailed information about the structure, such as amount of material used, weight, and estimated cost. Figure 5 presents the visual feedback of production and structural evaluation for a bookshelf with a Voronoi diagram. As can be seen, the pieces of plywood that are too small (less than 100 mm) are represented with a red line, and the angles that are too small (less than 35°) with a red dot. The user can re-arrange the shelf's configuration as much as he or she wants, but is required to ensure that all constraints are fulfilled.

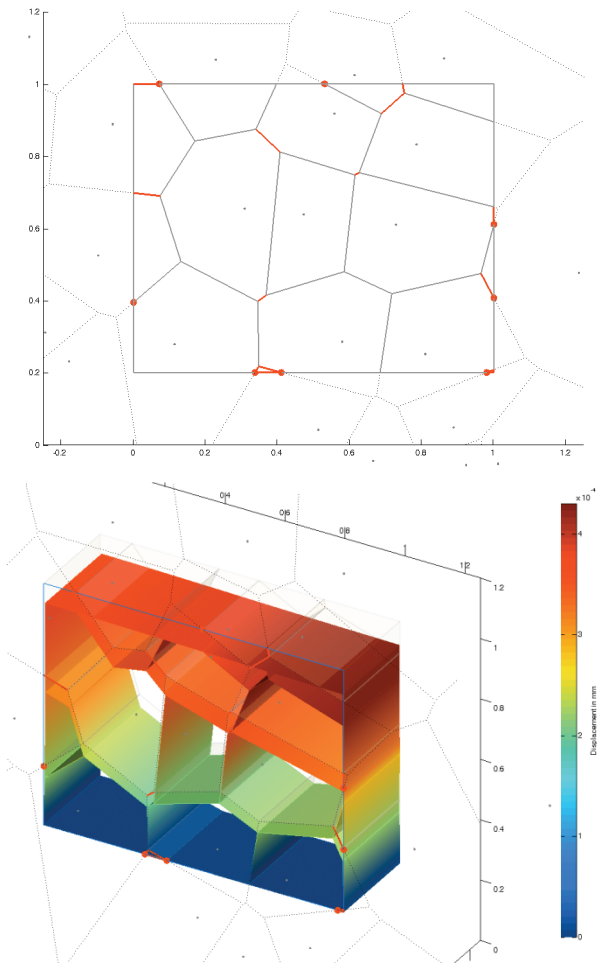


Figure 5. The visual feedback of production and structural evaluation for a bookshelf with a Voronoi diagram

Implementation of the no control strategy

For the no control strategy, a constrained optimization system was utilized which took the manufacturing and functional constraints and objectives into account, and offered the user a design suggestion after it had finished. The generation of design concepts took the generative design system around 15 minutes.

For the automated generation of the valid design solutions, the constraints were converted to a single “objective” through the use of a weighted sum of the constraint violations by the genetic algorithm (GA) implementation provided by Matlab using the coordinates of the form control points (see the next section) as the genome, a population of 50 individuals – and the stop criterion being that all constraints should be satisfied (i.e. the weighted sum of the constraint violations should be 0). The full algorithm is described in length in [16].

DESCRIPTION OF THE MORPHOLOGIES

In this section the morphologies used in the generative design system and their manipulation modes (how the morphology can be controlled by the user or constrained optimization system) are described. The morphologies have been chosen to represent both unconstrained and complex morphologies (the Voronoi diagram and the Chinese lattice), and more straightforward morphologies with few possibilities of manipulation (three isohedral tessellations).

Voronoi diagrams

A Voronoi diagram (Figure 6) can be described as follows: Let p_1, \dots, p_n be a set of n distinct points in the plane; these points are called the Voronoi sites. For each site, the set of points that are closer to it than to any other site form a Voronoi cell. A Voronoi diagram consists of all such cells. An overview of the properties of a Voronoi diagram can be found in [18, chapter 7]. The Voronoi diagram itself is manipulated by moving, adding, or removing the points p_1, \dots, p_n .

Even with relatively few Voronoi points the diagram becomes complex to handle. A small change in the position of one point can greatly affect the surrounding cells. This makes it a good morphology for testing how users respond to complex morphologies, which they have not previously come in contact with.

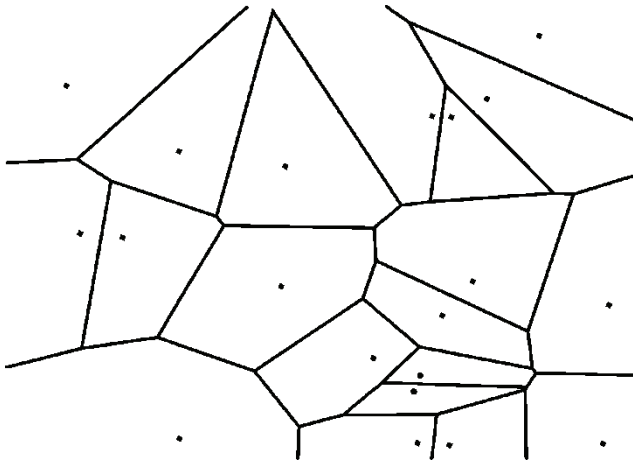


Figure 6. Example of a Voronoi diagram

Chinese lattice

The Chinese lattice structure is basically generated by dividing any polygon into two new polygons (see Figure 7). A thorough description of the generation of Chinese lattices can be found in [19]. The structure is manipulated by adding, removing or moving two points for each bisecting line to define its position and direction.

Similarly to the Voronoi diagram, this morphology can become quite complex to handle if many points are added. The logic of how the morphology is constructed might however be more intuitive than the Voronoi diagram, which makes it suitable for testing how complex, yet intuitive morphologies are perceived by a user.

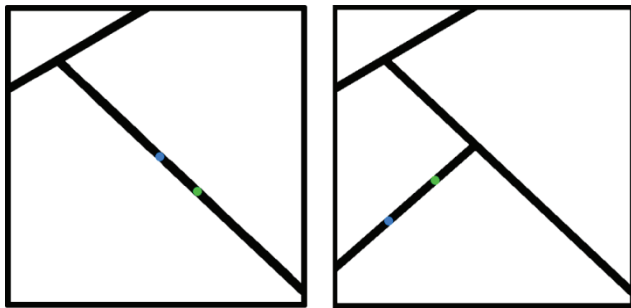


Figure 7. A Chinese lattice structure before and after one bisecting operation

Isohedral tessellations

The isohedral tessellations used in the application are two-dimensional and tile the Euclidian plane. An isohedral tiling consists of polygons surrounded by copies of themselves. There exist 42 unique isohedral tessellations consisting of symmetric polygons. An in-depth description of isohedral tessellations can be found in [20].

Three of these have been implemented in the application, the pentagonal D1, the hexagonal D1, and the kite tessellation, see Figure 8. The isohedral tessellations used in the application are manipulated by moving predefined vertices in the original

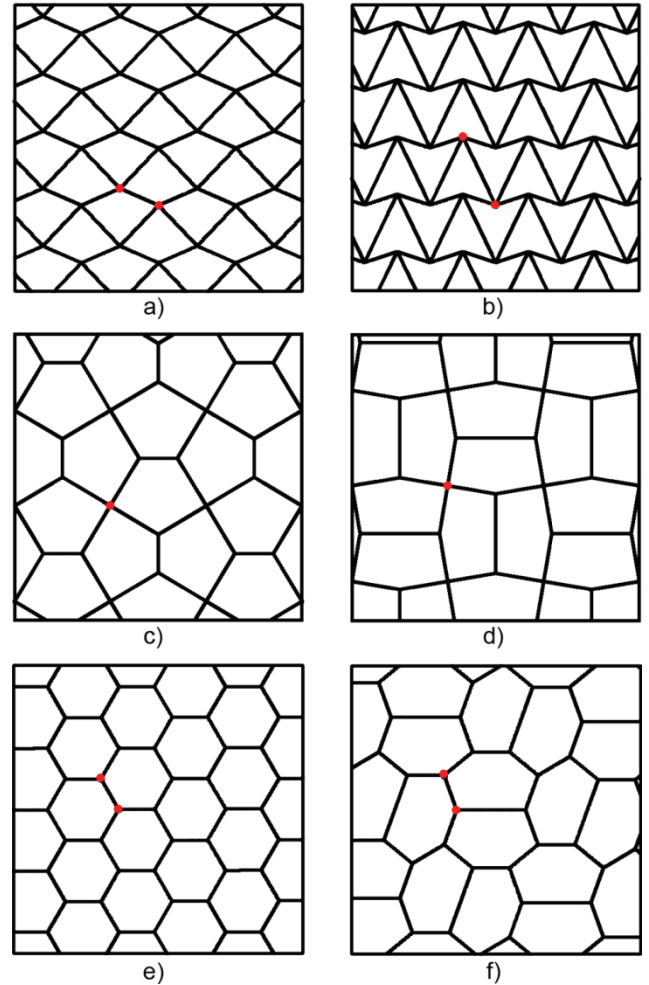


Figure 8. Two instances per morphology resulting from different locations of the control points (shown in red) are represented. a) and b) show the Kite morphology, c) and d) show the Pentagonal D1 morphology, and e) and f) show the Hexagonal D1 morphology

polygon. It is not possible to remove or add vertices to the polygon.

The mathematical formulations of the chosen isohedral tessellations allow for either one control point (as for the pentagonal D1 tessellation) or two control points (as for the Kite and Hexagonal D1 tessellations). The low number of control points makes the manual handling of the morphologies quite straightforward for the user in comparison to the Voronoi diagram and Chinese lattice.

THE STUDY

Aims

The study of the full control and no control strategy was decomposed into four aims:

1. Determine the satisfaction level for each control strategy

2. Determine whether one strategy is significantly more appreciated than the other
3. For the full control strategy, determine the satisfaction level of the defined morphology manipulation modes
4. For the no control strategy, estimate an acceptable waiting time for design generation

The test set-up and procedures

Basic set-up and procedure

To evaluate the two control strategies a test station was set up at a design exhibition center (Form/Design Centrum in Malmö, Sweden) attracting visitors with a strong interest in design and furniture. The set-up consisted in the display of one shelf and one table generated with the program, as well as general information about the application (see Figure 9). Individual visitors of the center were asked to participate in designing their own shelf or table using the application. The participants were diverse in terms of computer experience and aesthetic training, as well as age and gender. We chose the location and participants to ensure that the persons using the application would have an interest in buying design-oriented furniture. After a quick demonstration they were asked if they would like to use the total or no control mode of the application. They were guided through the settings and usage of the application, and could then individually spend any amount of time using the program. The volunteers desiring to test the system could either use the total control or no control strategy. It was chosen not to let the participants evaluate both systems in order to avoid frustration, fatigue or boredom which would affect their experience with the system. The participants were asked to fill out a questionnaire regarding their satisfaction with the design system immediately after they had finished their design task. In the case of the no control strategy the participant was asked to come back after 15 minutes to review the design proposed by the system, and then fill out the questionnaire.



Figure 9. Experimental set up at Form/Design Center

Design of the questionnaire

A questionnaire was selected as the method of evaluating the user's satisfaction with the generative design system. Other alternatives such as "thinking aloud" [21], co-discovery [22, p. 198] or interviews, were also considered but to get quantifiable results from the participants a questionnaire based on the visual analogue scale was selected. The visual analogue scale is relatively straightforward and quick for the participant to fill in and gives results which are easy to handle statistically.

Test procedure for the comparison of the total control and no control strategies (aims 1 and 2)

For determining the overall satisfaction level for each control strategy (aim 1), each participant was asked to evaluate his or her level of satisfaction with the system on a visual analogue scale, from 0 (worst possible experience) to 1 (best possible experience), as well as the satisfaction with the obtained design.

For determining whether one control strategy was preferred (aim 2), two tests were realized. First the users could spontaneously choose the type of control strategy they wanted to use. This would indicate that one control strategy is *a priori* more attractive than the other. The null hypothesis was that the number of users that would choose one control strategy would not be significantly larger than the number of users that would choose the other control strategy. Second, the satisfaction level for each control strategy could give an indication of whether the experience of one control strategy was better than the other. The second null hypothesis was that the satisfaction levels of both control strategies were not significantly different.

The difficulty for the second strategy was to establish a relevant "significant difference between satisfaction levels." It was estimated that a difference of less than 15% between the two control strategies would give no ground for deciding in favor of one over the other. Moreover, the standard deviation was supposed to be at most 15% (if one supposes a normal distribution around a mean of .50, a standard deviation (SD) of .20 means that 95% of the participants' evaluations are predicted to be between .20 and .80). This would give an estimated size effect of $.15 / .15 = 1.00$. With this estimation, it was also possible to determine the necessary number of participants. A power estimate of .80 was decided to be satisfactory, and to reach that level of power with the estimated effect size, 16 participants in each of the two groups were needed.

Test procedure for the total control strategy (aim 3)

The visitors who chose to use the full control strategy were asked to estimate his or her level of satisfaction with the manipulation mode of each tested morphology on a visual analogue scale with scores ranging from 0 (not satisfied at all) to 1 (extremely satisfied).

Test procedure for the no control strategy (aim 4)

After the participants obtained the generated results, they were asked to estimate how much time they were willing to

wait for the design to be generated (from 0 to 24 hours) on a visual analog scale.

Results

Comparison of the total control and no control strategies (aims 1 and 2)

Seventeen participants spontaneously chose the total control strategy and 9 participants chose the no control strategy. A double-sided binomial test showed that there was no significant preference for one strategy over the other ($p = .08$). In order to complete the test, 7 more participants used only the no control strategy, these participants did not belong to exactly the same group as the 9 participants that freely chose the no control group and this might have affected the test result. However, they were not made aware of the total control strategy and the mean of these 7 participants' level of satisfaction was actually higher than that of the self-selected participants. In total, 17 participants tested the total control strategy and 16 the no control strategy. In the first control strategy, the mean (M) satisfaction score was $M = .77$ ($SD = .15$), in the second control strategy $M = .84$ ($SD = .13$). The t test of the difference between means did not produce a statistically significant result ($p = .13$).

Each participant was also asked whether he or she was satisfied of his or her final design. For the total control strategy, the mean score was $M = .70$ ($SD = .27$), and for the no control strategy $M = .82$ ($SD = .11$). The t test of the difference between means did not produce a statistically significant result either ($p = .11$).

Total control strategy: Evaluation of the manual handling of the morphologies (aim 3)

Seventeen visitors chose to use the full control strategy. The Voronoi diagram got a mean score $M = .83$ ($SD = .21$) for a number (N) of $N = 10$ participants, the Chinese lattice a score of $M = .83$ ($SD = .20$, $N = 10$), the D1 pentagon tessellation $M = .79$ ($SD = .28$, $N = 10$), the D1 hexagon tessellation $M = .83$ ($SD = .18$, $N = 10$), and the kite morphology $M = .83$ ($SD = .16$, $N = 12$). The way the morphologies could be manipulated was by and large appreciated by all but a few participants (which explains the large SD for the D1 pentagon tessellation). There were no signs of frustration regarding the expressed limitations of the morphologies manipulated, unlike in the case of the partial control strategy [11].

No control strategy: Estimation of acceptable waiting time for design generation (aim 4)

Fifteen of the 16 participants answered this question. The average response was a waiting time of 20 h and 19 min ($SD = 7:19$, $N = 15$). One participant did not want to wait much more than half an hour (36 min) and another 4 h 36 min; all the remaining participants were willing to wait more than 20 h, some more than one day, with an average of 23 h 3 min ($SD = 1:06$, $N = 13$).

DISCUSSION

The total control and no control strategies, with satisfaction scores of .77 and .84 respectively, were equally appreciated by the participants, unlike the previously tested partial control strategy [11].

For the total control strategy, the different morphologies, with their different levels of complexity, were equally appreciated. The users of the total control strategy were also able to cope with the complex nature of some of the morphologies, and manipulate the tessellations to satisfy the constraints, based on the visual feedback, even though there were many parameters that could be adjusted. This seems to indicate, based on the research of Piasecki and Hanna [7], that the manipulation modes were both meaningful and rather intuitive to the user. The fact that morphologies of different natures were equally appreciated is a first step towards a generalization of the results although there is large leap from 2D morphologies to 3D or even 4D (dynamic) morphologies. Finding relevant and meaningful morphologies manipulation modes is however not straightforward (several alternative modes were originally devised for the Voronoi diagram) and rather time-consuming. This is an important factor to take into account in the development of such consumer-oriented generative design systems.

In the no control strategy, although the user could not influence the final result much, the perception was still that the product is tailored to individual needs and expectations. None of the participants expressed the desire to have a choice among several design proposals which is important given the time an automated design generation might require. The automatic design generation took around 15 minutes to complete. Although there might exist more efficient ways of implementing the optimization system described in this paper, the optimization of other, more complex products might still require a noticeable amount of time to finish. In this respect, a generation time of 15 minutes was deemed adequate as it did not give instantaneous results, but was fast enough so that the participants could review the results during their visit. Additionally, according to the questionnaire-answers, the participants were willing to wait almost a day to get results. This is a surprisingly high value, a finding that is counterintuitive within human-computer interaction research. This would allow much more freedom for the elaboration of any generative design system. This is to be compared to the long waiting times usually encountered by consumers when dealing with craftspeople and companies offering bespoke products (meaning: custom-made and built-to-order). If the consumer is certain of receiving a satisfying result where no further manipulation is needed, a long waiting time is not negatively perceived. However, two participants using the total control complained that the time needed to compute and display the feedback of manufacturing and stability issues (only 1-2 seconds) was too long in the full control strategy, which tends to show that the acceptable waiting time is strongly dependent

on the number of iterations between user and software that are needed to achieve a satisfying result.

The participants were also satisfied by their final designs. Such results must be handled with caution as the participants were by no means in a real design situation — where the finalized design would be put into production. Moreover, the different dimensions constituting the overall satisfaction (e.g. novelty) have not been investigated. But once again, the respondents did not present signs of dissatisfaction regarding their tessellations-based designs, which is a first positive result towards the use of complex morphologies in design.

Although the questionnaire was anonymous, different biases may have occurred. For example, the participants may have overestimated their satisfaction level as “a sign of encouragement” towards the developers of the system. Nevertheless, it is likely that the participants were not unsatisfied, or would have expressed their dissatisfaction, as the designers did regarding the partial control strategy. An aspect that has not been accounted for is the effect of training on the satisfaction level. A trained user would perhaps have a lesser level of satisfaction than an occasional or single-time user.

In this paper, we have investigated how 2D morphologies can be applied to furniture as it provides a suitable test bed because any person understands what furniture represents, and it is still constrained in terms of weight, stiffness and visual appeal. However, the approach should be possible to apply to other, more complex, product typologies and morphologies as well, and current studies are directed at exploring its domain of applicability.

CONCLUSION

The handling of complex morphologies is not straightforward, but the users seem to enjoy both total control and no control strategies. It seems that a solution with two different modes, as the one presented in this article, offers the user the most satisfaction, as opposed to a solution with only one in-between mode, as presented in [11]. At the outset of this article, the trend towards consumer participation in product design and realization was presented. The fact that there was no sign of dissatisfaction for the no control strategy implies that Toffler's ‘prosumer’ [1] not necessarily desires to be deeply involved in the intricacies of algorithmic design to experience new heights of empowerment. Moreover, the fact the users were ready to wait more than 20 h in average implies a large flexibility for online solutions (possibility to defer the calculation part to a remote server, possibility to queue and handle the requests in different ways, etc.).

REFERENCES

[1] Toffler, A., 1971, *Future Shock*, 2nd Edition, Bantam Books, New York, NY.
[2] Chau, H. H., Chen, X., McKay, A. and de Pennington, A., 2004, "Evaluation of a 3D shape grammar implementation", *1st Design Computing and Cognition Conference - DCC'04*, Cambridge, MA, pp. 357-376.

[3] EZCT Architecture & Design Research, Hamda, H. and Schoenauer, M., 2004, *Studies on Optimization: Computational Chair Design using Genetic Algorithms*, EZCT Architecture & Design Research, Paris.
[4] McCormack, J. P., Cagan, J. and Vogel, C. M., 2004, "Speaking the Buick language: Capturing, understanding, and exploring brand identity with shape grammars", *Design Studies*, **25**(1), pp. 1-29.
[5] Pugliese, M. J. and Cagan, J., 2002, "Capturing a rebel: Modeling the Harley-Davidson brand through a motorcycle shape grammar", *Research in Engineering Design*, **13**(3), pp. 139-156.
[6] Kram, R. and Weisshaar, C., 2003, *Breeding Tables*, <<http://www.kramweisshaar.com/projects/breeding-tables.html>>, last accessed: 22 February 2012
[7] Piasecki, M. and Hanna, S., 2010, "A redefinition of the paradox of choice", *4th Design Computing and Cognition Conference - DCC'10*, Stuttgart, pp. 347-366.
[8] Schwartz, B., 2004, *The Paradox of Choice: Why More is Less*, HarperCollins Publishers, New York, NY.
[9] Metlin, 2008, *Costa Minimal Surface [image]*, <http://commons.wikimedia.org/wiki/File:Costa_minimal_surface.jpg>, last accessed: 20 January 2013. CC BY-SA 3.0.
[10] Landis, N., 2008, *Cellular Automata [image]*, <http://commons.wikimedia.org/wiki/File:R090_pulse_wide.png?uselang=sv>, last accessed: 20 January 2013. CC BY-SA 3.0.
[11] Nordin, A., Motte, D., Hopf, A., Björnemo, R. and Eckhardt, C.-C., 2010, "Complex product form generation in industrial design: A bookshelf based on Voronoi diagrams", *4th Design Computing and Cognition Conference - DCC'10*, Stuttgart, pp. 701-720.
[12] Mugge, R., 2007, *Product Attachment*, PhD thesis, Dept of Product Innovation and Management, Faculty of Industrial Design Engineering, Delft University of Technology, Delft.
[13] Sims, K., 1992, "Interactive evolution of dynamical systems", *First European Conference on Artificial Life*, Paris, Toward A Practice Of Autonomous Systems, pp. 171-178.
[14] Secretan, J., Beato, N., D'Ambrosio, D. B., Rodriguez, A., Campbell, A., Folsom-Kovarik, J. T. and Stanley, K., 2011, "Picbreeder: A case study in collaborative evolutionary exploration of design space", *Evolutionary Computation*, **19**(3), pp. 373-403.
[15] Ren, Y. and Papalambros, P. Y., 2011, "A design preference elicitation query as an optimization process", *Journal of Mechanical Design*, **133**(11), pp. 111004-1-111004-9.
[16] Nordin, A., Hopf, A., Motte, D., Björnemo, R. and Eckhardt, C.-C., 2011, "Using genetic algorithms and Voronoi diagrams in product design", *Journal of Computing and Information Science in Engineering*, **11**(011006).

- [17] Austrell, P. E., Dahlblom, O., Lindemann, J., Olsson, A., Olsson, K.-G., Persson, K., Petersson, H., Ristinmaa, M., Sandberg, G. and Wernberg, P.-A., 2004, *CALFEM : A Finite Element Toolbox - Version 3.4*, Structural Mechanics LTH, Lund University, Lund.
- [18] de Berg, M., Cheong, O., van Kreveld, M. and Overmars, M., 2008, *Computational Geometry - Algorithms and Applications*, 3rd Edition, Springer-Verlag, Berlin.
- [19] Stiny, G., 1977, "Ice-ray: A note on the generation of Chinese lattice designs", *Environment and Planning B*, 4(1), pp. 89-98.
- [20] Schattschneider, D. and Dolbilin, N., 1998, "One corona is enough for the Euclidean plane", in Patela J. (Ed.), *Quasicrystals and Discrete Geometry*, 1998, American Mathematical Society, Providence, RI, pp. 207-246.
- [21] Ericsson, K. A. and Simon, H. A., 1993, *Protocol Analysis - Verbal Reports as Data*, Rev. Edition, MIT Press, Cambridge, MA.
- [22] Nielsen, J., 1993, *Usability engineering*, New ed. Edition, AP Professional, Boston.