Generative and Evolutionary Techniques for Building Envelope Design

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Abstract:

The authors have been involved in the use of generative techniques for building envelope design since 1968 and the use of genetic algorithms since 1990. Recent work has focused on incorporating optimisation functions into form generating processes in order for new forms responding to varied design environments to be created and determined. This paper will summarise the authors' previous work in this field and explain the theory behind this approach, and illustrate recent developments. While the initial implementation of a new building envelope design system is reported in more details in a related paper at this conference, this paper outlines its main features and points out the direction at which it is to be fully developed and further improved.

1. Introduction

At the first Generative Art conference in Milan in 1998 we presented a paper entitled "Macrogenesis: Generative Design at the Urban Scale" [25]. That was a reflective paper indicating key points in the authors' previous involvement in generative design. Selected work was summarised in a series of snapshots of key developments. The then most recent evolutionary work was explained more fully including the "Groningen Experiment" which applied generative ideas to an interactive city planning model for Groningen that enabled citizen interaction with a generative model. The paper concluded by explaining that the whole generative design project had been relocated in a newly formed Design Technology Research Centre (DTRC) in the School of Design at the Hong Kong Polytechnic University where the work was being expanded into the realm of industrial design and graphics. Subsequent papers at GA 1999, 2000 and 2001 presented work from the newly formed centre including [26, 27, 28, 29, 30, 31]. Five papers of recent work are to be presented by the DTRC researchers at GA 2002.

This paper serves as an introduction and overview and starts by restating the original premises of this research. In particular it introduces the generative and evolutionary techniques for building envelope design. One of the recent investigations is the integration of optimisation functions with the form generating processes in order for new forms responding to varied design environments to be created and determined through a series of complex mathematic transformations. In this new investigation, we combine a 3D solid modelling system kernel with a new partial ordering system based on an abstract optimisation technique derived from the theory of non-linear analysis. This approach provided great potential for the development of applications in which the construction and manipulation of complex 3D forms including 3D solid models are incorporated in a knowledge-based and automatic process of generative design. Whilst a related paper by [38] at this conference gives more information about the implementation of the system and the computational techniques employed, this paper presents our overall research in this area and highlights the theoretical issues that have to be addressed in order to develop an intelligent system for building envelope design.

2. Generative and Evolutionary Design

Generative and Evolutionary Design involves using the virtual space of the computer in a manner analogous to evolutionary processes in nature. Whilst the techniques described can be achieved with relatively simple design problems such as yacht design, architectural problems still require computing power in excess of what is yet readily available and are thus only on the cusp of being realisable. This theory is elucidated fully in the author's book, "An Evolutionary Architecture" [1].

In an attempt to achieve in the built environment the symbiotic behaviour and metabolic balance that are characteristic of the natural environment, it proposed the evolutionary model of nature as the generating process for architectural form. The profligate prototyping and awesome creative power of natural evolution are emulated by generating virtual architectural models, which respond to changing environments. Successful developments are encouraged and evolved. Architecture is considered as a form of artificial life, subject, like the natural world, to principles of morphogenesis, genetic coding, replication and selection.

Architectural concepts are expressed as generative rules so that their evolution and development can be accelerated and tested by the use of computer models. Concepts are described in a genetic language that produces a code script of instructions for form-generation. Computer models are used to simulate the development of prototypical forms that are then evaluated on the basis of their performance in a simulated environment. Very large numbers of evolutionary steps can be generated in a short space of time and the emergent forms are often unexpected.

These techniques had previously been limited to easily quantified engineering problems. Only now is it becoming feasible to apply them to the complex problems associated with our built environment. To achieve this it is necessary to consider how structural form can be coded for the utilisation of genetic algorithms, how ill-defined and conflicting criteria can be described, how these criteria operate for selection, and how the morphological and metabolic processes are adapted for the interaction of built form and its environment. Once these issues are resolved, the computer can be used not only as an aid to design in the usual sense, but also as an evolutionary accelerator and a generative force [2].

The evolutionary model requires that a design concept be described in a genetic code. The code is then mutated and developed in a computer program into a series of models in response to a simulated environment. The models are then evaluated in the simulated environment and the code of successful models is selected. The selected code is then used to reiterate the cycle until a particular stage of development is selected for prototyping in the real world.

In order to create a genetic description, it is first necessary to develop a design concept in a generative manner capable of being expressed in a variety of forms in response to different environments. This is a manner in which many designers already work in the sense that they have a personal set of strategies that they adapt to particular design circumstances. This strategy is often very pronounced and consistent to the point where a designer's work is instantly recognised.

3. **Flashbacks**

The 1998 paper then presented 6 flash backs starting by describing the start of this work in the late 60s with the beginnings of a search for an alternative design paradigm the Architectural Association in London in 1969. It was proposed that an increase in choice could be achieved by emulation of the processes of evolution and genetics, which produced diversity in nature. The project introduced the idea of genetically coded building descriptions and the idea of user interaction in the design process and subsequent reorganisation of the building in use. The genetic code of the building was manipulated in a primitive computer model. Later at Cambridge University access to computer power and software expertise allowed this concept to be turned into a working demonstration. [3, 4]

This research subsequently moved to the University of Ulster and then back to the Architectural Association in 1989. One example from this period is included here as a reference. In 1995 a dynamically evolving model for an exhibition in London and an Internet experiment was developed and implemented.

The model was organised by using a multiple hierarchical approach and a data structure which is recursively self similar. The simulated environment in which evaluation takes place was modelled in exactly the same terms as the evolving structures. The environment and the structure not only evolve in the same data space, but could co-evolve. Moreover competitive structures could also evolve in the same space. Environment in this case included user response and was modelled with virtual societies. The environment had a significant effect on the development of the concept using a genetic design language. Genetic algorithms were used to perform the selection and normal crossover and mutation were used to breed the populations.

The model consisted of an endless array of data points, which collectively constitute a data space. Each point in the data space was intelligent in the sense that it knew where it was and why it is there and it had a clear awareness of the spatial relationship of its neighbours. The laws of symmetry and symmetry breaking were used to control the development of the model from the genetic code. Information flow through the model took the form of logic fields. Externalisation of this data structure was process driven by modelling the process of form generation rather than the forms themselves.

The model was based on the sequential evolution of a family of cellular structures in an environment. Each cellular structure began development from a single cell inheriting genetic information from its ancestors and from a central gene pool. Each cell in a cellular structure contained the same chromosomes, which make up the genetic code. The cells divide and multiply based on the genetic code script and the environment with each new cell containing the same genetic information. The development process of each member of the family consists of three parts - cellular growth, materialisation and the genetic search landscape. A genetic algorithm is used to ensure that future generations of the model learn from the previous ones as well as provide for biodiversity during the evolutionary process.

The data structure of the model was based on a universal state space or isospatial model where each cell in the world has a maximum of 12 equidistant neighbours and can exist in one of 4096 states, the state of a cell being determined by the number and spatial arrangement of it's neighbours.

The local environment of a cell can thus be coded in a 12 bit binary string. The growth and development of the cellular structure is controlled by chromosomes.

Chromosomes are generated either by being sent in by any remote user, an active site or as a function of selection, crossover and mutation within cellular activity and are maintained in a main chromosomal pool. The physical environment determines which part of the main chromosome pool becomes dominant. The local environment of each cell then determines which part of the genetic code is switched on. The cell then multiplies and divides in accordance with that genetic code.

As cellular division takes place, unstable cells are generated. In the next generation this leftover material creates a space of exclusion within the cellular space. This space of exclusion interacts with the physical environment to create a materialisation of the model. Boundary layers are identified in the unstable cells as part of their state information and an optimised surface is generated to skin the structure. This material continues to exist throughout the evolution of the model and will initially affect the cellular growth of future generations.

The selection criteria in the model was not programmed but was an emergent property of the evolution of the model itself. A genetic search landscape was generated for each member graphically representing the evolving selection criteria within the model based on the relationship between the chromosomes, cellular structure and the environment over time. Form, or the logic of form, emerged as a result of travelling through this search space.

Once chromosomal stability had been achieved, the parent cellular activity was terminated. The final cellular structure, the materialisation and the genetic search space are posted out. A daughter cellular activity is then initiated from a single cell. The fittest chromosomes from the parent generation are bred using selection, crossover and mutation and combined with the new list of dominant chromosomes from the main chromosome pool to form a new chromosomes set for the daughter generation. The development process is then repeated for the daughter generation [9, 10, 11]

In January 1995 we constructed An Evolutionary Architecture [12] exhibition for the Architectural Association Gallery in London. The centrepiece to the exhibition, The Interactivator [13, 14], was an evolving environment, which was planned to respond to both interaction from the exhibition visitors and the atmosphere in the exhibition space. Visitors were to interact by proposing genetic information, which would influence the evolution of the model. Sensors in the exhibition space also affected the evolution of the model with data on temperature, humidity, noise, smoke and so forth. We extended this concept to allow co-operation on the Internet in three ways: First, by using the Internet to allow virtual visitors to input genetic information to the model just like actual visitors. Second, by allowing the program of the model to be downloaded to remote sites so that it replicated itself and each replication took on a divergent evolutionary path, the results of which could also be fed back to the central model to contribute to the gene pool. And third, by allowing access to the exhibition and the book via a conventional Web site so that the context could be understood and the stages in the development of the evolving model could be observed.

Genetic techniques for design model inner logic, rather than external form, and the exhibition afforded a glimpse of a future architecture as yet evolving only in the imagination of a computer.

Virtual visitors could view the current state of the model and receive an explanation, or they could participate by providing genetic or environmental information. For real enthusiasts, copies of the software were available for downloading. Feedback from remote copies of the software also affected the source model.

In the first two weeks after the launch of the model it evolved four family members based on the chromosomes received and those bred internally, each member achieving chromosomal stability in about 120 generations. Though it is impossible to predict the nature of the model, or its evolving internal logic, there seems to be a pattern emerging towards its selective and hence, evolutionary process.

With the assistance of Ellipsis publishers the virtual version of the exhibition was launched on the Internet in January 1995 [15]. There are some successes and failures to record with this experiment. The central model convincingly demonstrated the principle of evolving a structure under the influence of both public participation and environmental information. But the rate of change was too slow to give any indication of how any individual was affecting it, and the feedback to the net was never properly implemented to show any development. Downloading the model to remote sites revealed all manner of technical problems which meant that biodiversified genetic material never found its way back to the central model. The Ellipsis site was labyrinthine which delighted many visitors but frustrated others who never found how to input genetic information. Overall the experiment attracted a great deal of comment, both on the net and in the press including a feature in Wired [16] and an article in Architectural Design [17]. The Web site enjoyed a large number of visitors.

The 1998 paper finally described an experimental co-operative model for the city of Groningen in northern Holland. It then speculated on how such techniques could be broadened and applied to the possible global co-operative evolution of cities.

We produced a generative computer model, which could mediate in scale, space and time. - In scale between the urban context and the fine grain of the housing typologies. - In space between the existing fabric of Groningen and specific dwelling units. - In time between the life style of the medieval core and the future desires of citizens of the next century.

The Evolutionary Model explained the transition from the past to the present and projected trajectories for future possibilities : A "what if" model for exploring futures and evaluating them.

More specifically we developed a model, which simulated the historical development of Groningen in a dynamic and predictive manner. We searched the local situation for local rules, which would generate self-determining emergent properties for the whole. We looked specifically at the way in which the implications of changing life styles and work patterns could be incorporated into the model. We developed a structure for the model, which was strategically modular (in the sense that say a tree is) without being geometrically constrained to modularity. We embodied all ideas for the housing typologies and the site organisation including environmental influences.

The model was designed using the techniques, which we had developed over the last few years. The structure of the model was new and specifically tailored to the scale and nature Groningen.

Central to the Groningen model was the idea that the computer program inhabits an environment, enters it, reads it, understands its developmental rules and history, grasps its topography, latitude and climate, models its society and economy - and then starts to solicit suggestions and make proposals for possible features.

The model becomes an inhabitant. It maintains a discourse with other, human inhabitants and tries to understand and interpret their desires, aspirations, urges, expectations, and reactions to their existing environment and projected future environments. On the basis of this interaction with the actual inhabitants, the virtual Inhabitor patiently modifies its criteria for evolutionary development and selection, endlessly repeating the process of refining and modelling prototypical futures. As it does so, it occasionally produces experimental genetic mutations or amplifies variety.

The working prototype was demonstrated in Groningen and then in London in June 1996. It was subsequently exhibited at the Architectural Association in July [19]. An interactive map with video input of modelling blocks provided an easy interface to the system. The demonstrations were very favourably received and many valuable comments were recorded. The intention now is to seek further funding for a robust demonstrator system which can be used to test the system with the inhabitants of Groningen. Holland is a café oriented society. The intention is to provide interactive systems in some of the many cafés of the city [20,21,22, 23].

To paraphrase Stafford Beer "The public is conceived as a system, a model of which is contained in the computer. The public supplies minimal information, which the computer then synthesises in the model. This amplifies variety as required to help the public and attenuates variety to help the manager - thereby meeting the requirement of the law of requisite variety for each of them".

Interaction with the Inhabitor is achieved via the Enabler, which has connections to an interactive map (input desire lines etc) and an active output model.

We feel that this experiment went some way to realise, through the medium of modern digital technology, the preoccupation of Patrick Geddes that the ordinary citizen should have a vision and a comprehension of the possibilities of his own city. This experiment addresses the need for and value of "citizen participation" in town planning. It also demonstrates the need for a Civic Exhibition and a permanent centre for Civic Studies in every town - an "Outlook Tower". We are proposing that the cafes of Groningen should be the Outlook Towers of the future.

4. Post 1996 – Developments in Hong Kong

Generative and evolutionary design techniques are at the centre of the systems and environments being developed by the authors at the Design Technology Research Centre in the School of Design of the Hong Kong Polytechnic University. The DTRC was established in 1996 by Professor John Frazer and was formally validated by the Hong Kong Polytechnic University in 2000. A new and generic computational model of the design and making process consisting of a unified data structure of space, information and knowledge, an alternative computer enhanced design process, and an environment of design that relocates the user, the designer and the tool. A wide range of topics in this area have been investigated in order to define the primitives, rules, constraints, evaluation criteria and environments in order to make the best use of generative and evolutionary computational techniques including mainly genetic algorithms, neural networks, and machine learning techniques.

In order to develop a unified data structure of space, information and knowledge for intelligent design support, in an extension to conceptual seeding, we have further developed the representational schemes, which we call rudiments and formatives. In our new application domain of product design, a rudiment defines a set of the functional component classes with related design knowledge about their geometric and feature attributes. Rudiments are defined in the context of an evolving environment is which they may have the potential of being selected and further developed. And in particular they must be combined or structured in such a way in which genetic algorithms or other form of generative programming can be used to derive a new data structure we termed the formative. A formative encapsulates rudiments with their relationships in a meaningful design process, as well as the product configuration rules to be used during further design development stage. A rudiment is static in the sense that it is built in advance, whilst a formative is dynamic because it requires user's interaction to formulate a design problem space, which is loosely constrained by the instantiation of rudiments. This design problem space defines geometric as well as aesthetic and ergonomic constraints, which can be subsequently explored by genetic algorithms through a product component hierarchy. Design knowledge such as the strategies of Design for Manufacturability (DFM) can be encoded into the generative product design support system as rudiment definitions or selection criteria. A recently completed PhD thesis successfully demonstrated the feasibility of rudiments and formatives in the application of abstractive mobile phone shape design [34].

The second system that has been developed [36] deals with the complexity and collaborative nature of design in the context of using generative and evolutionary techniques in design in a generic manner in order to provide a system for exploring the complexity of design problems through a hierarchical representation of evolving elements and evolving mechanisms. This system attempts to develop a computational framework that supports design exploration at different levels of abstractions that are hierarchically represented and processed. A hierarchical evolutionary framework has been implemented, which consists of networked elements evolving and interacting with others according to their "evolutionary mechanisms". Each network element can be evolved to become next element down in the hierarchy with the evolutionary mechanism associated with it. When applying this hierarchical evolutionary framework to a design problem, the hierarchical network represents the whole design task or process whilst each element in the network represents an evolving sub-solution to the whole problem at a specific abstract level. Users and designers can interactively manipulate design objects at different levels. Genetic algorithms and cellular automata are used as the main evolutionary mechanisms that can be linked to any element in the hierarchy. This framework is currently being explored with experiments in both 2D and 3D design. In particular, it is being used to develop a system supporting Chinese font design, in which domain, the design of each stoke in a Chinese character, and the design of a coherent character with aesthetic and spatial integrity may be represented or processed in a hierarchical framework..

The third system is based on an alternative approach to the design of buildings. In this approach, the development of generative and evolutionary system in building design consists of three parts: (1) a method of designing that relies on an evolutionary software environment, (2) a computational strategy that describes how the evolutionary software environment might be implemented, and (3) a software development kit that provides software components that can be assembled to create customised evolutionary design environments.

In this system, the proposed design method splits the process of designing a building into two tasks. These two tasks are liked to each other via an entity referred to as a design schema. The first design task is to define the design schema. The use of a schema is a common tactic in design. In most cases, a design is not a one-off, but is instead one of a family of designs. This family of designs might be represented by a design schema that encompasses the variations within the family. The design schema is an idea that encapsulates the identifiable and recognisable character of the designs. The second design task is to instantiate a particular design form the schema using the evolutionary software environment. The proposed method therefore relies on a software environment for design that combines the design schema tactic with the use of evolutionary algorithms. Evolutionary algorithms are loosely based on the neo-Darwinian model of evolution through natural selection. Such algorithms consist of a cyclical process whereby whole populations of individuals are continuously being generated and manipulated in order to ensure that members of the population gradually evolve and adapt [32].

Other systems developed by the DTRC included a tree representation scheme with which genetic algorithms manipulate directly on tree, and to switch nodes in the tree in crossover and mutation to explore alternative and unexpected design solutions involving 3D products of more than one component [33, 35]. Other research projects in the DTRC are also exploring the possibility of using rudiments and formatives to develop systems for design for environment focusing on the embodiment of green product design [37]. All these projects are centred at the development of a taxonomy of generic forms by adopting methods of morphogenesis in the natural sciences. Using these methods a collection of industrial artefacts can be obtained to establish a taxonomy of form and to construct physical models showing morphogenetic processes, and then to develop virtual models that can be integrated in computer based design support systems.

5. Building Envelope Design System

This paper ends by introducing our latest work on the application of generative and evolutionary techniques for building envelope design.

The creation and exploration of unpredictable and non-repeatable forms with certain ways of controlling their abstractive nature are difficult tasks, especially when the outcomes of the system are not just images but solid models. Most existing CAD systems require detailed geometric specification through sketching and transformational methods in order to generate 3D forms. This presents serious limitations to the generative and creative capability of computer based design support systems. These limitations motivated the development of the new approach to architectural envelope design introduced in this paper. In this approach we combine mathematical functions with 3D solid modelling transformation methods to create abstract but novel forms.

Several difficult issues must be tackled before such a system can be practically used to support building envelope design.

- Computational techniques for creating and improving design alternatives in a goal directed manner,
- Creation and exploration of complex forms from basic but intelligent elements representing and stimulating the process of generating novel design concepts,
- Linear and non-linear algorithms for modifying abstract forms to obtain complex forms through spatial or conceptual transformations, and
- Visualisation and animation of the forms generated in a format compatible with main CAAD or CAID tools and environments.

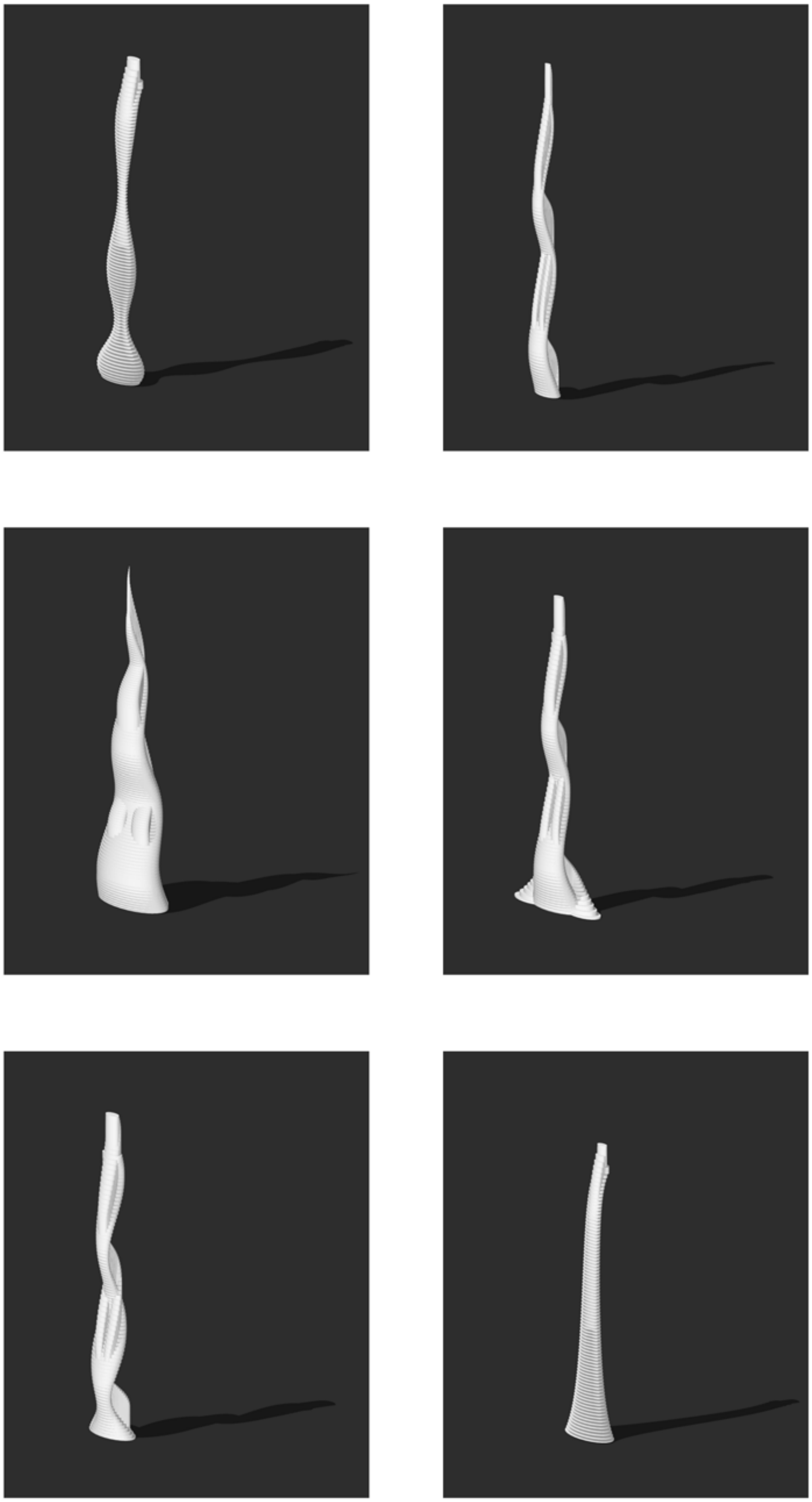

Figure 1. Forms generated by Building Envelope Design System

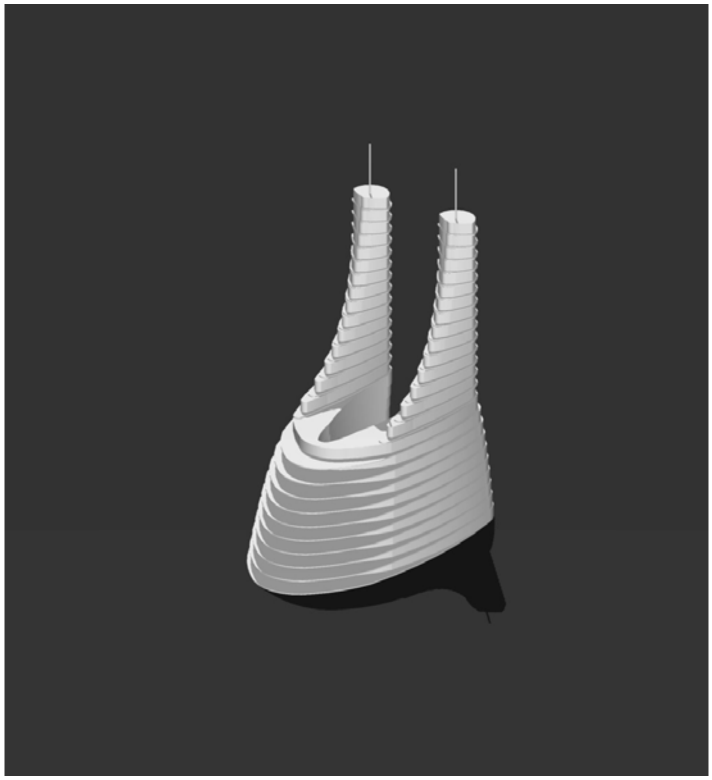

Figure 2. An example of a building envelope generated by the system.

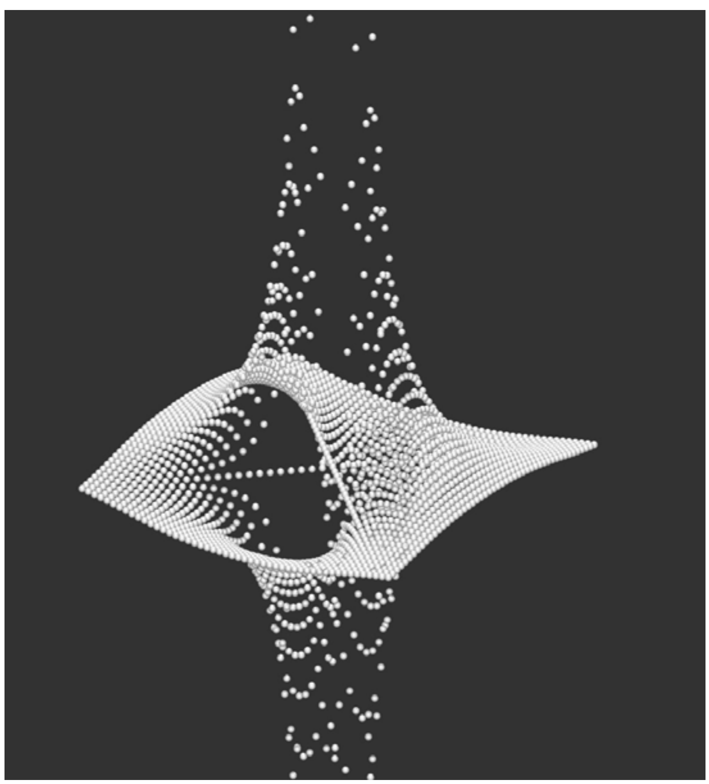

Figure 3. Generative nodes

Our particular concern is the formulation of computational complex form creation process with various generative processes in which genetic algorithms or other automatic computing methods such as partial ordering can be used to increase the novelty and creativity of the system. We decided to develop our system based on 3D solid modelling techniques enhanced with complex mathematic functions. The system kernel is compatible with object-oriented technology and 3D solid modelling and surface modelling standards. The images and rapid prototyping models generated using our system are otherwise impossible to generate by normal CAAD systems, without integrating generative and evolutionary computation techniques with 3D solid modelling techniques.

While the technical and implementation details of this system are described in a related paper by [38], the significant features of this system in relation to our past research and future direction for developing an intelligent system for building envelope design are highlighted here.

ACIS 3D Solid modelling kernel is the core used by major CAD systems including ProEngineer™ and SolidWorks™, With its numerous geometric manipulation and transformation methods for solids and surfaces, it is relatively easy to derive object oriented class definitions for creating architectural envelope models.

In the initial implementation of our building envelope design system, we have built an object library [38] containing 47 object classes derived from basic ACIS 3D solid or wire-frame models. Among these, 17 of them are form (complex solids, surfaces and wire-frames) creation classes whilst others perform transformation, interaction with users, or linking the form creation process with a genetic algorithm. With this domain independent object library, it is easy to develop new and domain specific architectural envelope models. For example, an instance or a number of alternative instances of a solid tower model can be created using an object definition in the library by specifying two mathematical functions, i.e., the centre line and the outline. This object definition can be easily extended to include outer surface profiles or interior details such as colours or textual mapping for the development of more domain specific features. In this library, surface representation (or boundary representation) and constructive solid geometry (CSG) are combined.

We also enhanced a commonly used solid representation called spatial partitioning in order to apply mathematical expressions to the form creation process. This is done by decomposing a complex solid (such as an architectural envelope) into a collection of smaller, adjoining, non-intersecting solids (floors or rooms) that are at a lower primitive level than the original solid (the whole structure of the envelope). A number of variations are used in the decomposition process. These included: cell decomposition, spatial-occupancy enumeration, octrees, and binary space-partitioning trees.

A tower, for example, is generated from many cells and layers. Once the centre line and outline are specified mathematically with a symbolic representation. Dividing the tower into cells and layers is then automatically handled by the system in a way similar to identifying the grids in a finite element analysis system, giving a few control parameters such as number of cells and layers. The interior details or the materials of the textual can be applied to different layers or cells. Once the model is complete, all the individual cells and layers are untied to form a single object, which can then be exported to other CAAD systems for further analysis and modifications. Additional functions and operations we termed mollifying operations are provided by our system to make sure the smooth transition from cells and layers to a united 3D solid model without discontinuity. Before the operation of uniting, any cell or layer in a completed model can be substituted with another model containing more detailed structure but with the same size and shape. After the uniting operation, a model can be used as a cell or a layer to generate more and more complex forms. The recursive transition of a cell or a layer to a model makes it possible to generate very complex forms with same mathematical centre lines and outlines.

In our system, we introduced a new version of genetic algorithm to enhance its generative capability. This is achieved by extending the classical powerful computational techniques based on modern non-linear analysis theory to the natural selection methods for optimisation of GA. This new version of genetic algorithm used the idea of partial ordering in topological spaces. A Zorn Lemma type of iterative procedure is introduced in the genetic algorithm to partially overcome the difficulty in implementing effective natural selection in the evolutionary process. Zorn Lemma is a basic result in partial ordering theory. It is a derivation of a set axiom. This lemma ensures that a maximal point in a certain subset can be obtained provided that it is totally ordered. Based on this lemma, we defined a multi-objective evaluation method, and accordingly, the fitness functions in the genetic algorithms must calculate appropriate information about the individuals, and then use this information to calculate how well each individual satisfies their particular criteria. The total fitness function is a map from each individual to a point in the high-dimensional Euclidean space with or without linear structures. In this space, partial ordering is an effective method to represent relations of points. The definitions and proposition of this theory are described and proved in [38].

Considering the complexity of real architectural envelope design with abstract or specific requirement specifications involving potentially large numbers of variables and constraints, the design problem space will be ambiguous and incomplete, and may never be explicitly quantified at a level comprehensible for the users. The partial ordering theory offers a way for introducing automatic natural selection into the otherwise more open-looped artificial selection process of genetic algorithms, such as those employed and reported in [31, 33, 34, 35]. However, this part of the work is still in the early stage as we write this paper. The issue will be thoroughly investigated in our next step since there is a great potential for the application of these ideas in an architectural context, but so far we have been unable to comprehensively demonstrate the value of this approach with convincing examples. However, it has been clearly demonstrated that our system implemented so far is able to provide powerful generic support for testing novel ideas in a domain specific context with complex forms of astonishing degree. It is obvious that even with the application of our system with simplified examples in architectural envelope design, computing power is being challenged and more intelligent software is needed for creating unexpected sophistication of beautiful architectural forms competitive to those created by human architects.

Whilst our system focuses on generating 3D solids and wire-frames compatible with main stream CAD systems such as MicroStation™ for architectural design or ProEngineer™ for product design or product design, additional rendering and lighting effects can be achieved by converting SAT files of ACIS kernel into other formats including rapid prototyping format (STL).

6. Conclusions

The integration of mathematical function within a 3D solid modelling kernel as the basis of a form generating system, the application of a partial ordering theory combined with natural selection criteria of genetic algorithms in a complex topological space, and the enhanced geometric transformation and repairing operations on complex solid and surface models are the key components of a building envelope design system that has already been implemented. Early testing of the system has shown some interesting and promising results.

Six years on, in the Design Technology Research Centre (DTRC), we are now in a position to develop a full-scale application for architectural envelope design, and indeed for product design as well, with the capability of generating complex and evolving forms that are otherwise hard or impossible to create and manipulate. With the exciting real design and development in Yunnan province in mainland China where potentially over a hundred cities and towns are to be redesigned on the balance of modernisation and preservation of ethnic minority culture and concerns for environmental and ecological protection, we expect to integrate generative exploration and constrained optimisation in large scale applications for which we can use our Global Virtual Design Studio for visualisation and evaluation of architectural envelope design concepts in a more interactive and collaborative manner. Our collaboration with Yunnan Development Centre will provide a unique opportunity for us to further develop and test the system described in this paper and a related paper [38].

Next, we will look at solar geometry or more general environmental concerns to formulate a multi-objective design problem based on partial ordering theory in a more domain dependent context. In the meantime, our other research projects in the DTRC on the taxonomy of generic forms based on morphogenesis, extension to rudiments and formatives in product design applications, and the development of a designer's workstation of the future, will provide further insight on how intelligent design tools can be developed to support designers, based on the principle of generative and evolutionary strategy, computer enhanced process, user centred interfaces, and integrated computational algorithms.

Acknowledgements

Our research projects on generative and evolutionary design are funded by a serious of Competitive and Ear-marked Research Grants (CERG) from Hong Kong Research Grant Council (HKRGC, Reference No. BQ271, BQ420 and BQ630), as well as PhD projects funded by the Hong Kong Polytechnic University.

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