DESIGN EXPLORATION WITH STOCHASTIC MODELS

Comparing two examples from façade subdivision

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Abstract. The imitation of natural processes in architectural design is a long-standing area of research in computational design. The approach of “directed randomness” permits the stochastic exploration of a vast space of design possibilities. Stochastic methods are well developed in mathematical biological and the physical sciences and their application in architectural design is beginning to emerge as a new area of investigation. This paper presents two examples of modelling design exploration using stochastic models of variation. A stochastic model of design exploration is one where a system’s subsequent states are determined by a combination of the process’s predictable actions and by a random element. The random element may be the function of either an algorithm or human intervention. The behaviour of a stochastic process is therefore inherently non-deterministic. The paper discusses two stochastic process models, one based on wind motion and the second based on rotation. The stochastic model based on wind motion is applied to a facade subdivision problem to generate a vast space of possible panel configurations. The model of stochastic rotation is applied to a moveable panel facade based on pentagonal tiling. The models combine known parameters such as number and spacing of elements with an uncertain stochastic variable, wind direction and velocity in the case of one example and 2D and 3D rotation in the second example. The paper concludes with a discussion on a need to make an explicit allowance for uncertainty.

Keywords. Design Variation; Stochastic Process Models; Design Space Exploration

1. Introduction: Stochastic Phenomena and Design

The application of scientific and logical models and methods to the generation of architectural design is a long-standing focus of design space explora-
tion research. In particular, stochastic methods are well developed in mathematical biological and the physical sciences. The use of stochastic models to architectural problems permits the use of “directed randomness” (Shea, 2004) as a design exploration strategy. The application of this strategy remains at an early stage of research. This paper presents the results of modeling design phenomena using stochastic models of variation as design drivers.

Stochastic models have proved effective in the modelling of many kinds of natural phenomena. For example, describing the motion due to wind phenomena is a significant example of a stochastic model. A stochastic model is one where a system’s subsequent states are determined both by the process’s predictable actions and by a random element. The behaviour of a stochastic process is inherently non-deterministic, so an explicit allowance needs to be made for uncertainty. The paper discusses two stochastic process models for exploring design variations. Robust methods for dealing with uncertainty have been developed in many disciplines. Stochastic processes are well known in mathematics, biology, physics and artificial intelligence wherein uncertain parameters are used to model complex phenomena. The financial markets use stochastic models to represent the seemingly random behaviour of assets such as stocks, commodities and interest rates. In the field of computer graphics, stochastic processes are used to generate natural landscapes, trees and model particle systems.

As the results of a stochastic process result from both known and unknown elements, such models are an effective means for experimenting with and developing better understandings of continuous design phenomena. They allow researchers to understand how design spaces are affected by uncertainty and randomness. Furthermore, the use of stochastic models in design permits the generation of complex geometry governed by simple rules. The inherent non-determinism of stochastic models raises questions about the logic underpinning architectural forms derived by stochastic means.

2. Related work

Generative modelling can be improved by the incorporation of optimisation and their application to architectural design. An early area of work has been the application of search and optimization methods for the automatic selection of design alternatives (D’Cruz, 1983, Radford et al, 1985). In this model, design exploration becomes finding an optimal combination of numeric values for a given set of variables in order to select the best solution for a given problem. In their seminal work, Radford and Gero (1988) propose the exploitation of pareto-optimal fronts to cope with combinatorial complexity.
in design for a given set of performance criteria. A significant body of work based on evolutionary optimisation has (Caldas, 2002; Shea 2004) further developed the field of design optimisation.

The interactive and visual manipulation of geometric models remains a related area of research. Welch and Witkin (1992) propose constraint-based tools to explore visual and functional criteria using “variational design”. Based on this early work, physics based models for discrete and continuous exploration is reported in the literature (Harada et al, 1995). Computer-aided design tools for the manipulation of constrained geometry have also been adapted for “aesthetic engineering” (Sequin, 2005). Theoretical computational frameworks to support “amplification” strategies for design space exploration (as opposed to optimisation) are reported in the literature (Aish &Woodbury, 2005, Woodbury and Burrow, 2006). The development of robust software tools such as Generative Components and Grasshopper permit a flexible combination of search, interactive manipulation and exploration of large spaces of designs. More recently, mathematical techniques from discrete geometry for optimisation of free-form surfaces (Pottman et al., 2007) have been applied in architectural design representations for development of complex tilings and paneling solutions.

The application of stochastic methods to the study of “branching” structures, occurring in natural systems such as trees and rivers, have been modelled with stochastic methods (Bovill, 1996; Greenberg, 2008). Becker (2006) demonstrated a novel method for modelling branch connectivity with smooth nodes based on iso-surfaces. Vanucci (2008) developed the notion of pluri-potential branching systems based on the interaction between biological processes and computation.

3. Exploring wind motion variations

This section presents examples of design generation that outline the problem of exploring a large space of design variations generated by a stochastic model based on wind motion. A model for representing the geometry of bamboo elements and its manipulation by wind motion (Datta et al, 2009) is applied to a facade subdivision problem to generate a vast space of possible panel configurations. The design space of facade variations generated is explored interactively through the manipulation of geometric constraints. The goal of the exploration is to develop a facade system that wraps the building envelope in a cohesive manner, responds to the western solar gain and also have visual interest in terms of its composition. The facade was largely planar, with small angular changes in orientation.
Models of stochastic wind motion developed in the simulation, graphics and animation literature are useful for understanding the applications of stochastic modelling. Shinya and Fournier (1992) propose a general model of stochastic motion of grass and trees due to wind. They develop a two-part model, one for describing fluid flow and another for the forces acting on the object under motion governed by Newtonian mechanics. Ling (1997) develops a model of cloth animation based on wind flow. In their stochastic model, wind phenomena are modelled based on the Navier-Stokes equations known from fluid mechanics. Specifically, the application of a stochastic wind motion model to the sub-division of an external envelope into smaller discrete components is addressed. Instead of deterministic subdivision constraints, explicit uncertainty is introduced into the system of subdivision.

In particular, the possibilities for variation under the influence of “wind” as a design driver for stochastic exploration are investigated. A representation for “bamboo” elements that can be deformed by stochastic motion based on a simple wind model (Figure 1) is proposed. The Western façade of the Kehua link building in Zheizhang, China, designed by Williams Boag Architects forms a test case for exploring stochastic subdivision (XX).

The model of stochastic design exploration was tested for façade subdivision within the following prescribed constraints:

- subdivide the west face of the link building façade by applying the wind motion model to the bamboo element representation;
- Generate and test alternative façade schemes visually using the bamboo deformation model;
• Alter the parameters and variables of the facade model using differing aesthetic and functional options. These constraints could then be varied rapidly using constrained motion of vertical elements; and
• Explore the design space of subdivision variations under stochastic control.

Figure 2. Development of the façade tiling scheme. The vertical strips between panels are developed as light elements.

The model demonstrates surface division controlled by a stochastic motion simulator. The outcomes of the exploration were three-dimensional surface models based on bamboo motion capable of generating the components of the façade and envelope system. This stochastic exploration of variations helped to make informed decisions about the geometry and composition of the façade, its potential for manufacture and the choice or combination of materials for its construction. The main result of the generation was the development of a planar façade tiling scheme and the spacing between them. The vertical joints between panels are subsequently developed into narrow strips for light and views (Figure 2). Areas requiring further research are quality control of the lighting through the strips as well as material optimization and fabrication.

4. Stochastic rotation

In this example, we present the results of a building envelope tessellation study based on façade components with rotation. The geometry and control of façade subdivision is based on 4-fold penttiles (also called Cairo pentagonal tiling), a dual semi-regular tiling of the Euclidean plane. The rotation of the panels is based on stochastic rotation of panels, primarily responding as a shading device to reduce thermal gain within the building. The problem of responsiveness to multiple criteria by applying stochastic methods for the
rotation of individual panels has been reported in the literature (Hanafin et al., 2011).

The results of a building envelope tessellation study based on façade components with stochastic rotation are presented. The geometry and control of façade subdivision is based on 4-fold penttiles (also called Cairo pentagonal tiling), a dual semi-regular tiling of the Euclidean plane. The rotation of the panels are based on stochastic rotation of panels, primarily responding as a shading device to reduce thermal gain within the building.

Each panel is positioned and angled in a fixed location based on an optimal shading parameter. In order to optimize performance, the problem of each component motion/rotation with respect to changing conditions needs to be addressed. As a first step towards understanding the shapes and rules to determine the facade composition, stochastic rotation is investigated. The tiling explored is the pentagonal tessellation known as Cairo tiling, which is classified as a type of polygonal isohedral tiling by pentagons (Grünbaum and Shephard, 1987). The Cairo tiling is classified as a regular tiling (each pentagon is identical), however, as the orientation of each pentagon changes, a multiple support method that generates an underlying support structure, allowing for the orientation property of four individual pentagons to be applied correctly is used. With the facade tiling established, the rotation of the individual tiles requires an axis for rotation defined by two attributes, centre point of the base horizontal line and the depth of the component. The pentagons are grouped into two sets, vertical and horizontal, using the point of rotation as defined in the base component. The point of rotation is placed 2/3 along the tile height to ensure the correct placement of the pentagon within the surface grid. By adding the rotation axis parameter, the each tile is able to rotate from the bottom of the pentagon regardless of its application orientation (Figure 3).

![Figure 3. Panel rotation based on stochastic rotation parameter.](image)
This method takes a predefined overall surface and applied two sets, the horizontal pentagons and the vertical pentagons to create the envelope tessellation. The first step in the horizontal application is to take the dimensions of the surface and divide it by a predetermined tile size, this number is converted to an integer to allow for a clean surface grid to be generated as close to the preferred tile size as possible. With a surface grid established the horizontal component is applied, which at contains two overlapping pentagons and each of their rotation axes. The development of a pentile tessellation with 4-fold rotation is described in Hanafin et al (2012). Once the tessellation is established, environmental conditions information is required from both the tile, in the form of a direction vector (tile orientation), and the environment, in the form of an attractor point. The model of stochastic design exploration is tested for façade rotation within the following prescribed constraints:

- Subdivide the faces of the building envelope by applying the pentile tessellation model;
- Establish a vector between each tile and the attractor point allowing for the angle to be calculated between this vector and the tile direction vector.
- Generate and test alternative tile rotation visually using the data set of angles processed to meet the requirements of either shading or views, and provides the rotation information to each tile; and
- Explore the design space of rotation under stochastic control of the rotation information of each tile.

Based on the dynamic experimentation, the horizontal and vertical tile sets can be manipulated using the same environmental conditions, or managed as separate sets to meet different requirements. Multiple environmental attractor points can also be calculated and optimised based on the desired performance metrics. While this information reacts to environmental conditions, the ‘jumbled’ pattern is lost due to the uniform nature of using attractor points. In order to achieve a balance between the two requirements a stochastic rotation is used to produce a set of values. These values are then combined with the calculated environmental values in order to provide the final rotational information to the panels.
A formal method for generating responsive envelope tessellation based on the Cairo tiling is presented. The façade scheme investigates the component design, tessellation and control methods for rotation of component panels. The outcomes of the responsive exploration were a flexible façade geometry based on tiling and tessellation, creating order and rhythm within the façade (Figure 4). In order to achieve the desired pattern, the tessellation and control methods become more critical than the tile itself, allowing for the control of the tiles both individually and as a group. This control uses a stochastic model, allowing for the pattern and rhythm of the tiling to be explored within set parameters and achieve unexpected results. The control can also be very strict and focused, taking advantage of attractor points representing environmental characteristics. This new method for supporting tessellation with Cairo tiling addresses the limitations evident in pentagonal collections and allowing the overall surface to be changed with the tiling being regenerated automatically.

5. Conclusions

The aim of the research is to understand how stochastic models can be applied to design space exploration. The model combines known deterministic parameters such as number and spacing of elements with an uncertain stochastic variable, wind direction and velocity in the case of the first example and 2D/3D rotation in the second example. The design space variations are naturally constrained without being prescriptive or totally open-ended. Ex-
ploring the trade-offs between randomness and direction, accuracy and precision of the models, the speed and interactivity of the experience and the linkages between continuous and discrete models remains the goal of research in stochastic models for design space exploration.

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