Complex product form generation in industrial design: A bookshelf based on Voronoi diagrams

Nordin, Axel; Motte, Damien; Hopf, Andreas; Bjärnemo, Robert; Eckhardt, Claus-Christian

Published in:
Proceedings of the 4th Design Computing and Cognition Conference - DCC'10

DOI:
10.1007/978-94-007-0510-4_37

2010

Document Version:
Publisher's PDF, also known as Version of record

Complex product form generation in industrial design: A bookshelf based on Voronoi diagrams

Axel Nordin, Damien Motte, Andreas Hopf, Robert Bjärnemo, Claus-Christian Eckhardt
Department of Design Sciences, Lund University, Sweden

Complex product form generation methods have rarely been used within the field of industrial design. The difficulty in their use is mainly linked to constraints – such as functionality, production and cost – that apply to most products. By coupling a mathematically described morphology to an optimisation system, it may be possible to generate a complex product form, compliant with engineering and production constraints. In this paper we apply this general approach to the designing of a bookshelf whose structure is based on Voronoi diagrams. The algorithm behind the developed application used here is based on a prior work submitted elsewhere [1], adapted to the bookshelf problem. This second example of product form generation, which includes specific constraints, confirms the relevance of the general approach.
The handling of complex morphologies is not straightforward. Consequently, an explorative study on that theme has been performed. A user interface has been developed that allows for designing a bookshelf based on Voronoi diagrams. The user interface was subsequently tested by peer designers. The results suggest that user attitudes diverge: one faction preferred maximum freedom of creation, that is, maximum control of the form creation process; the other faction wanted the application to generate a bookshelf based on their functional needs (e.g. adapt to the number and types of objects to be stored) and would ask for a "surprise me" effect for the final solution.

Introduction

Although complex – mathematical or nature-inspired – form generation methods have long been employed in the field of architecture [2, p. 137], this has rarely been the case in industrial design. One barrier for such development in the latter discipline is the multitude of constraints linked to

Design Computing and Cognition DCC'10. J.S Gero (ed), pp. xx-yy.

the form-giving of products; surfaces are often functional, the artefacts are produced in several exemplars – meaning that the product form must be modified to suit production systems; cost control is consequently important; finally, engineering constraints must also be respected. Another obstacle may be the lack of educational initiation in industrial design.

However, the situation is beginning to evolve; the ongoing digitalisation of the entire product design activity simplifies access to form generation tools whilst digital fabrication facilitates the production of physical prototypes. This digitalisation should allow for a much tighter integration of industrial design, engineering and production. Last but not least, one can sense an evolution of the by and large static relationship between the consumer and the product. There is an increasing desire to participate in the designing of products and the potential experiences consumers will share with them. As put forward by Friebe and Ramge [3], the upsurge of independent fashion labels, *crowdsourcing* initiatives or co-working spaces indicates the demand for consumer *empowerment*. This need for co-creation, implemented already in textile [4] but also in more advanced consumer goods businesses like sportswear, [5] and [6], goes well beyond mere material and colour choice – the future *prosumer* [7] desires control over form and function as well. Generative design can be one facilitator in such developments.

In a prior work [1], we have begun to study the use of complex forms in industrial design, taking into account functional, engineering and production constraints. The term complex is to be understood here in the sense that the form is virtually impossible to generate without computer aid. The present publication has two goals. First, we aim at partially validating the approach proposed in [1] by investigating another product type with different kinds of constraints and objectives. Second, the handling of complex forms is not straightforward. Most users (designers or consumers) cannot or do not want to manipulate directly the parameters linked to a morphology; in some cases this is even impossible. It is necessary to find alternative ways of controlling form that make sense for the user. We consequently reflect on the way the user can interact with these complex forms, and a user interface allowing for the development of the bookshelf based on Voronoi diagrams has been developed and tested.

Background

Expanding the morphologic repertoire in design

The morphologic repertoire is the infinite repository of all two- and three-dimensional forms, structures and compositions thereof. Although no morphology has *a priori significance* – its adequacy pertaining only to the intended usage criteria – a designer's command of an extensive morphologic vocabulary and grammar enhances creative expressivity, which, in turn, is no end in itself, but essential for a designer's ability to rise to the present and future economic and ecologic challenges [8].

The prevalent *modus operandi* concerning the form-giving activity in industrial design is characterised by explorations that depend on the individual capability to mentally manipulate a solution space from which to select and express the intended result. In that sense a designer or team of designers is equivalent to an *auteur*, because the initial objective and resultant object are inextricably linked by a volitional act [9]. The morphologic repertoire, on which the form-giving activity is based, is by and large rooted in artistic experimentation (serendipity), cursory inspiration (mimicry) or canonical stipulation (methodology). Reliance on such rather traditional approaches is not problematic *per se*; a trained designer generally will come out with a *satisfying* solution to a brief.

However, individualist or formal aesthetic motivations preclude the creative potential of *generative* mathematical and natural morphologies that could be equally inspiring points of departure. Even more importantly, once these morphologies are coupled to algorithmic design processes, they provide access to *performative* and *emergent* qualities only found in dynamic systems [9]. Algorithmically controlled morphologies not only pave the way for the unimaginable, they also present methods to handle and adapt them to an intended purpose. In that sense, the form-giving activity is augmented or rather transmuted into a *form-finding* process – an almost literary *meta-design* activity concerned with the formulation of rules and constraints from which desired or unintended, but feasible, results emerge. Quite possibly, the self-conception of what a designer is and does will change considerably in the future; designers may eventually become *scriptwriters*, *moderators* or *curators* – or even redundant altogether?

Form generation in the larger context

Apart from providing new creativity-enhancement tools, it is important to integrate them into the design context. As mentioned above, an industrial designer's activities in the product development process are intertwined with engineering and production preparation activities. Nevertheless, even in organisations were these different functions are well integrated, iterations are still unavoidable. Taking advantage of the digitalisation of engineering and production preparation activities, efforts have been made taking into account their different constraints early on in the development process (see e.g. [10]). In the latter context, the industrial design activity is still somewhat overlooked. By integrating critical engineering and production requirements in the design process, the likelihood for a designer to "get it right first time" – or at least to reduce the number of critical changes in the design– is higher.

If form is algorithmically generated and engineering and production constraints integrated in the process, partial or full transfer of the design activity to consumers becomes a concrete option – new business models will emerge as a result. Many businesses have already implemented mass-customisation to some degree, with the automotive industry being a precursor. That approach has been adopted in other industries like in the case of Threadless® (clothing) [4] or Innovate with Kraft® (food) [11]. The demand for bespoke products and services is increasing, even in markets where branding is important. "The world has changed. Consumers interact with brands on their own terms," says Trevor Edwards, Vice President, Brand and Category Management for Nike® [12]. Consequently, the NikeId® website and studios, [12] and [13], provide for high-level customisation of athletic footwear. Many consumers in saturated economies are decreasingly passive; it will be ever more important to hand over some control over the products-to-be they desire. Even if the traditional modes of product development remain dominant in the foreseeable future, the exploitation of niche markets becomes increasingly relevant and more profitable [14].

Handling complex forms requires the development of an adequate way for users to make sense of the creation process. The design environment is discussed in the section "User interaction".

Related works on generative product design systems

Generative design systems that take into account functional and technical constraints (engineering and production) as well as aesthetic intent have existed for long in the field of architecture while such systems have rather been the object of isolated research studies in industrial design.

In industrial design, generative design has primarily been used for stylistic purposes. In the seminal work of Knight [15], a parametric shape grammar was developed for the generation of Hepplewhite-style chair-backs. Orsborn et al. [16] employed a shape grammar to define the boundaries between different automotive vehicle typologies. Recent works have focused on branding related issues. With the help of shape grammars, new designs based on the Buick® [17], Harley-Davidson® [18], Coca-Cola® or Head & Shoulders® [19] brand were developed. Further research is undertaken towards rules that are linking form and brand (e.g. [20] for GA-based systems and [21] for shape grammars).

Some works are crossing the boundaries between engineering and industrial design, taking into account functional or technical constraints and aesthetics. Shea and Cagan [22] used a combination of shape grammar and simulated annealing for both functional and aesthetical purposes and applied it for truss structures (truss structures are commonly used for both heavy industrial applications and consumer products). Shape grammars are used to generate new designs while the simulated annealing technique directs the generation towards an optimum. The design objectives were functional (minimise weight, enclosure space and surface area), economic and aesthetic (minimise variations between lengths in order to get uniformity, make the proportions respect the golden ratio). Their model has been reused in [23] (shape grammar and genetic algorithm, or GA) to develop stylistically consistent forms and has been applied to the design of a camera. The designs generated took into account the constraints linked to the spatial component configuration. A designer was in charge of the aesthetic evaluation, following the interactive genetic algorithm (IGA) paradigm. Ang et al. [23], also using shape grammars and GA, developed the Coca-Cola® bottle example of [19] and added functional considerations (the volume of the bottle), that were constrained to approach the classic Coca-Cola® bottle shape. Morel et al. [24], within the IGA paradigm, developed a set of chairs optimised for weight and stiffness. Finally, Wenli [25] developed a system that, through adaptive mechanisms, allows it to learn the designer's intent faster; that system was implemented as a plug-in for a CAD system and applied to boat hull design.

Approach

In the works presented above, shape grammar is the main technique used. In our study, we use a pre-determined computational geometry (namely, Voronoi diagrams) instead and optimise the form according to engineering and production constraints. The use of mathematical and natural morphologies has not been the object of much applied research in industrial design, but has been implemented for the development of several products and prototypes in industry (see [1] for a coarse typology of such products).

An important observation is that, in many cases, plastics rapid prototyping is the fabrication system of choice. Restricting the application of an extended morphologic repertoire to rapid prototyping may not be sustainable in the long term as only a few types of products are suitable for this fabrication technology. Rapid prototyping is likely not to be the panacea. That is why we focused on “traditional” production systems such as laser cutting and CNC sheet metal bending. Defining and evaluating the aesthetics is up to the user through the IGA paradigm. This continuation of Nordin et al. [1] aims first at partially validating that paradigm by using a different product (bookshelf vs. table), another material (phenolic film – PF – coated veneer core plywood), and consequently a different manufacturing system (circular saw and strip-grinder) and different constraints (addition of a functional constraint). Second, the focus is on how new forms can be practically handled. The user (designer or consumer) may not necessarily be interested in a certain mathematical or natural morphology *per se*, but rather in its aesthetic potential. It is quite difficult to handle complex morphologies. Proper controls have to be defined and, to that end, a dedicated interface has been created and tested.

Short on the Voronoi structure

A Voronoi (or Thiessen) structure is a simple 2D tessellation, as shown in Figure 1. Structures based on a Voronoi structure (or Voronoi diagram) are often found in very robust yet lightweight structures in nature. Apart from aesthetic aspects, a Voronoi-based bookshelf would consequently have a structure well suited for carrying heavy loads such as books whilst maintaining a low weight. A Voronoi structure can be described as follows: Let $p_1,.., p_n$ 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 is constituted of all such cells. An overview of a Voronoi diagrams’ properties can be found in [26, chapter 7].

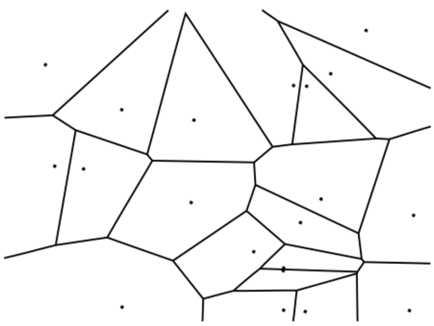

Figure 1. Example of a Voronoi diagram.

The bookshelf

As in [1], the Voronoi structure is applied to a common type of furniture - a bookshelf. In the table case, the Voronoi structure was used as support for a glass tabletop, see Figure 2. In case of the bookshelf, every Voronoi cell serves as a storage compartment, see Figure 8.

The manufacturing process consists of cutting, gluing and assembling PF coated veneer core plywood parts. Each Voronoi cell is manufactured as an individually cut and glued compartment. The critical constraints related to functionality and production methods are described later.

Figure 2. Example of table developed in [1]. The Voronoi structure was used as support for a glass tabletop and was optimised with respect to deformation and CNC bending constraints.

User interaction

The initial question regarding functionality, interactivity and output of a generative design and optimisation application is whether the designer or consumer is willing to relinquish control to a certain degree. An *auteur* designer-personality may hold the view that algorithms *seemingly* restrict creativity; an experimentally open-minded design-personality may, in contrast, actively seek for emergent behaviour to find unexpected solutions. . But it should be noted here that often, modern dance performances, music scores and contemporary architectures have been developed with help of algorithms – and the creativity of William Forsythe, Iannis Xenakis or Zaha Hadid has not been disputed. For consumers, control is important as it is not only the uniqueness of the product that matters, but also its personalisation [27].

However, in case the designer or consumer is attracted to generative design methodologies, the question then is in what way the degree of freedom is limited – and for what reason. The resultant output may either only remotely resemble the chosen start-up design, or turn out to be fairly predictable. One could therefore speak of *controlled serendipity*, wherein the number of constraints – whether aesthetic or functional – is the determining factor.

The sheer number of constraints – determining the degree of usability – must also be considered. Whereas a skilled designer may wish to *condition* a generative design and optimisation application with constraints beyond the aesthetic, e.g. complex functional and production constraints, an unskilled consumer is likely to not wanting to venture much beyond the aesthetic and overall dimensioning. Therefore, such application, if generalised for the widest possible range of input morphologies and output product typologies, needs a very customisable graphical user interface (GUI) in order to show and hide complexity depending on the task at hand. An interface in accordance with such conception of the design work with respect to an expanded morphology has been produced and is presented next. The acceptance of that interface has then been explored by letting a group of peer designers use it and elaborate on their experiences. Their feedback is presented in the second part of this section.

The interface

In [1], users were able to define only the contour of a table and could not affect the layout of the Voronoi cells; in the case of the bookshelf it was decided to concede greater control to users – manipulating the compartmentalisation of the bookshelf for both aesthetic and functional purposes– and get feedback from a group of designers on that matter.

To enable users to control the appearance of the bookshelf, several strategies were discussed. It would have been possible to give them complete freedom to place the points of the Voronoi diagram. This, however, would have be a tedious task for someone not interested in controlling every aspect of the tessellation – and would be too complex for someone not familiar with the specific behaviour of Voronoi diagrams. Instead, it was decided to offer users the option of controlling the compartmentalisation via a set of parameters. The *staggering* and *randomness* parameters allow for the control of the generation of aesthetically interesting structures. *Staggering* controls the internal angles of the compartments so that the user can create cell-forms ranging from square to hexagonal. *Randomness* controls the randomisation of angles and compartment sizes.

Beside the functional parameters that determine the external dimensions of the bookshelf (*height*, *width* and *depth*), its usability is also very much dependent on compartment sizes and forms. To that end, it was decided to offer users three parameters ruling the distribution, size and form of the compartments, namely *growth*, *sparsity* and again *staggering* (the same parameter as above). *Growth* controls how the sizes of compartments are distributed to enable users to generate a bookshelf with small compartments on top and progressively larger compartments towards the floor. *Sparsity* controls the scale of the entire Voronoi diagram to allow users to uniformly scale the compartments up or down.

Additionally, three variables (*x-position*, *y-position* and *rotation*) enable the user to fine-tune the bookshelf structure. Users may want to avoid small compartments at the outer perimeter; rotating and/or shifting the entire structure horizontally and/or vertically can achieve this.

To reduce the complexity of handling nine variables, the creation process was divided into three steps – in the first step, the dimensions of the bookshelf are set; in the second step, its internal Voronoi structure is defined and in the third step, the structure can be fine-tuned. Finally, the bookshelf is optimised and presented to the user (see Figure 4). The GUI is presented in Figure 3 with all steps shown at once.

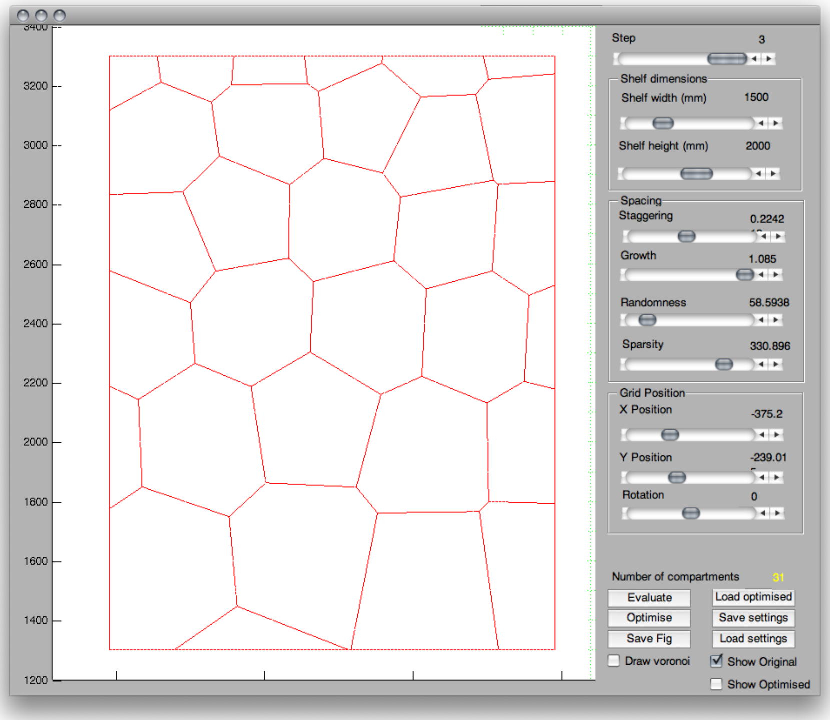

Figure 3. The GUI for the bookshelf creation application (all steps shown).

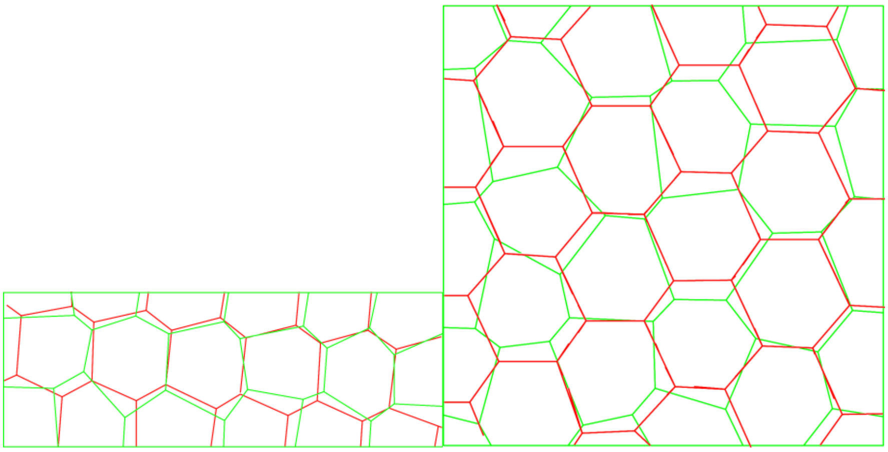

Figure 4. The original user defined structure in black, optimised solutions in grey (in red, respectively green in the colour version).

Interface evaluation

To assess the application's usability and the selection of parameters, four professional industrial design peers tested the interface. They were asked to use the application to create and optimise one bookshelf per person and were questioned on the tool's usability and their opinion of the amount or lack of control over the creation process and final solution.

What became apparent from the usability testing was that the designers were split into two distinct factions – either wanting maximum freedom of creation, or wanting the application to generate bookshelves based on their needs.

The designers requiring maximum freedom wanted to be able to edit the Voronoi structure in detail by adding, removing and moving the Voronoi sites (points) as well as defining the bookshelf's contour. They felt deceived noticing that the algorithms had changed their structure after optimisation for production and they felt that their work had been taken away from them. They would have preferred to be able to get continuous visual feedback on the bookshelf' properties and adjust the structure themselves according to the feedback.

The other faction of designers requested a feature to input information on their particular requirements, such as the types of objects to be stored and/or the dimensions of a room – and then automatically receive a few optimised solutions fulfilling their needs to choose from.

The conclusion is that the application needs to accommodate both types of users; those requiring absolute control and those only interested in the bookshelf's functionality – something which could be achieved by either offering two modes of operation, or two entirely different applications. The goal of allowing users greater freedom in designing the structure was achieved, but evidently it will be necessary to concede to both types of users even more and/or different kinds of control.

Although at first feared to be a usability problem, the time users had to wait while the final solution was being optimised was not considered a major drawback in the application. In fact, some were willing to wait as long as one evening before getting the result – given that it would be satisfactory.

A photo-realistic rendering of the final solution was also requested – or at least an isometric representation including a depiction of the material thickness.

The general search algorithm

The algorithm for optimising the bookshelf's structure is essentially the same as in [1], with some adaptations for the present project. As described in the section above, the user "designs" the initial prototype that will be used to create the first generation of individuals. Only one final solution is presented to the user, who, if not satisfied, can re-launch the optimisation process an infinite number of times. The user can change the newly obtained bookshelf at each iteration step (subsequent testing by the designers showed that this was superfluous, see last section). Because the interaction is limited to choosing or not choosing the outcome of the optimisation, the principle of the algorithm is more of a "semi-interactive" optimisation, than a usual IGA. The adapted algorithm is presented Figure 5.

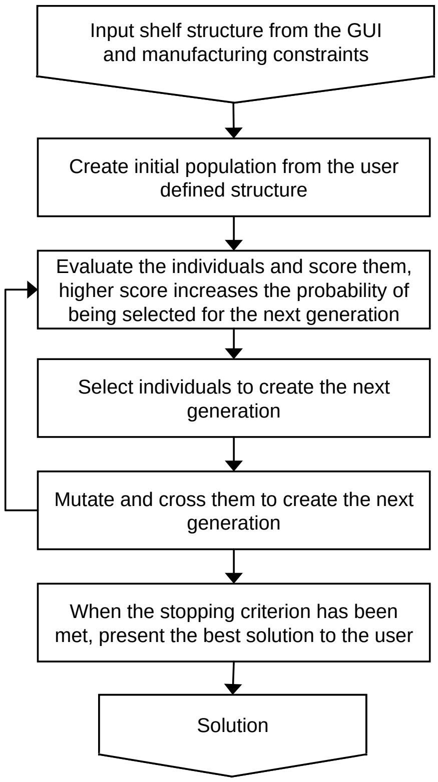

Figure 5. Diagram of the general algorithm.

The evaluation model for the multi-objective optimisation has also been modified to better suit the usability and production requirements of a bookshelf. In [1], a structural analysis was performed on the generated tables to ensure their stability – the most time-consuming evaluation step. Because a Voronoi structure is a robust tessellation and the material thickness can be over-dimensioned in the case of a bookshelf to eliminate the risk of structural failure, it was decided not to perform a structural analysis during the optimisation – but rather on the user's selected solution.

Simulations in [1] had also shown that one production constraint was more difficult to fulfil than others. These time-consuming tasks had resulted in a prioritisation of the resolution of the different constraints. In this case, such issues did not occur and the multi-objective optimisation model used is similar to [22], a weighted sum of both the constraints and the objective values.

The GA characteristics

As in [1], the *representation* of the structure to be optimised consists of the coordinates of the Voronoi sites, $p_1,..,p_n$. The number of Voronoi sites, n, depends on the user input.

(1) $$genome = \begin{bmatrix} x_{1,1} & x_{2,1} \\ \vdots & \vdots \\ x_{1,n} & x_{2,n} \end{bmatrix}$$

The Voronoi diagram is created from the coordinates of these sites and cut off along the edges of the user-defined contour of the bookshelf (see e.g. Figure 3). The resulting polygonal structure is used for evaluation (see below). The *mutation function* is identical to the one used in [1], and consists in displacing each coordinate, $x_{i,j}$ of the Voronoi sites in the representation by a random amount, $\delta_{i,j}$, varying between 0 and 10% of $x_{i,j}$. The maximum amount of change decreases linearly from the first generation to the last. The *crossover function* is also identical to the one used in [1], and consists in exchanging the coordinates of the Voronoi sites of two parents after a random mutation point to create two children.

As in [1] the *selection* is based upon ranking the individuals according to their fitness (the fitness function is described by Equation 5). An individual's probability for being selected is proportional to its ranking.

Duplicating the user-defined individual to fill the population creates the initial population; then the mutation function is applied to all individuals in the population apart from one, which remains unchanged.

The parameters of the search algorithm were chosen to give a feedback time of around one hour, which was deemed reasonable, as well as a high probability of receiving a solution that fulfilled all constraints. Therefore the stopping criterion was chosen to be the maximum number of generations, which was set to 300. The size of the population was set to 50 individuals. This proved to give feasible solutions to all user-defined structures during the testing. See Figure 7 for an example of a typical fitness curve.

Constraints, objectives and evaluation

For the table example of [1], it was required that the cells have walls longer than 30 mm and the internal angles are larger than 33° in order to be suited for production with a CNC sheet metal bending machine [28]. It was also necessary to take care of the stiffness and deformation (engineering constraint). In the case of the bookshelf, the properties of a strip-grinding machine constrain each PF coated veneer core plywood segment's geometry. The segments need to be attached to a support at a fixed distance from the strip. Given the minimal length needed to fix the parts to the support and the length from the support to the strip, which depends on the slipping angle, it was decided that the minimal segment length should be 100 mm (lmin) and the smallest angle 33° (αmin).

These requirements are expressed by the following function:

$$\begin{aligned} &p_l = k_l \cdot \min(l) \text{ } if \text{ } \min(l) \le l_{\min} \\ &p_l = 100 \text{ } otherwise \\ &k_l = 100 / l_{\min} \end{aligned} \tag{2}$$

where min(l) is the shortest cell wall found in an individual and

$$\begin{aligned} &p_\alpha = k_\alpha \cdot \min(\alpha) \text{ } if \text{ } \min(\alpha) \le \alpha_{\min} \\ &p_\alpha = 100 \text{ } otherwise \\ &k_\alpha = 100 / \alpha_{\min} \end{aligned} \tag{3}$$

where min(α) is the smallest angle measured in an individual.

The chosen plywood thickness is 9 mm, which is overdimensioned, meaning to be stable enough for whatever Voronoi network. Consequently, there was no engineering constraint. As a control, the final bookshelves presented in this paper were subsequently analysed (see the Results section), and showed no excessive deformation. A functional requirement for a bookshelf is how well books stack in the compartments. A critical factor for this is the angle between the lower walls in each compartment. A 90° angle is optimal for books to be stacked in a compartment, an angle β_0 between 80° and 100° is considered acceptable. The individual is therefore scored after its percentage of cells that fulfil this specification.

$$p_\beta = k_\beta \cdot n(\beta) / n(cells)$$
$$k_\beta = 100 \quad (4)$$

The objective function to be maximised is

$$p = p_l + p_\alpha + p_\beta \quad (5)$$

which corresponds to the fitness of each individual. The constants k_l, k_α and k_β have been determined so that the maximum score for fulfilling each of the requirements is the same, in this case 100 points (in other words this is a sum for which all the requirements have the same weight).

Results

Sample bookshelves generated by the designers who tested the interface are presented in Figure 6, showing variations in terms of dimensions and compartments. Figure 7 shows the fitness curve of the evolution during the optimisation of one of the designer's bookshelves. The population converges towards the feasible solution space; using a population of 50 individuals during 300 generations was satisfactory.

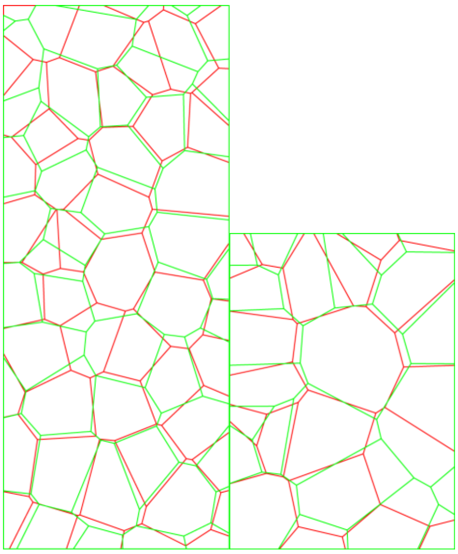

Figure 6. Examples of bookshelves generated by the designers. The original user defined structure in black; optimised solutions in grey (in red, respectively green in the colour version).

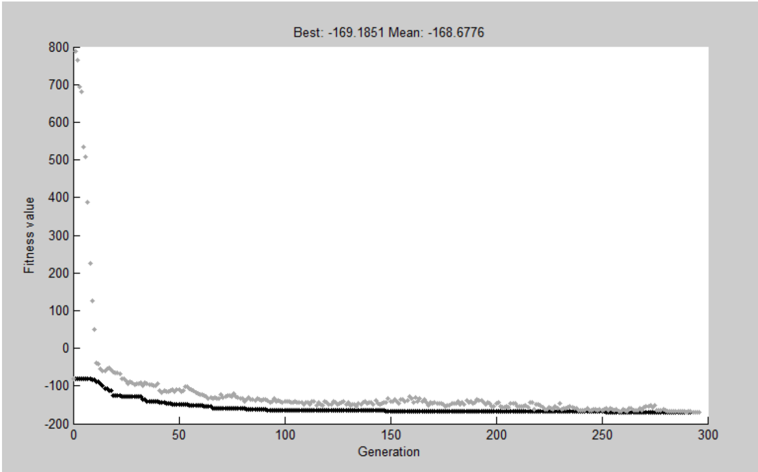

Figure 7. Typical appearance of the fitness curve during the optimisation. In black: the fitness of the best individual, in grey: the mean fitness of the current population.

Two shelves are presented in more detail. Both (700x2000 mm and 2000x2000 mm, 9 mm plywood) were generated using the application and are shown in Figure 4 and Figure 8. Their optimisation took around 1 hour on a dual-core 2.2 GHz processor.

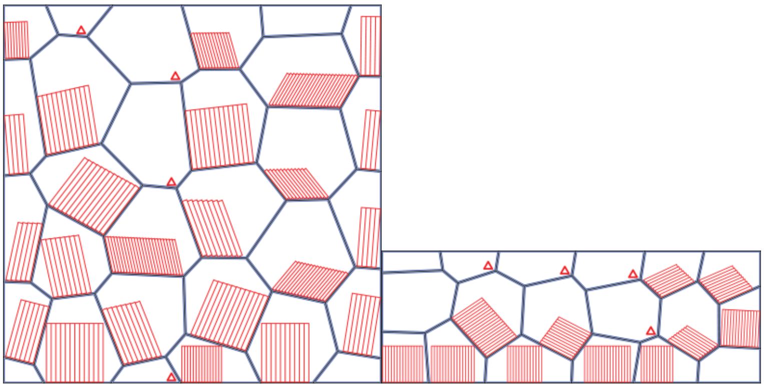

Figure 8. Illustration of the final bookshelves with stacked books. The triangles indicate where the functional objective (equation 4) has not been met.

To verify that these bookshelves were structurally sound and stable, they were tested with FEM-analysis. To simulate the weight of books, the bookshelves were subjected to a load of 10 kg in each compartment as well as the standard gravitational acceleration. The material used was 9 mm

Low-density fibreboard (LDF-board, an engineered wood product that has properties similar to PF coated veneer core plywood, but is isotropic, which makes the analysis simpler and more conservative), with the modulus of elasticity being 8 GPa, Poisson's ratio being 0.3 and density being 500 kg/m^3 [29]. The analysis was done in ANSYS Workbench®. The structural analysis indicated that the maximum deformation of either bookshelf never exceeded 0.4 mm. The results are shown in Figure 9 and Table 1.

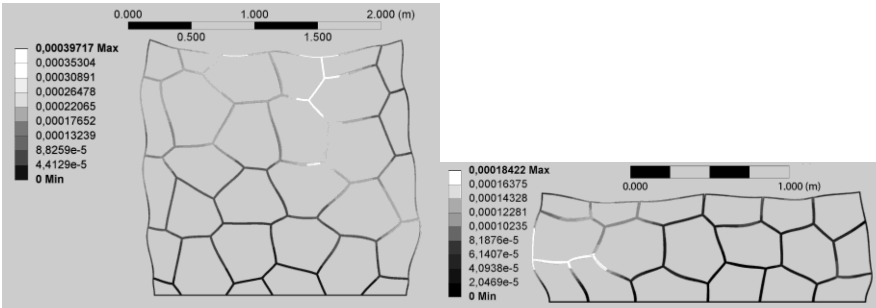

Figure 9. Structural analysis of the two bookshelves using ANSYS Workbench®.

Table 1. Results from the analysis in ANSYS Workbench®.

Bookshelf	**Volume(m^3)**	**Weight(kg)**	**Max. deformation(m)**
700x2000	0.0538	26.911	1.84×10^{-4}
2000x2000	0.1225	61.259	3.97×10^{-4}

To verify the aesthetic qualities and their commercial potential, the two bookshelves were subsequently 3D-modelled with 9 mm board thickness; then photo-realistically rendered based on the output geometry of the application and subsequently shown to peer designers. The photo-realistic renderings are shown in Figure 10 and were very well received. To confirm the bookshelves’ manufacturability, drawings have been produced from the output and two prototypes are being built.

Figure 10. Photo-realistic renderings of two bookshelves.

Conclusion and further research

In this study, a bookshelf generating system using computational geometry (Voronoi structure) – taking into account functional, engineering and production constraints – has been developed. This second application further validates our approach and confirms that using complex forms for designing artefacts has the potential to become a more common practice.

Higher levels of user control, feedback and automation could be implemented in the present and similar applications. In terms of user control, a higher degree of freedom in manipulating the structure would be desirable, for example adding, removing and moving points and defining a custom contour of the bookshelf. Concerning feedback, visual indicators relating to the monitoring of functional and production parameters in the creation and manipulation process could be integrated. Equally important would be to allow users to input individual requirements such as what types of objects are to be stored and in which quantity. Surprisingly, some designers actually desire to relinquish control and let the algorithm determine the design in the full for them. Automated production drawing or data generation would be a useful feature as well as an approximate estimate of cost dependent on material choice, but also weight and sizes of items to be packed and shipped. The interface has been tested by some designers, but the generation of the bookshelf could be equally controlled by consumers to provide them with *bespoke* products.

It is foreseeable that the continuation of this work may result in a generalised tool; that is to say an application that allows designers or consumers to chose from a much wider range of tessellations in order to generate an equally wider range of product types. It is well conceivable that such application will allow for any user-created or user-input tessellations but also integrate entirely new usability, functionality and production constraints for new types of products. This will be the object of future research.

References

1. Nordin A, Hopf A, Motte D, Bjärnemo R, Eckhardt C-C (2009) Using genetic algorithms and Voronoi diagrams in product design. Journal of Computing and Information Science in Engineering - JCISE, submitted.
2. Shea K (2004) Explorations in using an aperiodic spatial tiling as a design generator, 1st Design Computing and Cognition Conference DCC'04, Cambridge, MA, 137-156.
3. Friebe H, Ramge T (2008) The DIY Brand - The Rebellion of the Masses against Mass Production (In German. Original title: Marke Eigenbau: Der Aufstand der Massen gegen die Massenproduktion). Frankfurt: Campus Verlag.
4. Lakhani KR, Kanji Z (2009) *Threadless: The Business of Community*, Harvard Business School Multimedia/Video Case 608-707, Harvard Business School, Cambridge, MA.
5. Moser K, Müller M, Piller FT (2006) Transforming mass customisation from a marketing instrument to a sustainable business model at Adidas. International Journal of Mass Customisation 1:463-479.
6. Bouché N (2009) Keynote V: How could we create new emotional experiences with sensorial stimuli?, 4th International Conference on Designing Pleasurable Products and Interfaces - DPPI'09, Compiègne.
7. Toffler A (1971) Future Shock. 2nd ed. New York, NY: Bantam Books.
8. Hopf A (2009) Renaissance 2.0 - Expanding the morphologic repertoire in design, 23rd Cumulus Conference 23/09, Melbourne.
9. McCormack J, Dorin A, Innocent T (2004) Generative design: a paradigm for design research, Futureground, Melbourne.
10. Lin B-T, Chang M-R, Huang H-L, Liu C-Y (2009) Computer-aided structural design of drawing dies for stamping processes based on functional features. The International Journal of Advanced Manufacturing Technology 42:1140-1152.
11. Kraft Foods (2006), Innovate with Kraft, <http://brands.kraftfoods.com/innovatewithkraft/default.aspx>, last accessed: January 17, 2010.
12. Nike Biz Media (2007), New NIKEiD studio opens at NikeTown London giving consumers a key to unlock the world of design, <http://www.nikebiz.com/media/pr/2007/11/01_nikeidlondon.html#>, last accessed: January 17, 2010.
13. NIKEiD (1999), <http://www.nikeid.com/>, last accessed: January 17, 2010.
14. Anderson C (2006) The Long Tail: Why the Future of Business is Selling less of more. New York, NY: Hyperion.

15. Knight TW (1980) The generation of Hepplewhite-style chair-back designs. Environment and Planning B 7:227-238.
16. Orsborn S, Cagan J, Pawlicki R, Smith RC (2006) Creating cross-over vehicles: Defining and combining vehicle classes using shape grammars. Artificial Intelligence for Engineering Design, Analysis and Manufacturing - AI EDAM 20:217-246.
17. McCormack JP, Cagan J, Vogel CM (2004) Speaking the Buick language: Capturing, understanding, and exploring brand identity with shape grammars. Design Studies 25:1-29.
18. Pugliese MJ, Cagan J (2002) Capturing a rebel: Modeling the Harley-Davidson brand through a motorcycle shape grammar. Research in Engineering Design 13:139-156.
19. Chau HH, Chen X, McKay A, de Pennington A (2004) Evaluation of a 3D shape grammar implementation, 1st Design Computing and Cognition Conference DCC'04, Cambridge, MA, 357-376.
20. Cluzel F, Yannou B (2009) Efficiency assessment of an evolutive design system of car contours, 17th International Conference on Engineering Design - ICED'09, Stanford, CA.
21. Orsborn S, Cagan J, Boatwright P (2008) Automating the creation of shape grammar rules, 3rd Design Computing and Cognition Conference DCC'08, Atlanta, 3-22.
22. Shea K, Cagan J (1999) Languages and semantics of grammatical discrete structures. Artificial Intelligence for Engineering Design, Analysis and Manufacturing - AI EDAM 13:241-251.
23. Ang MC, Chau HH, McKay A, de Pennington A (2006) Combining evolutionary algorithms and shape grammars to generate branded product design, 2nd Design Computing and Cognition Conference DCC'06, Eindhoven, 521-539.
24. Morel P, Hamda H, Schoenauer M (2005) Computational chair design using genetic algorithms. Concept 71:95-99.
25. Wenli Z (2008) Adaptive interactive evolutionary computation for active intent-oriented design, 9th International Conference on Computer-Aided Industrial Design and Conceptual Design - CAIDCD'08, Kumming.
26. de Berg M, Cheong O, van Kreveld M, Overmars M (2008) Computational Geometry - Algorithms and Applications. Berlin: Springer-Verlag Berlin Heidelberg.
27. Franke N, Piller F (2004) Value creation by toolkits for user innovation and design: The case of the watch market. The Journal of Product Innovation Management 21:401-415.
28. Ferrum Lasercut GmbH, personal communication.
29. Wood Handbook - Wood as an Engineering Material (1999). Madison, WI: Forest Products Laboratory.