A Symbiotic Interaction of Virtual and Physical Models in Designing Smart Building Envelope

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The building needs to be designed to minimize its environmental footprint and to be sufficiently adaptive to changing indoor and outdoor environmental conditions. The smart building envelope is an interactive system which is adaptive to environmental conditions by transforming its shape and functions. This is a kind of machine, not like a traditional building component, which should be based on integrated engineering design methods in addition to the exploration of formal aesthetics. As artistic genius or technical skill alone cannot not fully support the design of such a novel product, the design needs to be systemized by introducing a product development method such as prototyping in other industries. Prototyping needs to be integrated in school environment, even if it requires fundamental reconfiguration of current computer-based design studios. This paper aims at proposing a teaching methodology for educating the prototyping-based design of smart building envelope system in digital design studio. This methodology allows novice designers to operate interactions between virtual-physical models. And sketches are used to share ideas to other collaborators such as programming, mechanical operations without technical knowledge. The interactions between virtual-physical models and sketches contribute to not only complement virtual models and physical models, but also achieve high-performance of smart building envelope practically.

**Keywords:** Digital Model, Prototyping, Design Media, Design Process, Design Education

BACKGROUND

The building needs to be designed to minimize its environmental footprint and to be sufficiently adaptive to changing indoor and outdoor environmental conditions: the building design needs to deal with climate changes and energy depletions (Wilde 2012). The overall performance of a building is heavily dependent on that of its envelope system. It is an indispensable subsystem which is tightly linked to all other elements such as structures, technical services and spatial configurations. Accordingly, the envelope system significantly affects not only the overall
energy efficiency and the carbon emission of a building (Schittich 2006, Bader 2014), but also the symbolic image of a building.

The smart envelope, a.k.a. 'responsive facade' or 'intelligent facade', is an interactive building envelope which is adaptive to environmental conditions by transforming its shapes and functions (Weng 2013, Ron 2012, Gruber 2014, Salim 2014, Zari 2014). The beauty of the smart building envelope system can be obtained by its seamless interactions with the environment while its structural integrity is maintained during the continuous transformation. A smart building envelope system is integrated with ICT-embedded components like sensors (sensing environmental conditions such as air flow, pollution, temperature, etc.), actuators (controlling the movement of physical parts or the change of their materiality) and processor to perform desired functions. Therefore, the success of smart building envelope design necessitates the collaboration among multidisciplinary experts from robotics (movements of components), embedded programming (interactions between exterior environmental conditions and specific functions of a system) and interaction designs method (interactions between users and building systems) (Wang 2010).

The smart envelope is a kind of machine, not like any traditional building component, which should be based on integrated engineering design methods in addition to the exploration of formal aesthetics. Such design process then becomes a series of optimization seeking for the most suitable configuration for environmental conditions while adopting smart components and technologies to realize the design concept (Kirkegaard 2011). As artistic genius or technical skill alone cannot fully support the design of such a novel product, the design needs to be systemized by introducing a product development method such as prototyping in other industries.

The prototyping method is a proven technique to accommodate empirical sources to a design process, which has been widely adopted in product design field such as car or airplane (Fu 2008, Guimaraes 1991). Prototyping-based design process usually allow designers to not only adapt unacquainted technologies into architectural components, but also find design solutions of better performances. Prototyping needs to be integrated in school environment for these reasons, even if it requires fundamental reconfiguration of current computer-based design studios.

The combined use of virtual and physical models has become a promising method in the process of evaluating the usability of design to accommodate user requirements (Schmitz 2013, Wolfe 2011). Users are able to evaluate building performances and investigate problems caused by physical operations, then solve those problems by reconfiguring the system. However, the prototyping method tends to increase cost for fabricating various types of mock-ups, and requires high level of expert knowledge about smart technologies (Z corporation 2010). As the details of this new technology is not fully considered during the phase of conceptual design, unexpected problems may occur by the time when the installation expert tries to apply the smart component (Vries 2012). On the other hand, architects sometimes understand the smart technology at the superficial level, which hinders the design of efficient building systems (Silver 2009). Particularly, the prototyping method combining virtual and physical models is difficult to be introduced into architectural design studios in school environment as due to the constraints in time, cost, and human and physical resources.

RESEARCH OBJECTIVES & METHODOLOGY
This paper aims at proposing a design process model for educating the prototyping-based design of smart building envelope system. The prototyping method is introduced to help architecture students deal with the conceptualization and development of this machine-like product. The backbone of this design education process, then, is the prototyping process that utilizes the complementary use of virtual model and physical model. This process entails the generation of numerous design versions since the genera-
parametric tools are employed as a main vehicle for developing the virtual model. Furthermore, the design needs to be supported by the extensive use of simulation tools, which makes it inevitable to conduct various data transformation tasks and create numerous intermediate data objects. It is not easy for a novice designer, i.e. architecture student without the knowledge of programming or parametric tools, to deal with such tasks against the limitation of class hours and physical resources, and eventually to deliver a successful product. Furthermore, the physical model required for the prototyping of smart building envelope is not just a static object but an actually operating machine. Thus, the difficulties are compounded by the burden of training the basic skills of physical computing and digital fabrication even at the basic level.

Based on the above observations, this paper presents a complementary prototyping process of virtual and physical models: a symbiotic model, and this model considers the limitations of resources in the field of education. In order to proceed with the research, traits of both virtual and physical model are examined. Then, an evolutionary process is modelled where the design evolves through the iterative analysis, evaluation, and refinement of design alternatives represented by both type of models. A design studio whose task is on "biomimetic kinetic façade" was coordinated and necessary courseware was also prepared by reflecting this process model. The studio was conducted for one semester (16 weeks), and the whole process and the results have been recorded and analyzed.

The focus of analysis is on how the two models can enhance the traits of the other, and the design productivity. The role of sketch, in particular, is of special interest in term of facilitating the interaction of two models, and helping students to better deal with those two models, and yielding better design solutions. Accordingly, such use of sketch, e.g. flow chart for algorithm, by the architecture student was carefully observed.

SYMBIOSIS OF VIRTUAL MODEL AND PHYSICAL MODEL

Virtual models have evolved to expand design language through developments of computer technology which make complicated forms and experimental systems (Kim 1997, 2012). Moreover, the convergence of heterogeneous technologies (e.g. Virtual reality, Internet of things, Physical computing) enables people to broaden sensuous experiences of virtual space to real world (Say 2014). Parametric designs and optimization techniques facilitate to generate alternatives of various forms and find optimal ones among numerous alternatives in accordance with design requirements (Carpo 2013, Shelden 2002). And fully fledging technologies, digital Fabrication and 3D printing, help designers to conduct rapid prototyping (Singh 2011, Volnder 2014, Calado 2013). Furthermore, interactions between virtual model and physical model help designers not only simulate their performances but also test operations to improve design fidelity (De 2014).

The virtual model (Figure 1, (A)) captures the information of the smallest components to operate smart building envelope by reacting to environmental conditions. Also, it contains invisible relationships among building components and smart elements such as sensors and actuators. On the other hand, physical model (B) is confined by physical forces (such as gravity and collision among components) which influence on assemblies of components and changes of behaviors. Designer generates variations by controlling sub-parameters that cause changes in operation while maintaining critical relations between virtual components (1). If versions are transfered to simulation tools, environmental performances are simulated (2). Using those simulation results, designer decides parts to investigate in physical model (3). Designer fabricates prototypes of versions that need to be tested in physical environment (4). And then they find problems that cannot be detected in virtual model by activating the combinations (5). Also by only changing sub-parameters in virtual models, various shapes of prototypes are assessed for perfor-
Virtual models have underlying parametric variations which are important evidences for representing desired images (Figure 2, (1)), such as a control range of motions (e.g., angle of rotation, distance of shifting), which are used to revise forms or replace material properties with keeping semantic orders in overall configurations or their sizes (2). When iterative parts in the design process are constructed as an algorithm, virtual models are used to generate similar offspring versions. And, by connecting simulation or optimization tools, optimum forms are found which is close to design requirements (3). But if previous versions are not able to fully satisfy design requirements by changing only parametric variations, a different solution will be designed (4). Novel versions are evolved for semantic orders as mentioned above. By such an iterative process results in a multitude of different versions, heterogeneous versions enables to be generated rapidly (A). On the other hand, physical models are constrained compared to virtual models, non-parametric, but it enables to assess practical operations in physical conditions through moving kinetic parts (5). The designer can directly operate the system so that the interaction facilitates to grasp overall mechanism of the system. Through those operations, it becomes even easier for the designer to replace parts or accommodate tiny components considering movements of components (6). Also, the operations are used for evaluating physical performances by adding environmental factors artificially, e.g. ventilation, daylight, human’s behavior (7). However, physical models will be generated only for some prototypes which are critical enough to spend the cost of fabrication (8).

In spite of the usefulness of two models, it is difficult for students to operate virtual models as well as physical models. The reasons are as follows. Compared with filed experts, students tend to spend much more time to grasp the mechanism of the smart building envelope system rather than to establish design strategies. Also, the students experience difficulties in explaining to other collaborators about the technical content of virtual components or algorithms. They can also consider the integration of smart technologies in implementing forms.
(2). This is why students have difficulties handling two models in educational field directly. Both models require considerable technical skills, expense, and time. To overcome these problems, this research puts an emphasis on the roles of sketch. Sketches are easy to modify by intuitions (Elsen 2012) and explain forms or principles logically (Johnson 2009). Sketching, as a familiar design method to novice designer, not only supports functions of virtual-physical models but also being a catalyst to help to utilize both complementary models in the whole design process. For example, sketches allow designers to share ideas with other collaborators without technical knowledge. Therefore, virtual models, physical models and sketches support designers to specify systematic structures and achieve successful results for implementing high-performance smart building envelope.

- Conducting design studio
  1. Modelling itself needs to be closer to actually operating object. So tutors choose general tools for making forms and fabricate smart devices (Virtual models - Rhinoceros and Arduino, Physical models - Arduino, sensor and actuator), so that students construct and operate virtual models and physical models. Tutors also provide tutorials for basic implementation skills.
  2. Several types of sketches are served for students to share design concepts, operation of kinetic parts, and assembly mechanisms. Students are instructed to brief the progress of design using sketches along with written document.
  3. Students are asked to utilize three media (virtual model, physical model and sketch) in progress and to write out design history focusing on how they defined problems and generated solutions. The design history provides important clues to investigate the roles of three media in design process. It involves numerous design contexts, such as cost, preference of forms, difficult problems for operations, which affect final results.

- Observation & Analysis
  1. Types of virtual models and physical models, their functions to complement other models are investigated in prototyping process.
  2. The design history is used to investigate the stream of design thinking which interacts between problems and solutions as well as complementary interactions between prototypes and sketches.

**DESIGNING DIGITAL DESIGN STUDIO**

The digital design studio is a course targeting advanced students who have fulfilled a prerequisite basic CAD class. This studio deals with not only parametric design knowledge, but also recent technological trends in architectural design. Students are able to find potentials by coordinating design forms and technical elements. On the other hand, biomimetic design has been recently introduced as a method to enhance the environmental adaptability of a building envelope (Gruber 2014, Park 2014, Salim 2014, Zari 2014). The biomimetic smart envelope has recently gained a potential to be one of the essential features of the future building systems.

In this research, kinetic facade designs and biomimetic approaches are converged in digital design studio for implementing smart building envelope using prototyping-based design process. Due to kinetic system embedded sensor, actuator and processor, designers interacts to implemented models spontaneously (Kim 2012). However, kinetic systems need to be implemented as an operational mechanism in articulated steps to mimic organic systems in nature.

Biomimetic design is an approach for reinterpreting principles in Biology into architectural design (Davis 2013). Designing kinetic facades using this approach is to find optimal functions of components and high-performance of holistic systems adapted to design requirements (King 2014, Zari 2007, Imhof 2013).

In the digital design studio, virtual models and
physical models are used not only to grasp fundamental mechanism of kinetic building facade, but also to create desired systems. Functions of two models were classified into ‘before establishing concepts (Figure 3, Level A)’ and ‘after establishing concepts (Figure 3, Level B)’. Designers establish design concepts close to an ideal solution while describing the solution using sketches along with the construction of virtual models and physical model (Level A). Sketches are used for representing simplified shapes to describe images by translating bionic principle into envelope systems (1). Virtual and physical prototypes are refined repetitively until they are close to the intended design (2). By interactions between virtual models and physical models, a practical operation is conducted (Level B). In this step, systems are tested for operation whether they can satisfy target performances. Based on the test result, systematic configurations or algorithms are modified to solve the problem. If two models need to be modified to solve investigated problems in (3), algorithms (4) or systematic structures (5) are changed.

In the process of designing biomimetic envelope system, designers are able to compensate problems by interactions between virtual models and physical models. Depending on what designers would like to evaluate, sketches need to be proposed differently. Sketches are classified into three types: about elements belonging to performances for evaluating virtual models (Figure 4, (1)): about system structure for evaluating physical models (2): about data flow for evaluating interactions between virtual-physical models (3).

First, when simulation results do not satisfy a target performance, major factors are checked and shapes and behaviors are modified (1). Second, when operations are abnormal, behavior and relationships between components are modified (2). Third, when evaluating overall performances, data flows are changed or components are added (3). Using sketches such as (1), (2) and (3), virtual versions and physical prototypes are created according to modified logics and replaced components (4).

**CONDUCTING DIGITAL DESIGN STUDIO**

Special lectures on virtual model, physical model, and sketches were offered to students. These lectures were coordinated according to the phase of design process. Three media are incorporated to design simplified smart building envelopes: Rhinoceros is for representing geometries: Arduino is for analyzing data collected sensors: Grasshopper is for changing geometries using parameters.

Figure 5 shows technological background and educational materials provided on each step of design process. First, the tutors explained some examples of constructed kinetic façades focusing on their design process and operation principles(E-(1)). Students selected the examples of kinetic façade.
and analyzed their operation principles and design requirements (D-(1)). Second, the students make up the design requirements which would be fulfilled by the kinetic façade system (D-(2)). They selected an object which would be reinterpreted from the biomimetic point of view and designed the overall operational principles (D-(3)). Third, tutors introduced some similar cases of sketches and diagrams about the kinetic façade system: architectural details, structure of system, and data flow (E-(3)). Students explained the design through discussion using sketches (D-(4)). Students made a prototype with virtual and physical models and analyzed to find out which prototypes perform appropriately for the design requirements with the tutors (D-(5)). Tutors asked the students to predict and improve the errors of the system considering the connection between their components and its data flow (E-(4)). Finally, students completed the final prototype through improving the selected prototype or creating another one (D-(6)).

The prototyping process (Figure 5, (5)) consists of the four steps (Figure 6):

- Design a module (A)
  1. Construct physical and virtual model by defining the structure of the system and data flow which satisfy specific target performance set on the conceptual stage (A).
- Evaluate the performance of the module via interaction between virtual and physical model.
- Replace the components or modify the structure of the system.
- Add requirements (B)
  1. Add the new design requirements and check if there are components which contradict each other when a prototype of module is completed.
  2. Adjust the target performances and the structure of the system to get the best solution satisfying the requirements.
- Expand systems using different modules (C)
  1. Find problems occurring when new module type is added (A) or the existing module was expanded.
  2. Complete design (D)
    1. Improve the system so it can provide the best performance (C).

**DISCUSSION**

The design process is progressed not only to adapt to the design requirements using smart components, but also to specify the desired form according to concepts: prototyping process. Virtual models, physical models and sketches were categorized into 6 works from the 6 project teams. A team which produced balanced quantities of three media (virtual models, physical models and sketches) was selected and their roles were analyzed in terms of complementary roles of models and media. This team designed a kinetic façade to mimic a leaf like Carpinus laxiflora to improve the quality of the indoor environment. Kinetic parts in this project operate in response to the
presence of human with the help of a proximity sensor. The design process can be divided into 2 stages based on the function change of three media. Definitions of stage A and B are based on the chapter of 'designing digital design studio': In stage A, connections between virtual models and physical models are not fully constructed for real-time operations: In stage B, connections between virtual models and physical models are completed for real-time operations.

- **VIRTUAL MODEL**
  1. A stage: method to implement geometries
  2. B stage: method to evaluate performance - for acting by both adapting a luminous intensity and a distance between a user and the envelope, simulation results are compared with each other.

- **PHYSICAL MODEL**
  1. A stage: method to apply the movement of the leaves to folding mechanism of the façade.
  2. B stage: method to find physical problems by operating the parts as in the real smart building envelope.

- **SKETCH**
  1. A stage: It is used to skematize the image of the facade. Virtual models and physical models are implemented same as drawn using sketch
  2. B stage: When awkward movements or physical crashes are detected, it is used to analyze imperfections for factors or set complementary mechanism using connection between virtual models and physical models.

When designers operate virtual models and physical models separately (A stage), they need to compare different versions or prototypes to improve design fidelity. In this stage, they are able to implement desired form and choreograph systematic movement in accordance with design concept. After schematic design are built in a simplified form (B stage), they operate system in real-time and interacts to achieve high-performance of 'smart building envelope'. And Symbiotic virtual-physical models play a key role to de-
velop smart envelope systems. Sketches also help implementing virtual model and physical model in early design stages because they help facilitate the communication among participants.

CONCLUSION

Prototyping is a critical design method for smart building envelope which needs to be developed with step-by-step evaluations on its operations and various required performance factors. Also, reflecting the trend in contemporary architecture which becomes similar to engineering product packed with ICT technologies, a more systematical learning is needed to be integrated especially in digital design studios. Old-fashioned CAD teaching curricula providing the content according to the difficulty of tools, e.g. 2D drafting - 3D modeling - Visualization - Simulation, are not able to fully support those requirements. To integrate the prototyping method into the learning process, a holistic strategy is needed to encompass various requirements such as determining the type of design product, levels of implementation, coordinating tools, providing necessary knowledge and skills. This paper tried to address this strategy in a digital design studio where the theme was to implement a smart building envelope, then analyzed the content of the class. In this paper, a symbiotic model between virtual-physical models was proposed. The symbiotic interactions enable both virtual and physical models evolve in parallel, and help the novice designer conduct the prototyping efficiently in a school environment which suffers from the limitations of time and resources. Particularly, this paper investigated how two models complement other’s disadvantages in deriving successful design. Another interesting point was how traditional sketches facilitates the interactions between two models. In conclusion, a framework for prototyping-based design studio was proposed which is based on the symbiotic virtual-physical models. Also, the integrated use of traditional design media in digital design process was emphasized. A rigorous analysis method was not fully developed to quantify the statistical significance of the observation. The symbiosis model was also proposed by an empirical study without a full support of quantification, which needs to be enhanced in future works.

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642 | eCAADe 33 - Smart and Responsive Design - Concepts - Volume 2