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TOWARDS MORPHOGENETIC ASSEMBLIES

Evolving performance within component-based structures

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Abstract. Performative design can be understood as the combined usage of spatial analysis simulations and form generation procedures to imbue architectural form with material characteristics and behaviours which define desirable structural, environmental and economic performance. However, to date, design processes that facilitate the integration of 'form generation' and 'spatial analysis' remain under-developed, making existing performative design methodologies highly reliant upon the manual execution of analysis and evaluation procedures. This paper presents an evolutionary design process that uses integrative computational pipelines and generatively defined component-based assemblies to produce performative structures in response to solar performance. The resulting structures demonstrate how performative composite behaviour can emerge within 'disassociated' componential assemblies and produce complex formal interrelationships which surpass simplistic parametric logics. This offers new possibilities for conceiving highly integrated 'morphogenetic assemblies' and suggests trajectories for further research within the field of morphogenetic design.

Keywords. Morphogenetic; evolution; performative, assemblies.

1. Introduction

Performative design can be understood as the combined usage of spatial analysis simulations and form generation procedures to imbue architectural form with material characteristics and behaviours which define desirable structural, environmental and economic performance. However, to date, design processes that facilitate the integration of 'form generation' and 'spatial analysis' remain under-developed, making existing performative design methodologies highly reliant upon the manual execution of analysis and evaluation procedures. This disconnection between 'form generation' and 'spatial analysis' has been widely discussed (Kolarevic, 2003; Kolarevic and Malkawi, 2005; Oxman, 2008; Fernando et al, 2010; Toth et al, 2010) and has prompted new research with a focus on highly integrated early stage design processes using 'computational morphogenesis'.

Morphogenesis is the biological process of growth and differentiation which occurs to form the structure of an organism. Within architecture the term 'computational morphogenesis' is used more generally to describe bottom-up form-finding processes that manage form and performance simultaneously, thereby facilitating the emergence of performative architectural characteristics. Whilst much work has been done to define a theoretical framework within which to situate 'morphogenetic design' methodologies (Hensel et al, 2006; Roudavski, 2009; Oxman, 2009; Leach, 2009), successful implementation of such methodologies are still in the early stages of development (Menges, 2007; Hensel et al, 2010).

Central to the emerging discourse on 'applied morphogenetic design systems' is an understanding of architectural form existing as 'complex assemblies' which operate with non-linear behaviour and are comprised of highly integrated and heterogeneous sub-components, in a manner analogous to the structure of rudimentary natural ecologies.

The operation of natural ecologies has since become an important mechanism for understanding 'morphogenetic design systems' for two principle reasons. Firstly, as Wiscombe (2010) discusses, natural ecologies are able to express 'extreme integration' between their constituent elements making them highly efficient and adaptive systems; that, in contrast to traditional architectural design, are not defined through a layering of engineered parts but instead, emerge out of a massively parallel and 'messy' accumulation of local interrelationships and dependencies. Weinstock (2006) suggests that such integration and complexity requires systems that produce redundancy and differentiation which conflicts with traditional engineering concepts of optimisation and standardisation. Secondly, the self-organising properties of natural ecologies provide rich potential for early stage design systems. Menges (2007) suggests that design approaches that embed analytical procedures into the early stages of design are capable of producing far greater integration of performative qualities than methods which rely upon post rationalisation and mass production.

This paper presents an evolutionary design process that uses integrative computational pipelines and 'generatively' defined component-based assemblies to produce performative structures in response to solar radiation, daylighting and economic material usage.

Throughout this paper the term *'assemblies'* will be used to refer to component-based systems which operate with bottom-up control(s), whereas the term *'formal strategies'* will be used to discuss emergent form-based character traits derived from morphogenetic design processes.

2. Evolutionary computation

Evolutionary computation is often used within existing morphogenetic design systems as a means of finding formal and behavioural properties which perform efficiently in response to explicitly defined design criteria.

Evolutionary computation can be defined as a process of solving non-linear problems using populations of candidate solutions that breed or die according to how well they fulfil a given criteria and can be considered roughly analogous to Darwin's model of natural selection. Various types of evolutionary algorithms have been applied to design, see Bentley and Corne (2001) for an extensive overview; however, within architecture there have been two primary uses of evolutionary computation. Janssen (2006) introduces two terms for these types of application: 'Parametric evolutionary design' which is used to optimise a set of parameters that define an architectural solution in the late stages of design and 'generative evolutionary design', initially pioneered by Frazer (1995), as a means of explorative 'form-finding' in the early stages of design.

There are several examples of 'parametric evolutionary design' which use genetic algorithms (GAs) to evolve architectural form in response to environmental feedback, including Cladas (2008), Kawakita (2008) Besserud and Cotton (2008) and Turrin et al (2010). All of these authors successfully demonstrate the use of an iterative design process that integrates 'environmental analysis' and 'geometric transformations' to produce performative structures. However, they all rely upon extensive parameterisation, which render them incompatible with morphogenetic design strategies for two reasons. Firstly, as the models require definitive parameterisation prior to evolutionary processes, the application of the GA is limited to late stage design and parameter optimisation. Secondly, simplified parametric encodings tend to favour isolated optimisation of particular components rather providing the potential to construct new interrelationships between components and define composite behaviour. As Cladas (2008) states, future developments of existing studies require "a method of incorporating functional and spatial requirements while allowing for the emergence of shapes that we not initially specifically encoded" within the parameterised model (Cladas, 2008, p.69).

Within computer science much research exists which illustrates the creative potential of evolutionary computation beyond parameter optimisation

(Bentley, 2000; Bentley et al, 2001; Hornby and Pollack, 2001; O.Stanley and Miikkulainen, 2003). These studies suggest that when evolutionary systems use parameters which do not directly represent the design solution, thus tending towards 'generative evolutionary design', it is possible to construct efficient design solutions which are not restricted by the initial parameters. Similarly within architectural discourse the possibility of producing performative structures which surpass limited parametric-based design representations has been discussed by Janssen et al (2002), Frazer et al (2002), Janssen (2006), Menges (2007) and Ahlquist and Fleischmann (2008). These authors have demonstrated how indirect design representations can be managed within an evolutionary computational framework to output highly diverse, yet performative, formal characteristics.

The objective of this paper is to demonstrate how we might extend existing 'parametric evolutionary systems' towards 'morphogenetic design systems' that integrate generative and analytical procedures and surpass optimisation, suggesting novel 'formal strategies' which exist beyond a narrow spectrum of possible formations. This is approached by firstly, addressing how parametric 'assemblies' are encoded and processed as part of an evolutionary design system; and secondly, by establishing an alternative design methodology that advocates scripting and 'novel computation' within open-source programming languages to facilitate communication, or 'integrative pipelines', between existing CAD and analysis platforms.

3. Project description

This project builds upon existing studies (Cladas, 2006; Kawakita, 2008; Besserud and Cotton, 2008; Turrin et al, 2010) and provides an alternative approach to evolving efficient material assemblies in response to solar performance. The project develops a series of small scale 'pavilion' structures, each of which are 4m x 4m x 2.5m free standing structures that seek to minimise direct solar radiation to an internal space, whilst minimising material usage and maximising natural daylighting. The pavilion structures are created by populating a surface with a collection of components that define static assemblies and express passive solar performance.

The core computational framework has been developed within the open source scripting environment 'Python' and consists of a GA and scripted pipelines to the CAD packages '3ds Max' and 'Ecotect' in order to perform 'form generation' and 'solar analysis' processes remotely. The following section precludes a detailed technical description of the computational workflow, which will be discussed in a separate paper, but instead focuses on how three principle aspects of the evolutionary system, component encoding, integrated analysis and selection, contribute towards a morphogenetic design strategy.

3.1. COMPONENT ENCODING

In order to discuss an extension of 'parametric evolutionary systems' towards 'morphogenetic design systems' it is important to first address how 'parametrically' encoded structures can be converted into 'generatively' encoded structures and how this difference is qualified. Rather than viewing parametric and generative encoded models in binary opposition we may, as Bentley (2000) discusses, consider the difference characterised by how knowledge-rich or knowledge-lean the design representations appear. 'Knowledge-rich' representations are more rigorously defined and parameterised, such that changes made to parameters have predictable effects within a limited spectrum of formal possibilities. In contrast, 'knowledge-lean' representations are constructed from a collection of lower level components which are less constrained to limited transformations, thus design representations have much more varied and less predictable formal possibilities.

In this project each pavilion structure is composed from a collection of components which populate a host surface. Figure 1 illustrates the method by which each component is encoded and compares this with a commonly used knowledge-rich component used within previous 'parametric evolutionary design' studies.

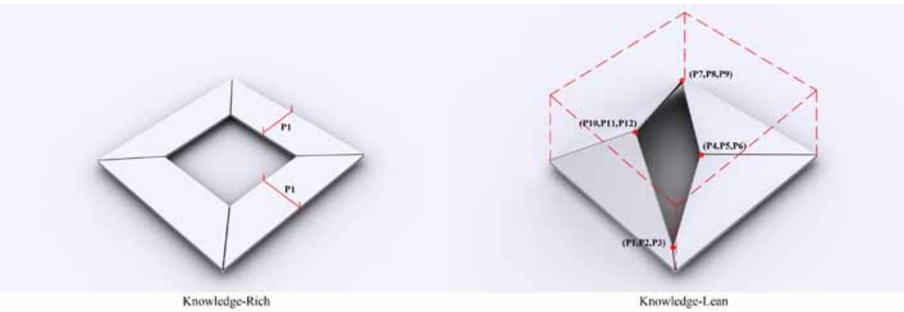

Figure 1. Component encoding mechanism

Each component is defined by the location of four vertices which are permitted to be positioned freely within a volume that is defined relative to the populated surface normal. The vertices are then combined to form a three dimensional component which has many formal possibilities and is therefore considered 'more' knowledge-lean when compared with conventional knowledge-rich parametrically encoded components. The encoded instructions, which define the complete positions of all component vertices of any pavilion structure, are stored as a string of digits on a text file and become the pavilions' genetic description (or genome).

3.2. INTEGRATIVE ANALYSIS

'Python' is used to construct a unifying computational framework between existing CAD and analysis software to enable integration between generative and analytical procedures.

Once pavilion structures have been generated from their genetic description they are exported to 'Ecotect' for environmental analysis. Here two calculations are performed. The surface beneath the pavilion is split into 156 segments and each segment is assessed for how closely it meets a specific daily 'solar radiation' value and 'daylighting factor' value. The result of these calculations is two numbers which represent the accumulative differential between an ideal (uniform) solar radiation value and an ideal daylighting factor value - the optimum solar radiation being a low value and the optimum daylighting factor being a high value. These two values are then combined with a measurement of how much material is used to construct the pavilion to produce a singular fitness score; the fittest pavilion being that with the lowest score (smallest differential between solar radiation and daylighting values and least material used).

This information is then stored within 'Python' so that each genetic description can be compared to a population of similar structures for how well it 'performs' to minimise direct solar radiation and material usage whilst maximising natural daylighting.

3.3. SELECTION

Each generation of pavilions comprises of a population of 100 candidate structures which have been generated from genetic descriptions and analysed for solar performance. The next step in the evolutionary design system is to select structures which will reproduce to create new genetic descriptions for the next generation and thereby complete an iteration of the design process.

The GA uses 'tournament selection' to maintain formal diversity within the population of structures whilst selecting structures to breed to create new genotypes for the next generation. In this process 5 structures are selected at random from the possible 100 and ranked; the fittest two are then combined using a crossover function and subjected to potential mutations to produce a new pavilion genotype. Rather than seeking to always breed the best structures together which can quickly homogenise the population of possible solutions, tournament selection slowly eliminates the worst performing structures and is more forgiving to initially detrimental or redundant character traits. This provides the potential for novel component interrelationships to emerge over time, thus transforming initially inefficient formal quirks into actively performative formal qualities that are not explicitly encoded by the component parameters.

4. Results

This section compares two pavilion structures that are each the result of 150 generations of the evolutionary development. The first structure is defined by the knowledge-lean components described in the previous section. The second structure is defined using conventional knowledge-rich components (as illustrated in figure 1) which correspond to 'parametric evolutionary design' design representations that have proven successful in generating highly efficient formal organisation in previous studies.

Figure 2 illustrates the passive solar performance of the two pavilion structures and demonstrates how the two structures have evolved in relation to four performative aspects: average fitness, average daylighting, average solar radiation penetration and average material usage.

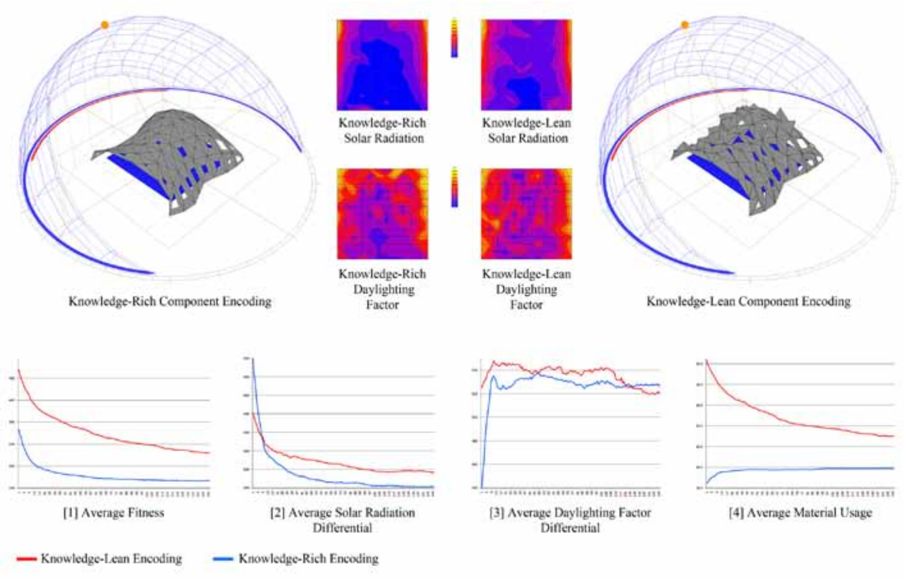

Figure 2. Top- Comparitive pavilion performance. Bottom - left to right: average fitness, average solar radiation, average daylighting and average material usage

The graphs in figure 2 demonstrate that the knowledge-rich structures are able to define more efficient structures much more quickly than the structures with knowledge-lean encodings. This is primarily due to the relative length of the genomes, the knowledge-lean structures being 12 times longer, this significantly increases the space of possible solutions making it much harder to find optimal results through evolutionary search. However, the largest contributing factor to the comparative fitness of these structures is the large difference between material usages – the three-dimensional knowledge-lean components using considerably more material than the knowledge-rich components which are limited to a two-dimensional plane.

These results support existing studies and demonstrate that knowledge-rich encoding systems coupled with evolutionary design processes can produce successful optimization systems. However, the strength of knowledge-lean encodings and vast potential for morphogenetic design is evidenced by comparing the behavioural properties of each structure.

Figure 3 illustrates how solar rays behave upon hitting the surface of each structure and the subsequent 'formal strategies' that emerge. The knowledge-rich components behave in a predefined manner oblivious to the reflected rays. In contrast, the knowledge-lean components are able to exploit the daylighting potential of the reflected solar rays by adapting their geometries in such a way that they actively bounce light off neighbouring components and into the interior space. Therefore the knowledge-lean encoding produce highly complex and integrated composite behaviour that is not predefined but emerges through time in a manner analogous to ecological structures.

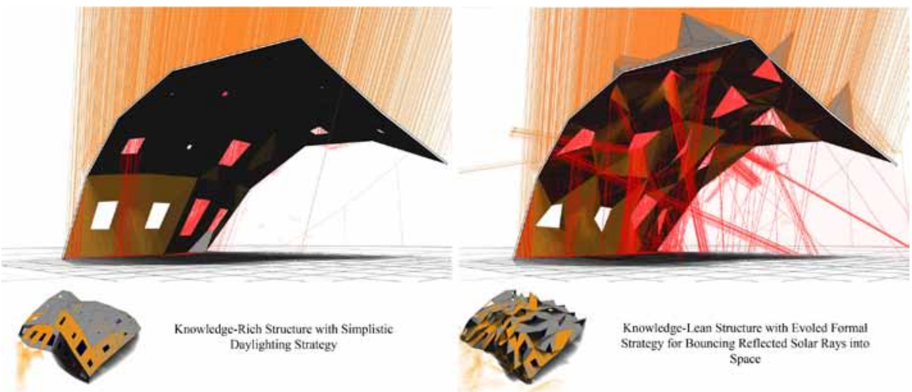

Figure 3. Emergent formal strategies

7. Conclusions

This paper demonstrates how architectural assemblies defined by knowledge-lean encodings and processed via a genetic algorithm, can acquire performative formal attributes in response to environmental stimuli.

Currently this system does not consider the material properties of emergent structures or related construction processes, which are required to develop material-specific 'formal strategies' and define highly integrated 'morphogenetic assemblies'. However the methodology presented does allow for expansion and the inclusion of additional analysis procedures via integrative scripted pipelines. Simulation run-times within the evolutionary design system currently present a severe limitation; however, recent research has evidenced how such design processes might be distributed over multiple computers to significantly reduce run-times and increase the creative potential for future applications in early stage design (Janssen, 2009; Turrin et al, 2010).

Further research is now underway and seeks to explore how material and structural properties can be embedded within knowledge-lean assemblies to facilitate the production of highly integrated 'morphogenetic assemblies' that express material-specific formal attributes and performative composite behaviours.

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