A FRAMEWORK FOR THE DESIGN OF KINETIC FAÇADES

JULES MOLONEY
University of Melbourne, Australia

Abstract. The particular requirements of kinetic façades are discussed in relation to a general model for future CAAD research – a 3D digital prototype based on (1) the concurrent evaluation of quantitative and qualitative performance over time (2) the calibration of geometry and physics to materiality and mechanics. Concurrent performance in the case of kinetic façades is determined by the dual role as environmental screens and the socio-cultural function as the public face of architecture. From these principles a framework is proposed that informs the conceptualisation of software that will address unique requirements - the design of façades as process systems that perform over a range of time scales.

1. Introduction

There has been interest for some time with 'intelligent' façades that can react to changing climatic conditions and user needs in order to improve functional performance (Wigginton 2002). Design of such environmental screens has concentrated on technical developments with little appreciation that façades are the public face of architecture. As well as providing comfortable enclosure, façades form the backdrop to urban spaces to help shape cultural identity and social behaviour, an issue that informed psychological studies in the 1960's and 70's (Norberg-Schulz 1971, Rapoport 1969). The socio-cultural performance of façades has re-emerged as part of contemporary discussions on the quality of the built environment (Leatherbarrow 2002). It has been argued that intelligent façade design based on techno-functional performance is socially inert and offers little cultural value (Anshuman 2005). By comparison a parallel form of kinetic façades – media screens – act as urban interfaces to information and allow engaging contemporary artworks (ag4, 2006). Intelligent façades and media screens are two examples of kinetic façades. The novel aspect to their design requirements is that they are temporal artifacts, or more correctly process systems, that are required to perform over time. These temporal requirements together with the need for architectural façades to perform to

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both environmental science and socio-cultural agendas suggest a holistic approach to CAAD tools is required. From this viewpoint, the research presented below addresses the question - how might design software be developed to accommodate the temporal, and the dual performance role of kinetic façades?

This paper is organised in two sections. The first places the design of kinetic façades in the wider context of CAAD at the early design stages. Through this overview and discussion a general model is proposed based on a performative 3D digital prototype. This research approach is in line with current thinking on new generations of CAAD that proposes an emphasis on support for creativity at the early stages of design (Reffat, 2006). The general model described here is based on two principles: (1) the concurrent evaluation of quantitative and qualitative performance over time (2) the calibration of geometry and physics to materiality and mechanics. This generic approach is refined in section 2, which adopts a methodology from the discipline of information systems (IS) that proposes 3 research stages – conceptualisation, implementation and evaluation (Nunmaker 1991). Conceptualisation involves the identification of user needs and the development of design methods, theoretical models and system architectures. This section reports on the conceptual stage for the design of a CAAD system to support the requirements of kinetic façades. Within the IS research framework the conceptual stage generally does not involve implementation but some experiments and trial applications may be developed to illustrate the approach. Here we develop a theoretical model for a general system to support the design of kinetic façades and illustrate the concept via a particular example - the design and simulation of kinetic sunscreens for a tower building type. The requirement for the example sunscreen system is that it operates in relation to environmental and occupant needs, but also integrates the abstract display of information and the capacity to act as a large scale kinetic artwork.

2. The Function of a Digital Prototype in the Early Design Stages

2.1. CONCURRENT EVALUATION

When the term 'performance' is used within CAAD research the tendency is to regard this in relation to the legacy of design science – structural, environmental and planning performance from which comparative data can be produced to aid the decision making process. This continues the legacy of the early history of CAAD which is aligned with the re-definition of architectural education in scientific terms implemented in the 1960's and '70's after the 1956 RIBA Oxford conference (Glanville 1999). Architectural design was rationalised as a series of quantifiable problems mapped against physical, environmental and sociological data and an analytical 'methods' approach to producing design solutions became prevalent. Within this scientific paradigm the foundations of CAAD were established and developed (Atkin 1986; Gero 1977; Maver 1970). The computer as a decision support tool was framed against architecture as design science and the challenge was to calculate solutions to design as a series of quantifiable problems.

While it is now acknowledged that architectural design must perform in an expanded field, in which performance in socio-cultural and aesthetic terms should be considered alongside functional performance, there is a lack of CAAD research that supports concurrent evaluation. The initial sticking point would appear to be around the issue of measure. Proportional systems or shape recognition techniques can be used to determine objective qualities, but this is based on an outdated gestalt model in which perception is explained in terms of neutral cognition of figure ground relationships. While there is still much more research to be undertaken within psychology, the current agenda is to consider perception a complex interplay between the full range of sensory inputs, memory and in the case of architecture the local cultural and environmental framing of the architectural design (Montagna 1995).

If objective measure is improbable, advances in design visualisation offer the potential for the simulation of designs in a photorealistic temporal context that enhances subjective evaluation prior to construction. We should be cautious in accepting the veracity of any simulation as they will never capture the full range or nuance of actual experience, but developments such as augmented reality (AR) show much promise. If combined with the graphical display of scientific performance, AR offers the potential for the concurrent evaluation of the quantitative and qualitative attributes of design options (Moloney 2006). The need for CAAD to consider performance in an expanded field in which the concurrent evaluation of environmental performance and performance in socio-cultural terms is possible would seem a logical and necessary development.

2.2. CALIBRATED PERFORMANCE

At a recent design workshop digital theorist and architect Greg Lynn raised the issue of closer correlation between design software and the constraints of fabrication (VC Lecture series, University of Auckland, 2004). He made the observation that architects who wish to engage with spline geometry often use software developed for product design. Other designers such as Lynn, who use animation as part of the conceptual design process, typically use software from the motion graphics industry. While such applications may be effective for small scale products or filmic effect, when the design outcomes have to cross over into the constrained world of architectural fabrication there is often a mismatch between the digital form and the reality of construction. By contrast previous analogue methods for designing non-standard geometry often have the constraints of construction embedded in the design tools. For example Ronchamp and other curvilinear designs by Le Corbusier were developed on the drawing board using the technique of ruled surface, an approach that has a direct correlation to construction techniques (Evans 1995). Another precedent outside architecture is the automotive industry where full scale physical prototypes were sculpted using tools calibrated to the curvature of metal stamping machines used to produce car bodies. The car shaper using analogue tools could work in an intuitive and creative manner, secure in the knowledge that the prototype shape could be translated to manufacture.

There would appear to be a gap in CAAD software for design applications that can be calibrated to in particular, the construction challenges of non standard geometry. While there are parametric libraries of window joinery and the like provided by manufacturers, these are not particularly useful at the early stages of design. In an earlier publication, we discussed the possibility of a CAAD interface that started from the basis of materials that incorporated physical constraints, such as minimum curvature or typical manufacturing dimensions. Rather then using abstract geometry, the designer would select materials that would then constrain geometry within the tolerances of the material and typical fabrication (Moloney 2003).

In the case considered here, the design of kinetic façades, the issue of correlating the design simulation to achievable construction is complicated by the kinetic requirement. The degree and speed of translation and rotations in the physical world are constrained by both the geometry of the components and the mechanics of the kinetic system. However in comparison to static façades we anticipate there will be a limited number of construction systems, which make the possibility of implementing physical calibration feasible. In addition there is a greater designer need, as in this emerging field the impact of the construction limitations is comparatively untested. Software that realistically simulates physical movement in relation to construction systems will facilitate a shift of emphasis - from the design of the components to designing the kinetics. This is new territory for architectural designers who will be required to think of performance and composition over time as opposed to the design of a static artefact. With static façade design, experienced design architects soon develop an intuitive understanding of materials and a personal vocabulary of geometry related to construction. This enables design at the early stage to occur using sketches and physical or computer massing models that operate as a form of notation that references previous experience. In effect the experienced designer intuitively calibrates the sketch design to a logic of construction. However with the design of kinetic façades the architect is removed from this mode of intuitive calibration as there are minimal examples of working systems to reference, nor is it probable that the designer can imagine the full range of kinetic outcomes. This is particularly so if the kinetic system interacts with weather patterns or human input that adds an additional level of complexity over that of static architectural composition.

2.3. NEW GENERATIONS OF CAAD RESEARCH

A recent journal article provides a useful summary of computing in architectural design and an approach to new generations of CAAD (Reffat 2006). The approach articulates a shift of emphasis from the design development stages to the early concept forming stage of design and proposes a research model for CAAD that has three aspects: Design occurs in a collaborative 3D virtual environment; this environment is intelligent utilising a software agent approach; the design aids are situated. The proposal here is aligned with this research approach, but at this stage the focus is on the development of the 3D environment rather then software agents or situated design. However rather then referring to the design media as a virtual environment we prefer to use the term digital prototype. Virtual is a loaded term that is perhaps now best returned to its role in philosophical discussion (Leach 1997).

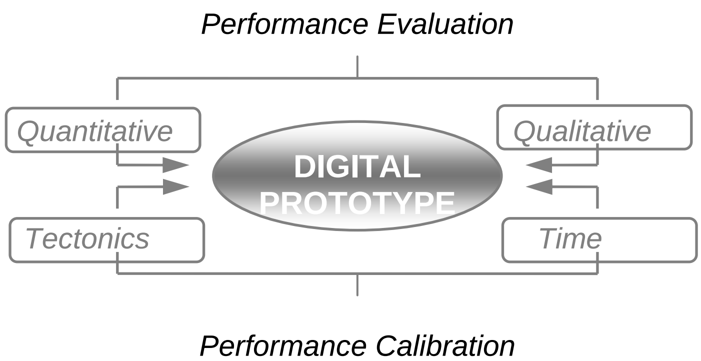

Figure 1. Requirements of a Digital Prototype

Figure 1 summarises the requirements of the digital prototype in reference to the principles discussed above - performance evaluation and performance calibration. The diagram articulates the requirements of a digital prototype that supports an inclusive and holistic approach to design and simulation during the early design stages. In summary: *performance evaluation* occurs in relation to an expanded field where the evaluation of *quantitative* data and *qualitative* experience is concurrent; *performance calibration* of the prototype constrains design options in regard to the reality of *tectonic* limits; the evaluation and calibration of the prototype is determined in relation to multiple viewpoints over a range of *time* scales.

3. Software Conceptualisation

The aim of this section is to refine the concept of the digital prototype above in relation to a particular case - the design and simulation of kinetic façades. Conceptualisation is the first of a three stage approach to research as established in the field of Information Systems (Nunmaker 1991). The methodology is useful for architectural researchers, as it allows the development of a theoretical model that can be handed over to those with programming expertise for the subsequent implementation and evaluation stages. Conceptualization is structured here around the identification of the likely user requirements, the articulation of a design methodology and the development of a theoretical model.

3.1. USER REQUIREMENTS

Who are the potential users and what are the range of requirements for this digital prototyping system? As outlined in the introduction there are currently two distinct groups – designers of intelligent and media façades.

3.1.1. Intelligent Façades

In the last twenty years advances in electronic control systems have progressed to where a building can be described as intelligent rather than responsive. A recent overview defines the basic criteria by which a building can be so considered (Wigginton 2002) .These are (1) an input system, (2) a processing or control system which analyses this input , (3) an output system which reacts to the analysis of the input, (4) this response occurs with a consideration of time (5) learning ability (although earlier definitions of intelligence often do not include this last criteria). The idea that buildings should be some sort of intelligent entity separate from users has not surprisingly being subject to debate. There are a few examples which break the closed system of input / control /output to include the user in the monitoring and decision making process. The control system of the GSW headquarters building in Berlin makes recommendations to users about the selection of natural or mechanical ventilation by means of green or red lights on the window transoms. The user can decide to accept or override the recommendation from the control system. Such examples suggest a transition from the intelligent façade as an autonomous machine, to that in which the user engages with and is part of the decision making.

The definition of intelligent façades above provides a useful guide to the range of design decisions for functional performance. 1) *Input* methods need to be determined – what environmental data and user requirements are going to be monitored and how? 2) The *control* system to process the input data needs to be designed 3) The design of the *output* system – mechanical and/or electronic kinetic systems. In relation to qualitative performance requirements we can first consider the form of the output device. There are some recent systems that change the material properties of glass to affect light penetration and thermal performance. However, most environmental control systems are based on mechanical systems - louvers or fins of varying materials, profiles and proportions. There are two general tectonic approaches to mechanical systems: either to embed the kinetic component or fin within the composition of the façade thus minimizing aesthetic impact; or to design the shading or ventilation elements as a separate prosthetic device which serves the building. In either approach seldom are the mechanics of the device articulated with any great aesthetic attention, perhaps reflecting the typical separation between architect and environmental engineering consultants.

A notable exception that seldom finds its way into surveys of intelligent façades is the Arab institute in Paris designed by Jean Nouvel in 1988. The southern wall is protected from the sun by a 60 meter wall composed of multiple panels composed of variously dimensioned metallic diaphragms. These operate like a series of camera lenses, shrinking and widening in response to sensors in order to control the penetration of sun light into the building. Even when at rest the tectonic quality and detail of this wall is stunning, while the dappled light which results generates seductive internal spatial qualities. This iconic building sets a precedent for the integration of functional performance and aesthetic effect in kinetic façades. Besides the material form of the façade the type of movement and its control has a major effect, which suggests that the process control should also be examined in relation to qualitative performance. In the case of the Arab Institute the contraction expansion movement is purely reactive with each panel individually controlled by a local sensor. This gives an engaging albeit random dynamic to the façade. In contrast to this on/off reactive approach a central control system could for example 'orchestrate' patterns of movement over time within a functional performance threshold. The opportunity for embedding qualitative aspects within the operation of environmentally driven kinetics is an aspect that is seldom exploited.

3.1.2. Media Façades

Anders in his work on what he terms cybrid architecture suggests the needs of contemporary society have extended beyond that of a communal physical reality (Anders 2005). Media screens can be seen as early manifestations of architecture adapting to an information rich society and adding to its sphere of practice by mediating between physical and information space. As would be expected at these early stages the majority of such media screens take the form of large scale computer displays, using data projection or video walls on the façades of buildings. More recently light-emitting diodes (LED) have been utilized to turn whole buildings into a computer controllable image. A more low tech, but highly effective approach is the 'BIX', a 900 sq. m. light installation set behind the double curved acrylic surface of the Kunsthaus in Graz, Austria. Made up of standard circular fluorescent lamps, these act equivalent to pixels, each individually controlled by a central computer to enable the generation of low resolution imagery. Regardless of the time of day, or content, the tectonic quality of the BIX wall is engaging beyond that achieved by standard video screen technologies. Rather then been perceived as applied surface or screen, the display reads as building skin integrated into the constructional logic of the whole, and has a tectonic quality over and above its display function. Another example that falls between object and surface and operates at an urban scale is the D-tower, an art piece commissioned by the city of Doetinchem in the Netherlands. The D-tower consists of three parts: a website (accessible to everybody), a questionnaire (accessible to a hundred different people each year) and a 12 meter tower. All three parts are interactively related to each other, with the tower being internally lit with a mix of red green and blue light. Updated each night, the mix of color reflects responses to the questionnaires, which are intended to gauge the mood of the town in relation to a variety of issues. The tower is expected to stay in place for decades and has already added to a sense of social cohesiveness in this small provincial centre.

A primary problem with light based media walls is they are only marginally effective in day light. The Agesis Hyposurface is an example of an alternate approach, in which imagery is created through physical movement of architectural surface. Made up of triangulated metal plates driven by a bed of pneumatic pistons, dynamic 'terrains' are generated in real time. In this way imagery on a computer can be transferred to a three dimensional relief, the triangulated plates operating as 3D pixels. At the other end of the technical spectrum, artist Ned Kahn was commissioned to produce a wind veil for a non-descript parking building in the small town of Charlotte, USA. Any wind eddy is picked up by the 75mm reflective disks, generating an effect not unlike the quality of metallic fluid. This skin as installed is reactive only to wind, but suggests possibilities for low tech systems that have passive energy sources.

Returning to the digital prototype framework, we can summarise the requirements for designers in a similar manner to that of intelligent façades. Media screens may have a functional performance, the communication of information, but more often the emphasis is on qualitative performance - presenting information in a socially engaging and culturally enhancing manner. The extreme end of this qualitative function are those designed solely to an artistic agenda to operate as a public work of art. Despite this shift in emphasis, the same underlying *input-control-output* structure identified for intelligent façades can be applied to media screens. The input may be sampled environmental data, information networks, or human interaction. Media screens also require a processing unit and a method of display, which may be tectonic mechanical systems or electronic light systems.

3.2. DESIGN METHODOLOGY

Despite the different agendas of the designers of kinetic environmental systems and those designing cybrid interfaces to information embedded in building façades, the novel requirement in comparison to static façades is that both groups require the design of a process rather then an artifact. Where do the design decisions occur when considering the design of process for kinetic façades? The objective here is to identify the factors to be considered, rather then the prescription for any particular design approach. We propose a general methodology built on the input-control-output structure identified in the discussion of user requirements.

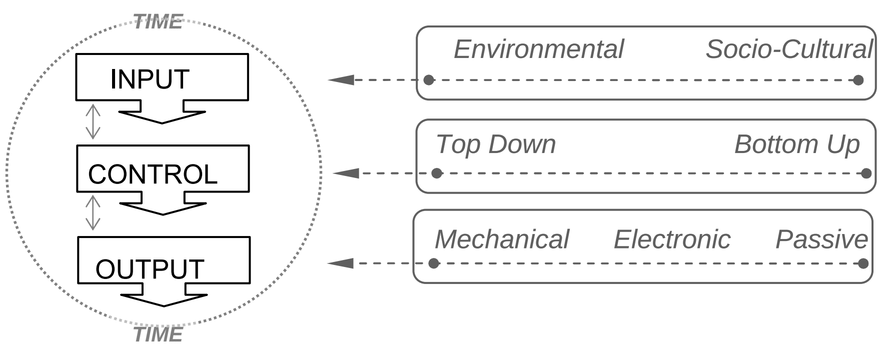

Figure 2. General Design Framework for Kinetic Façades

On the left side of figure 2 are the three design stages, while on the right is the 'range' within which primary decisions are undertaken: for the input stage this is a broad distinction between environmental and socio cultural data / user interaction; for the control system we can distinguish between a bottom up or top down approach where the outcome is to varying degrees emergent or prescribed; while the output would be located within a range of mechanical, electronic and what we term passive or low energy systems. The aim of the diagram is to identify where design decisions are made and the general range of approaches that may be considered by the designer.

We would argue that the key design decisions occur at the process stage where the design of the control system can address qualitative as well as functional performance criteria. Here there may be an opportunity for auto-poesies in which design occurs at the level of determining the parameters or rules from which kinetics is emergent. Alternatively the personal aesthetic of the designer may be embedded in a similar manner to, for example, such proportional systems as used by Le Corbusier.

The diagram also foregrounds that all design stages – input, process and output – are made in relation to time. Designers of kinetic façades need to consider foremost that the design and simulation of performance needs to consider a range of time scales, from the micro to the macro. For example input may be processed to output in a real time response and/or be processed to create macro scale trends that affect kinetics that emerge over a longer time period.

3.3. THEORETICAL MODEL

We have outlined user requirements and identified a general design framework. The objective here is to develop a concept for design software to meet these unique requirements. This is based on the CAAD digital prototype developed in section 1 where a key aspect is the calibration of performance to the geometry and physics of construction.

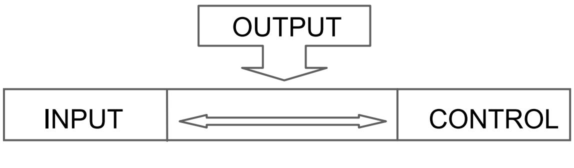

Figure 3. Revised design process for Calibrated Kinetic Façades

As illustrated in Figure 3, the starting premise is that the software architecture would reverse the input-control-output sequence and proceed from the basis of user choice of the output technology. It is proposed that the development of the software architecture would proceed first with the identification and design of a range of output mechanisms presented to the user as parametric libraries. These parametric library parts would consist of: associative geometry cognizant of standard component dimensions; materials; a range of kinetic parameters calibrated to typical mechanical, electronic or passive motor physics; fabrication options that are calibrated to fabrication logistics; and designer preference for detailing.

The second premise of the software architecture is the requirement for temporal visualization that allows concurrent evaluation of quantitative and qualitative performance across a range of time scales. This is in recognition that the novel design challenge for kinetic façades is that the outcome is a process system that can only be evaluated in relation to performance over time. Elsewhere we have developed an approach to temporal visualization based on screen based AR that allows real time animation and the simultaneous display of functional performance (Moloney 2007). This approach can be utilized here to provide a degree of photorealism to enhance the qualitative assessment of the design. Moreover it was proposed that the display of the functional performance should be displayed in graphics alongside the 3D visualization to allow the designer a broad brush and intuitive understanding of quantitative performance *as* the model is being interactively designed. As well as real time simulation it was proposed the AR environment should incorporate time-lapse approaches to allow a range of time scales to be considered.

We have outlined two aspects of the theoretical model - that user interaction starts from the choice and customization of a parametric library and secondly concurrent evaluation occurs in a screen based AR visualization system allowing real time animation, time lapse functionality and the display of functional performance data.

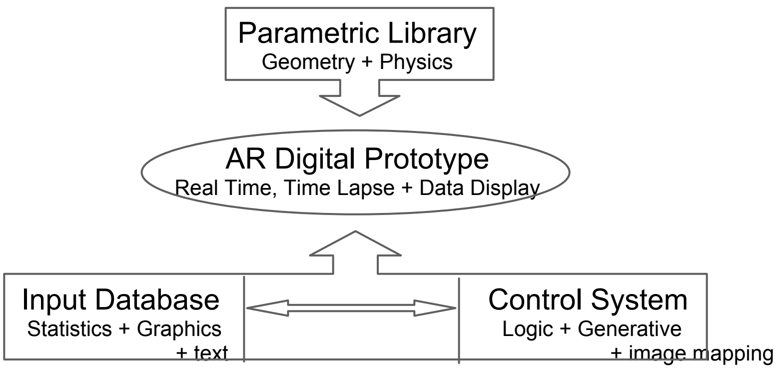

Figure 4. Software Architecture for Kinetic Façade Design

Figure 4 illustrates that once the parametric library has been customized by the user, performance within the AR environment is simulated by the design of the control system in relation to a database. For the design of a process over time the control system is where we argue the crucial decisions occur. We propose the software architecture of the control system module should allow a range of approaches: a generative 'engine' that maximises functional performance but also allows design preconceptions (Janssen 2006); a shape grammar approach that enables experimentation with proportional relationships over time (Stiny 1980); an image mapping module that allows translation of graphics to kinetics. Given this range, we anticipate the control system will require an interactive graphical user interface (GUI) and a scripting interface. The final component of the proposed architecture is a database that would allow users to evaluate the control system against the relevant input. In the case of intelligent façades this may be, for example, historical weather data collected over time that can allow a fine grained and localised testing of daily and seasonal variation. This data could be used to also project future longer term variation as a result of global trends in temperature and sunlight frequency. In the case of media façade the database can be linked to streaming input from information networks that would include data in graphical and text formats.

3.4. ILLUSTRATION OF APPROACH: ITERATION 1

Typically the IS Research method adopted here refines the software architecture conceptualization to a level of detail and then proceeds to collaboration with software engineers to implement a full working beta application and formal user trials. Given the novel aspects of kinetic façades and the lack of precedent, we have decided to implement initial tests or 'illustrations' of the model during the software conceptualization. These are to be undertaken in an iterative manner looking at a range of example case scenarios, and then reflecting on the outcomes in order to develop the theoretical model in more detail. The intent is not to develop full functionality but to enable preliminary evaluation of the design sequence – specification of the output via a parametric library, then design of the control system and evaluation of the outcome sampling input from a real time database. The first iteration examines the case of an external sunscreen system for a high rise building. Typically the control mechanism for such a system would be developed by a consultant in relation to a purely functional agenda. The intent of the trials is to test the premise of the concurrent evaluation of environmental performance and allow the design architect to experiment with the qualitative outcomes of the kinetics.

The design scenario for this first iteration is to develop an aesthetic quality to the kinetics as the control system evaluates the environmental data and operates the individual sunscreens. When the light levels are such that sun shading is not required the kinetic façade can be utilised as a media screen to communicate local and global information, or be made available for public art purposes. Figure 5(a) illustrates a parametric sunscreen component where the user can customize geometry including overall proportions, frame dimensions, materials, type of detailing. In addition there are physics parameters such as pivot points, rotation and / or translation speeds calibrated to typical drive mechanisms. Figure 5(b) and 5(c) illustrate two options for sun tracking where the sun angle is articulated as a slow moving 'wave' across the façade. The two options are differentiated by in this case by the rotational axis of the individual screens.

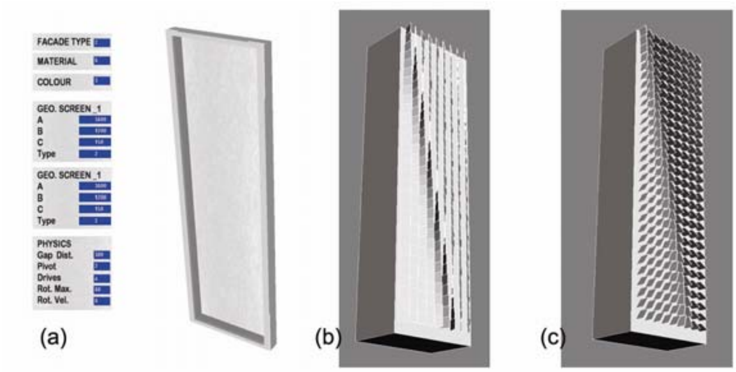

Figure 5. Illustration iteration 1 – screen grabs of parametric module and experimentations with kinetic control module.

The examples illustrated here show a 'top down' design approach where the façade is conceived as a compositional whole mapping environmental change and articulating the edge condition and the overall chiaroscuro effect. Currently in development is a more bottom up design approach that simulates a scenario where occupants have the ability to affect the position of individual screens. In combination with a graphic display of environmental performance the intention is for the designer to be able to test the qualitative and quantitative impact of limiting the degree of occupant control.

4. Further Work

The intent of the illustration was to test the software architecture concepts in a similar manner to the reflection-in-action approach associated with architectural design (Schön 1983). Similar to a sketch, these preliminary moves clarify intentions and demonstrate the significance of the unique challenges of kinetic design. Iteration 1 will be further developed as indicated and this conceptualization stage will continue via a series of other iterations that explore a range of technologies and case scenarios. The objective is to use the iterative ‘conceive- test via particular example – reflect’ approach to ensure a well thought through architecture is established before a full software implementation.

References

ag4: 2006, *Media Façades*, Ralf Daab, Cologne.

Anders, P: 2005, Cybrid Principles: Guidelines for Merging Physical and Cyber Spaces, *International Journal of Design Computing,* **3,** pp 391-406.

Anshuman, S: 2005, Responsiveness and Social Expression; Seeking Human Embodiment in Intelligent Façades, *ACADIA***,** pp. 12-23.

Atkin, O: 1986, *Psychology of Architectural Design*, Pion, London.

Evans, R: 1995, *The projective cast: architecture and its three geometries*, MIT Press, Cambridge, Massachusetts.

Gero, J (ed): 1977, *Computer Applications in Architecture*, Applied Science, London.

Glanville, R: 1999, Researching Design and Designing Research, *Design Issues,* **15**(2): 80-92**.**

Janssen, P: 2006, The Role of Preconceptions in Design: Some Implications for the Development of Computational Design Tools, *in* J Gero (ed), *Design Computing and Cognition '06***,** pp. 365-384.

Leach, N: 1997, *Rethinking architecture: a reader in cultural theory*, Routledge, New York.

Leatherbarrow, DMM:2002, *Surface Architecture*, MIT Press, Cambridge, Mass.

Maver, T: 1970, A Theory of Architectural Design in which the Role of the Computer is Identified, *Building Science,* 4**,** pp 199-207.

Moloney, J: 2006, Augmented Reality Visualisation of the Built Environment to Support Design Decision Making, *Information Visualization 2006***,** pp. 687-692.

Moloney, J: 2007, Screen based augmented reality for architecture, *CAADRIA***,** pp. (Publication pending).

Moloney, J, Issa, R: 2003, Materials in Architectural Design Education Software: A Case Study, *International Journal of Design Computing,* **1:** 46-58.

Montagna, C, Bonnes M, Secchiaroli, G: 1995, *Environmental Psychology: A Psycho-Social Introduction*, Sage, London.

Norberg-Schulz, C.:1971, *Existence, Space and Architecture*, Praeger, New York.

Nunmaker, J, Chen, M., and Purdin, TDM: 1991, Systems Development in Information Systems Research, *Journal of Management Information Systems,* 7**(**3**):** 89-106.

Rapoport, A: 1969, *House Form and Culture*, Prentice-Hall, New Jersey.

Reffat, RA: 2006, Computing in architectural design: reflections and an approach to new generations of CAAD, *Electronic Journal of Information Technology in Construction,* **11:** 655-668.

Schön, DA: 1983, *The Reflective Practitioner*, Harper Collins, USA.

Stiny, G: 1980, Introduction to Shape and Shape Grammars, *Environment and Planning B* **7:** 359-367.

Wigginton, MHJ: 2002, *Intelligent Skins*, Butterworth-Heinemann, Oxford.