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Early studies in the field of computer-aided design/computer-aided manufacture (CAD/CAM) focused on the effects of digital media on the thought processes of designers; however, research has recently shifted to issues of parametric design and building information modeling (BIM). The objective of this study was to compare the parametric design process with BIM to conventional CAD/CAM without BIM in the development of free-form designs. The result proposes some observational phenomena of comparing the two very common methods of the digital design and fabrication in today's digital era, as a reference for the design practice.

Keywords: computer-aided design/computer-aided manufacture (CAD/CAM) technique; digital fabrication; building information modeling (BIM); parametric design

1. Introduction

Not until the digital era did the digital design emerge [12]. One of the best known projects is a fish sculpture by Frank Gehry in 1992, located in front of the Port Olímpic, in Barcelona. Gehry adopted computer-aided design and computer-aided manufacture (CAD/CAM) technology to assist in the design. Since that time, this approach to design has been widely adopted to deal with the complicated free-form architectural design and construction processes [6–8,16,17].

Digital fabrication is a subcategory of CAD/CAM, in which computer-controlled machines as tools are utilized to cut or make parts [4]. Numerous researchers have investigated fabrication techniques associated with the aid of digital design and digital manufacture. Digitalization of the design process enables designers to present their ideas more easily and has led to an increase in the complexity of architectural forms. Design has gradually moved toward free forms, characterized by continuity as well as dynamic designs and textured surfaces [9,11,13,15,18,20,27]. These innovations have imposed on architects and engineers intense challenges from the design stage to construction, which has led to the development of various approaches to design and fabrication.

Parametric design, one of the relatively recent approaches, was in fact one of the earliest applications envisioned for CAD [4]. This approach enables designers to define relationships between elements and groups of elements, and to assign values or expressions to organize and control those definitions. Object-based parametric modeling is based on the concept of building information modeling (BIM), which was developed for the design of mechanical systems with a predefined set of object families, which does each have behavior programmed with them [5]. Preston and Bank [14] used this approach in their construction of a temporary structure comprising a series of interconnected arches. Various circular segments observed in 2-D X-ray images and CT scans of the skull were transformed into mathematical variables for representation in the geometry of circular arches. This led to a beautiful architectural creation based on strict principles of biological engineering. The actual fabrication was performed by hand without the use of CAD/CAM technology, despite the fact that the form was created through the application of parametric design. Baek and Lee [1] proposed a novel parametric human body shape modeling framework. The approach progresses through three phases: (1) database construction, (2) statistical analysis, and (3) model generation. In the same time, a number of researchers proposed various methods of parametric modeling [3,21,22,25]. Nonetheless, parametric design is usually applied to small-scale projects such as those found in product design, rather than large-scale endeavors such as architectural design.

One disadvantage to the parametric design is the time consumption in the initial design process, particularly for those with limited experience. However, controlling the objects in a model using parametric rules makes it possible to construct 3-D models capable of reducing the tedious, time-consuming tasks associated with typical design changes. A number of cutting-edge architects, like Norman Forster and Zaha Hadid, have begun applying the concept of BIM to their design work. Recent BIM design tools include Autodesk Revit, Gehry Technology's Digital Project, Geometric Component, Rhinoceros, Grasshopper, and ParaCloud.

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Generally, the digitized design and construction of free-form spaces progresses through the following stages. 3-D CAD software is first used to generate free-form design entities, which can then be transformed into a physical model with the aid of CAM machining. This stage is commonly referred to as *form-finding*. The detailed design stage relies on 3-D drafting and analysis software to create comprehensive drawings, while RP and CNC machines are used to manufacture physical mock-ups, resulting in a *3-D master model*. The actual construction process is largely the same as the fabrication process, in which 3-D free-form designs are decomposed into 2-D units or elements in the form of *CAM physical models*. In this stage, unfolding and division processes are crucial. The *mock-up or pre-fabrication* process is carried out in the factory for assembly procedure testing. Finally, *on-site construction* and *assembly* processes can be conducted far more efficiently following these pre-fabrication processes [10].

2. Problem and objective

Early studies in the field of CAD/CAM focused on the effects of digital media on design thinking and design process. Designers and research has recently shifted to issues of parametric design and the concepts of BIM because of the maturity of computer technology and the sophisticated CAD/CAM ability of designers. How has this shift affected the design thinking in the design process? No previous study has performed comparative analysis on the effects of using parametric design and conventional CAD/CAM techniques on design thinking and process. Therefore, the objective of the study was to compare two free-form design cases in practice of parametric design with the concept of BIM and the conventional CAD/CAM techniques without the concept of BIM. The study attempts to propose some observational phenomena of comparing the two very common methods of the digital design and fabrication in today's digital era, and as a reference for the design practice.

3. Methodology and steps

This article is presented in three parts. In part one, a hypothesis is suggested. The design process and thinking involved in parametric design (based on BIM) differ from those used in conventional CAD/CAM techniques (without BIM). Part two presents two free-form architectural projects selected in accordance with the research objectives. Part three is case studies, a form of qualitative descriptive research. The two free-form architectural projects are analyzed and compared.

3.1. *Hypothesis*

The primary objective of this research was to identify differences in design process and thinking when taking a parametric and conventional CAD/CAM approach. The hypothesis is that the parametric design (based on BIM) is efficient because the design information modeling can be integrated into one system and be simplified in the whole process of design and construction. There is an opportunity for designers to obtain better and more creative results.

3.2. *Case selection*

This study selected two free-form architectural projects in Taiwan as case studies. The case selected for use with parametric design was "freedom" space furniture, which was on display at the Taipei World Design Expo 2011 under the theme of "Green and Sustainable." This project was presented by CHU-studio. The case selected for use with conventional CAD/CAM techniques was a "Calligraphic House" project, one of the "Next-Gene 20: Ao-Di Housing Projects" in Taiwan. This project was proposed by *Aleppo*ZONE. The authors were the team members of the above-selected projects. A great design material and research data could be obtained in this article.

3.3. *Case analysis*

The two cases were analyzed according to the three design stages outlined in previous studies [10], as follows: (1) form-finding, (2) 3-D digital model, and (3) CAM physical model/mock-up.

4. Case study

4.1. *Case 1: parametric design based on the concept of BIM*

4.1.1. *Form-finding*

The design concept in this case was adopted from historical images of Chinese and Buddhist chairs. In ancient China, woven mats were commonly combined with arm rests or low tables for sitting on floors. Raised platforms evolved as honorific seats for special guests or officials, and longer version of the mats were used for reclining. These eventually evolved into multiple functions as benches, daybeds, and beds (Figure 1(a)).

The method in the "form-finding" stage was to derive the design form by means of Rhinoceros, a NURBS-based 3-D modeling software and simple named Rhino. The design form was designed and adjusted based on several defined postures and dimensions using free-form non-uniform rational B-spline (NURBS) modeling (Figure 1(b)).

Rapid prototyping (RP) was used to render the "temporary final forms," which were fabricated into a physical model from CAD/CAM drawings based on the design concept (Figure 2).

4.1.2. *3-D master model*

Designers begin by importing the temporary final form into the BIM design tool, Grasshopper, a graphical

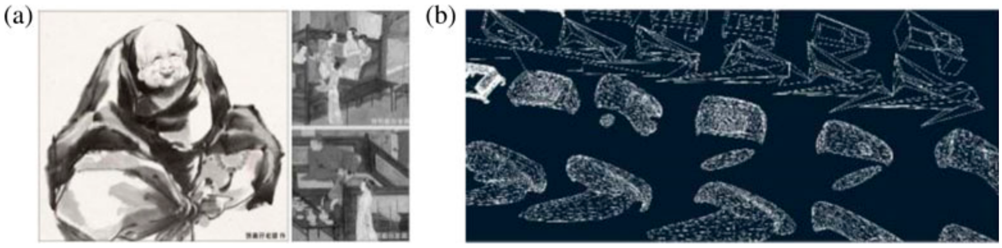

Figure 1. (a) Paintings of Chinese couch, (b) design stage of form-finding.

Figure 2. RP models of final form.

algorithm editor tightly integrated with Rhino's 3-D modeling tools. A string of visual codes is then edited to enable the cutting of a 3-D model of the temporary final form into a number of modular units according to the size of the recycled wood pieces used for fabrication (Figures 3(a) and 3(b)).

The layout of the design on the raw wood pieces is then taken into account in order to avoid wasting material. The pieces of wood are then classified according to length as follows: A (<30 cm), B (30–70 cm), and C (>70 cm), based on the collection of recycled material size. These calculations are obtained and coded in Grasshopper simultaneously, as shown in Figure 4. The use of BIM makes it possible to output fabrication data automatically, as shown in Figure 5.

Finally, Scan & Solve software (a plug-in of Rhino) was used to analyze the load-bearing strength of the design (Figure 6), and the first design form was modified accordingly. Thus, the design process goes back to the first step of form-finding in order to define the final form. Nonetheless, by this time, the automated construction process has already been set up in Grasshopper, such that the designer need not repeat all of the processes in the second step of the 3-D master model.

4.1.3. *CAM physical mock-up*

The fact that the construction process is pre-defined in Grasshopper means that the shop drawing of the final design can be output automatically without the need for draftsmen, as shown in Figure 7. This makes it possible for the fabricators to build free-form outcomes quickly and easily. Figure 8 presents the process used in rough mock-up construction.

Computer-generated design data were loaded into a Computer Numerical Control (CNC) machine for production based on the 3-D master model. The rough mock-up was milled smoothly using CNC machine and then partly by hand, as shown in Figure 9. This

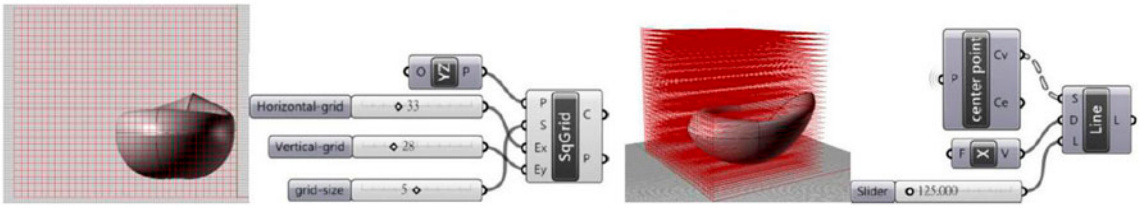

Figure 3a. Creation of grids for use in cutting free-form model.

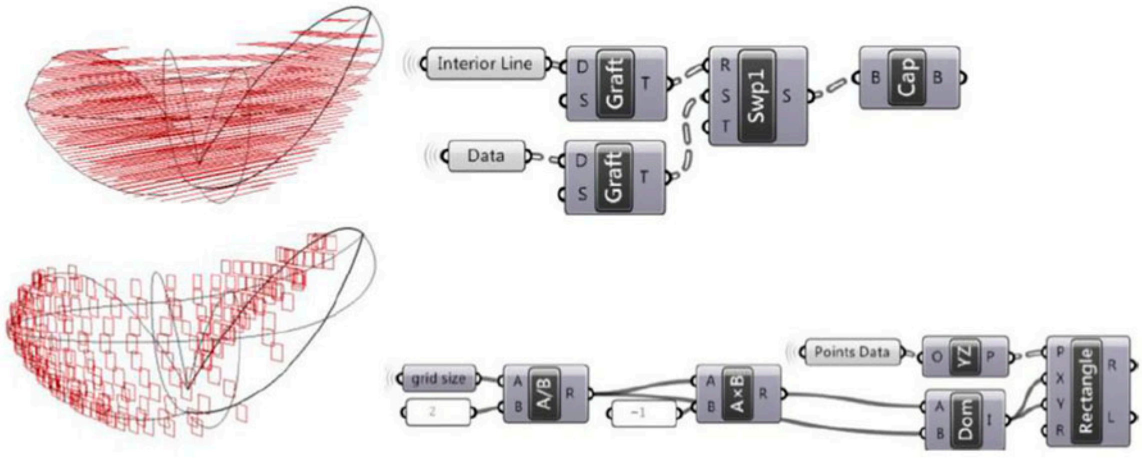

Figure 3b. Creation of wood piece models substituting for the free-form model.

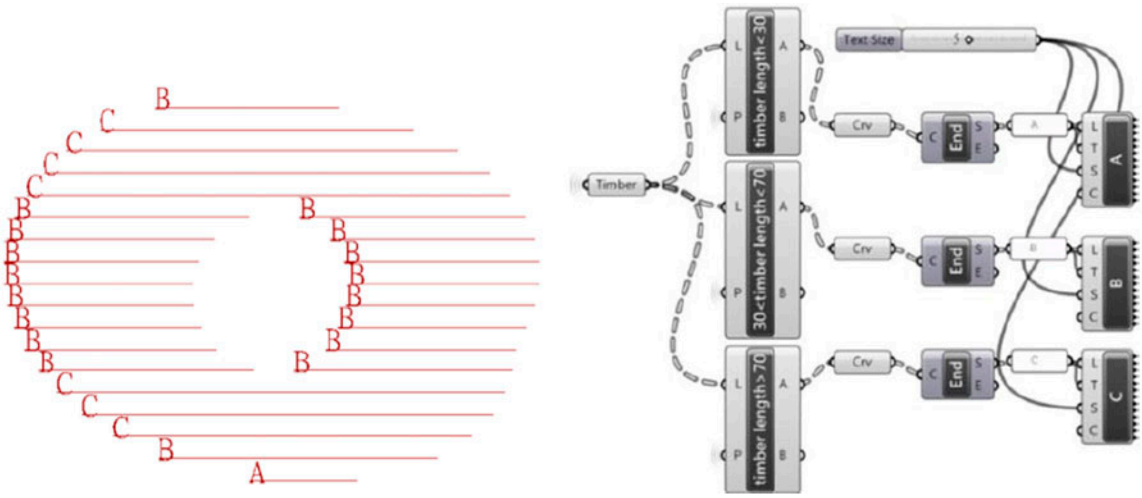

Figure 4. Classification of a wood according to length to facilitate layout.

significantly reduced the time and cost required to produce free-form and geometric features.

Grasshopper provides numerous benefits, in particular the ability to integrate all of the design processes using digital computing, in order to extend the possibilities of design and reduce the time required for fabrication. This is a practical demonstration of the integration of BIM and a parametric design process with modular production methods and budget control. This makes it possible for the designers to transform recycled wood which would otherwise have been wasted into stunning artwork. Figure 10 presents a parametric design framework integrated with BIM based on analysis of Case 1.

4.2. *Case 2: conventional CAD/CAM methodology without BIM*

4.2.1. *Form-finding*

The design concept in Case 2 was inspired by monochrome paintings created using calligraphic ink. In this case, a residence was designed and the project is termed "Calligraphic House." The aim was to create a residence with the momentum and verve of traditional cursive scripts. In the process of the concept development, the designers began with analysis of the relationship between the written strokes of cursive scripts created by Huai-Su (懷素) in the Tang dynasty (Figure 11(a)).

The process of form-finding started with transforming the 2-D strokes of Chinese calligraphy into 3-D strokes using the 3-D dynamic simulation software of MAYA (Figure 11(b)). The designers then used the "edit surface" function of the 3-D parameter software to create spatial strokes following analysis of the continuous lines that form the curves in the calligraphic strokes in order to construct a curved surface (Figure 11(c)).

A physical model of the final form was then output using RP to examine the design form. The momentum and verve of Chinese calligraphy is evident, regardless of whether it is rendered in two-dimensional, elevation, or perspective spaces (Figure 12).

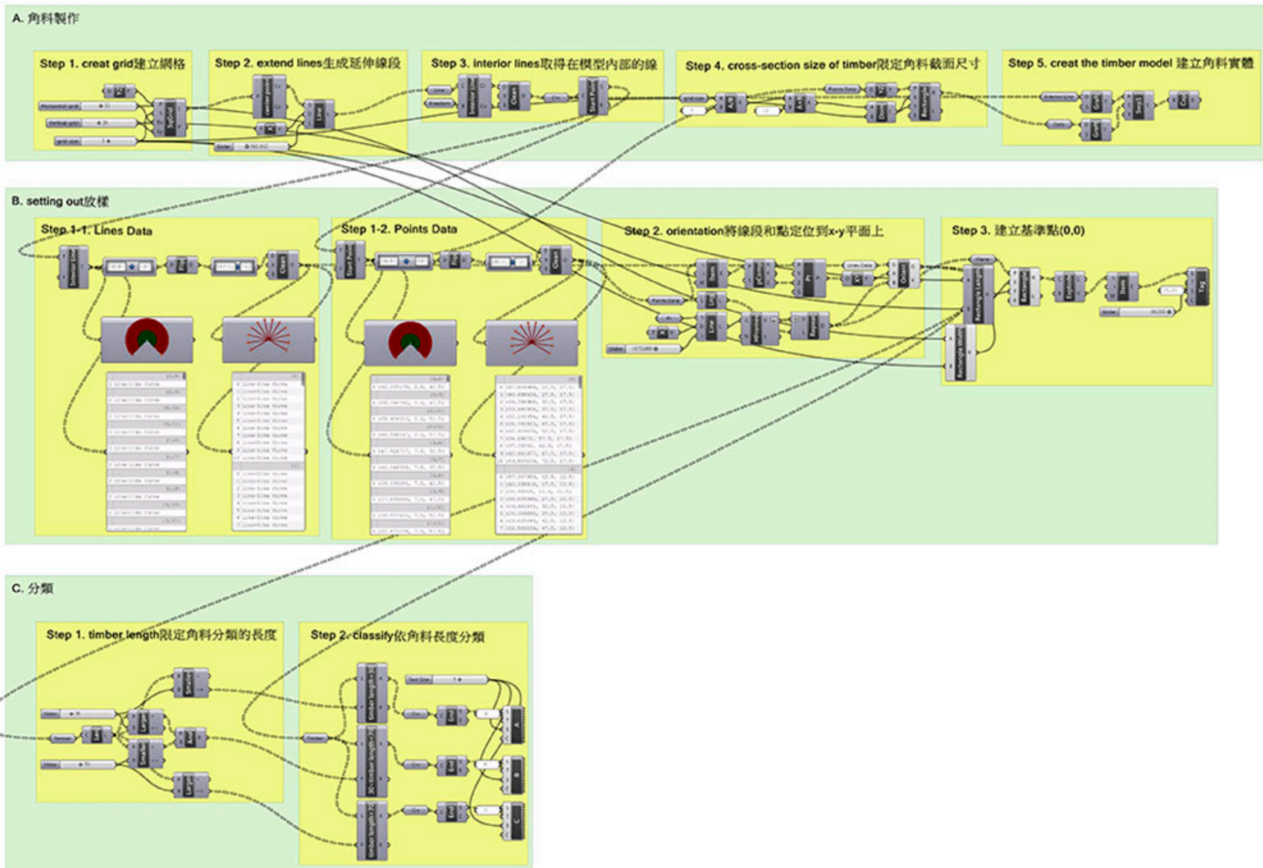

Figure 5. Grasshopper layout.

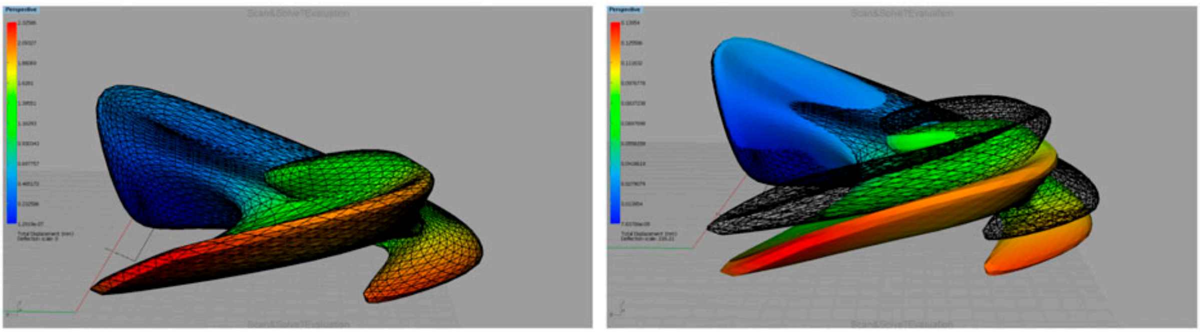

Figure 6. Structural analysis.

4.2.2. *3-D master model*

Once the master form was finalized, the curved surfaces were smoothed to facilitate division of the frame and the skin. The designers adopted a cylindrical tube framework system to accommodate the free curves of the design. Data related to the divided framework were submitted to structural technicians to proceed with analysis of the drawings and perform finite element analysis of the structure as well as structural analysis of the load characteristics of the curved floor (Figure 13). The roof surface was also analyzed using the Gaussian curvature algorithm in Autodesk Revit, which required that the form be adjusted to a reasonable degree, according to the structure and analysis of the curved surfaces. As for the division of curved wall made of glass, designers also operated with the technicians of Bentley Microstation in the development of the curved glass. The aim was to divide the glass in a standardized and rational manner in order to reduce manufacturing costs. The frame and the skin were then revised in

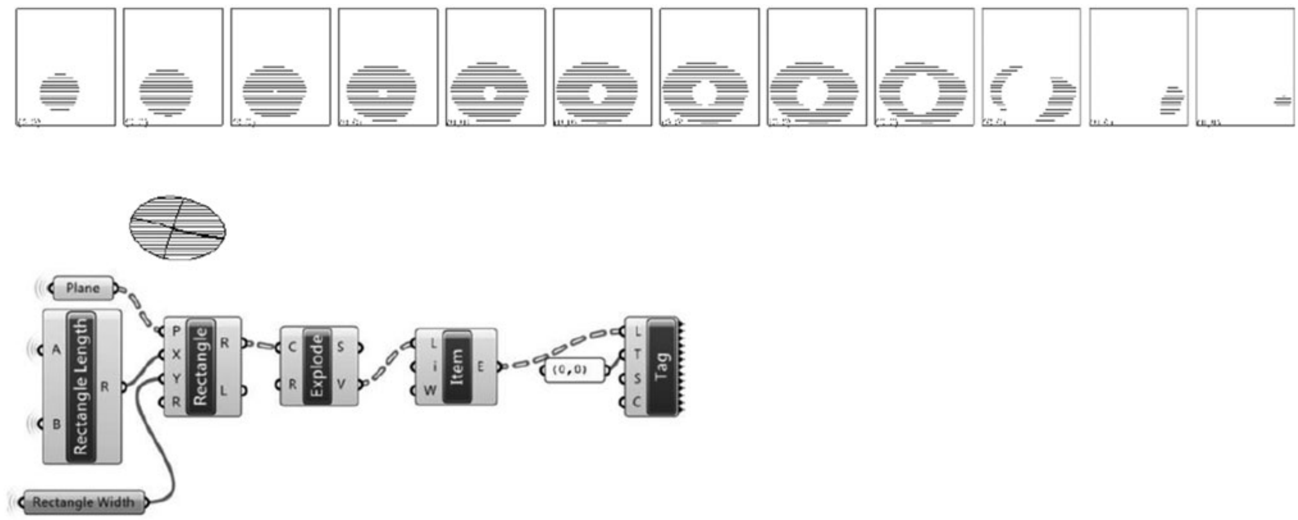

Figure 7. Detailed drawings and segments of Grasshopper code.

Figure 8. Mock-up construction process.

Figure 9. Final product.

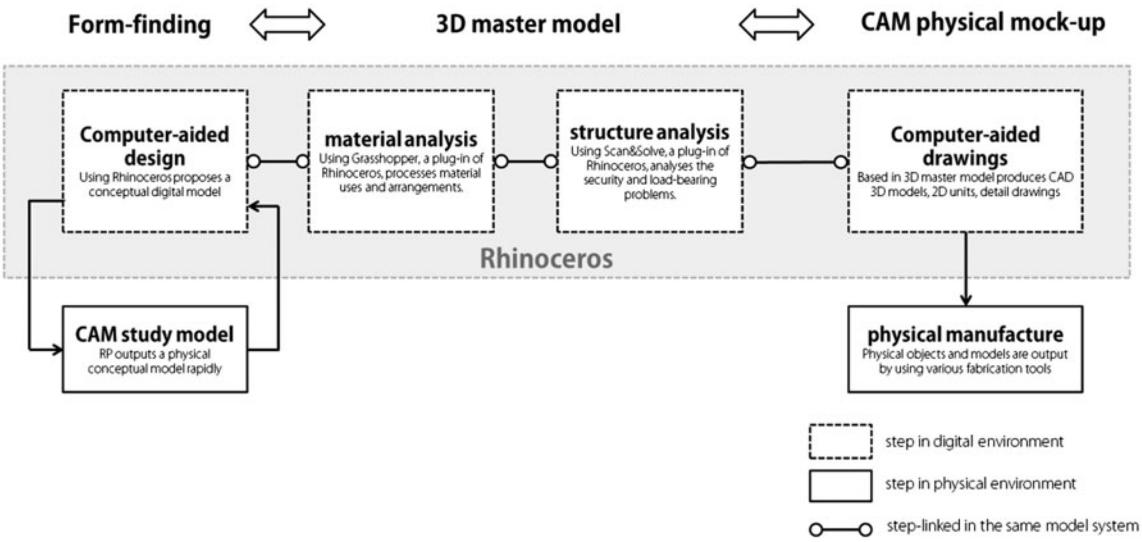

Figure 10. Framework parametric design process integrated with BIM in Case 1.

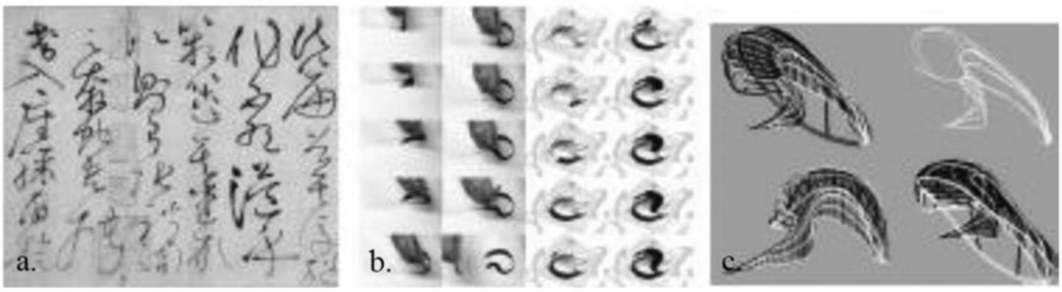

Figure 11. (a) Example of ancient calligraphy, (b) 2-D images of calligraphy strokes and 3-D dynamic simulation, (c) form-finding.

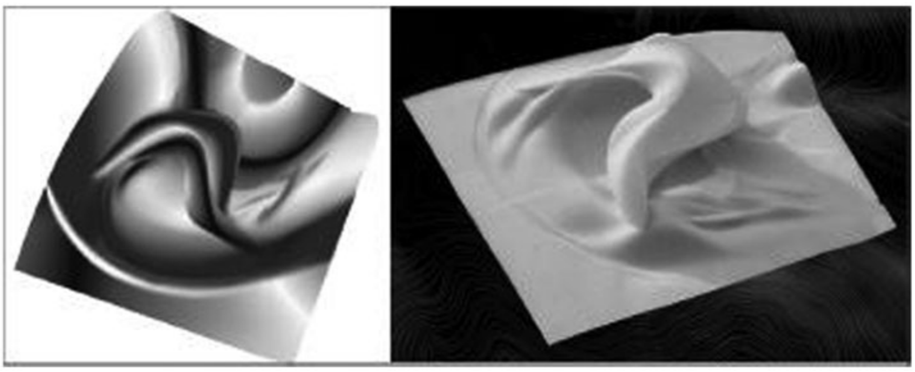

Figure 12. Final form RP model.

accordance with analysis of the drawings, which resulted in the final design, the “3-D master model” (Figure 14). This design was used as a reference for the acquisition of drawing-related data in the next stage of planning.

4.2.3. *CAM physical model*

In addition to rationalizing the frame division model, the divided frame is cut in a one-meter unit to manufacture 2-D unit drawing. A CAM laser cutter was utilized to cut the unit before assembling the physical model of the

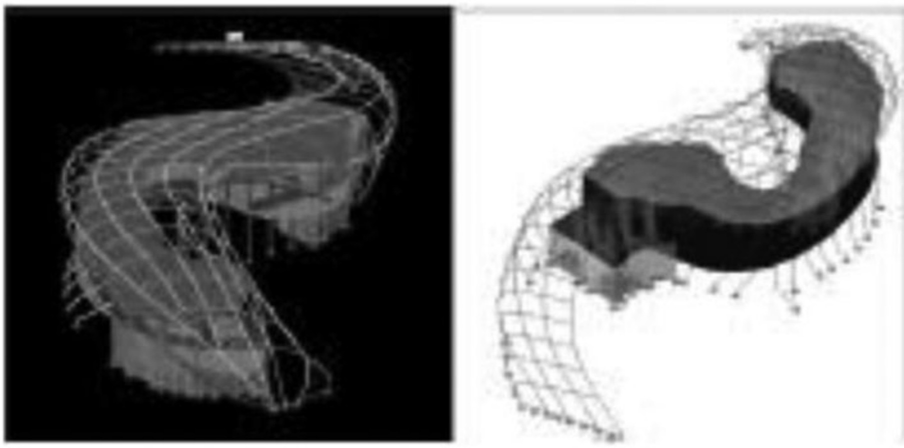

Figure 13. Structural analysis.

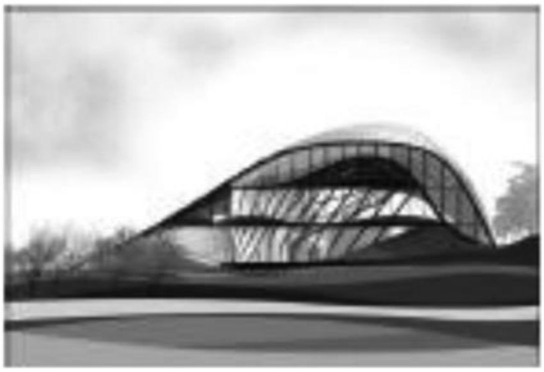

Figure 14. 3-D master model.

frame for discussing the structured form and its rationality (Figure 15(a)). The skin model of the form was also manufactured using RP equipment in order to investigate the curved surfaces in the early stage of design development (Figure 15(b)). Following numerous revisions of the design, the designers delivered the data for the "*3-D master model*" to a commercial factory. The curved terrain is made of CNC machine and RP output. Figure 15(c) presents a completed CAM physical model produced at a scale of 1:100.

The detailed design and shop drawings of the "Calligraphic House" are based on the 3-D master model. This free-form design must be presented in three dimensions, as even a large number of floor plans, elevations, and sections would be insufficient to illustrate a design of this complexity. 3-D models are essential for the expression of the spatial relationship between the various elevations. This is different from the collection of traditional 2-D shop drawings. Figure 16 presents a conventional CAD/CAM design framework integrated without BIM based on analysis of Case 2.

5. Summary and discussion

A preliminary framework of digital design and fabrication in free-form architecture is proposed as shown in Figure 17 based on the above two studies. Clearly, digital media plays an important role in the process of free-form design. Clearly, digital media plays an important role in the process of free-form design. Particularly, in the 3-D master model stage, analysis is required before outputting physical designs to ensure that they fit the physical environments to which they are intended. It could save time and money in fabricating the CAM physical model and test various kinds of design results in digital environment in advance to improve design outputs.

The objective of this study was to compare two design processes: parametric design with BIM and

Figure 15. (a) Laser-cut frame model, (b) RP skin model, (c) CAM final model.

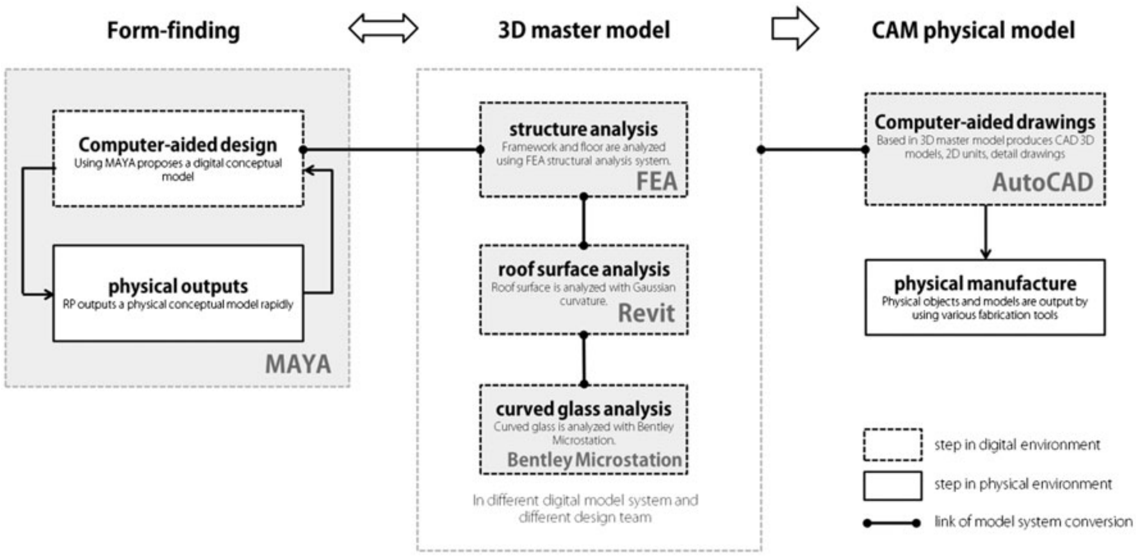

Figure 16. Framework of conventional CAD/CAM design process without BIM, as performed in Case 2.

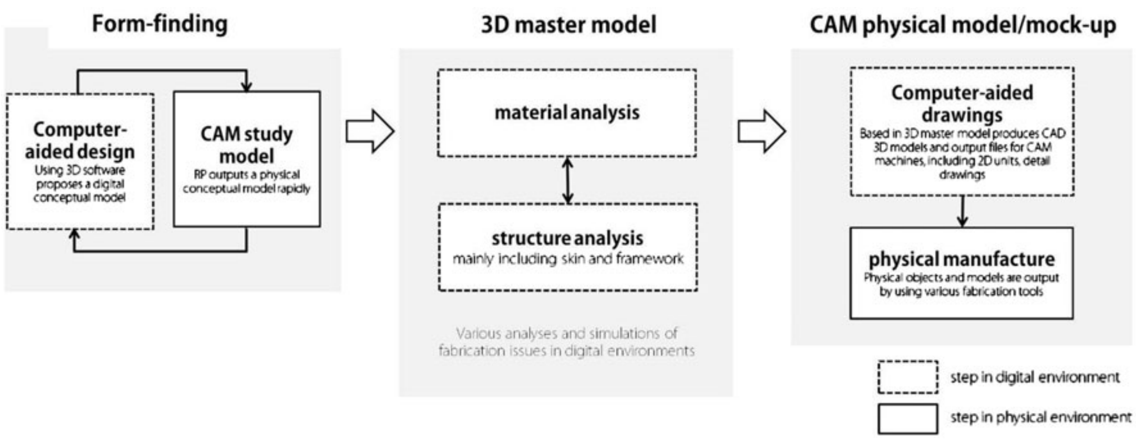

Figure 17. Preliminary framework of digital design and fabrication for free-form design.

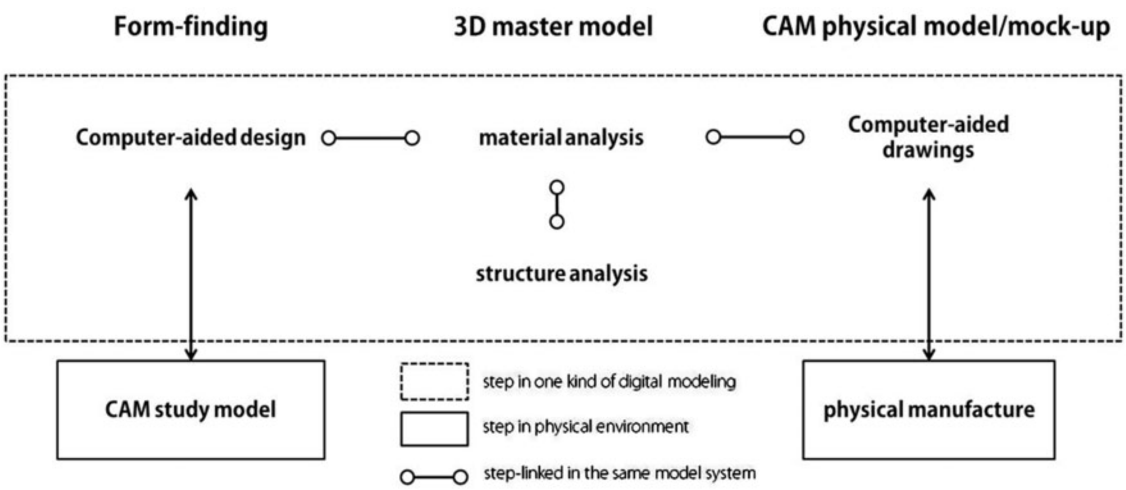

Figure 18. One digital model system framework of parametric design with BIM.

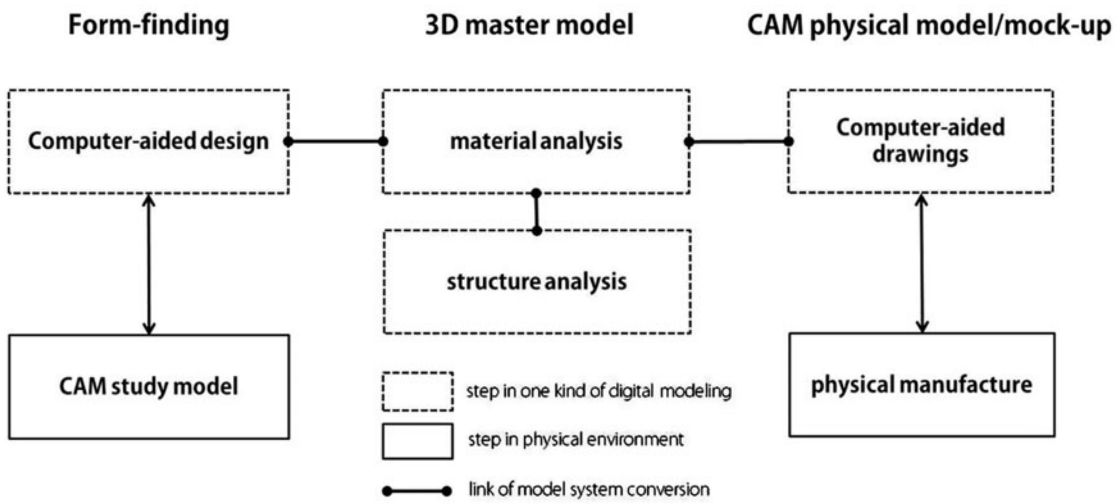

Figure 19. Multiple systems of conversion digital models associated with conventional CAD/CAM techniques without BIM.

Table 1. The comparison of characteristics of two case studies.

Parametric design with BIM	Conventional CAD/CAM without BIM
The mock-up is designed and built in one single digital modeling system.	The mock-up is designed and built using a diversity of digital modeling systems.
Design content is easy to revise, and designers are more willing to renew design results.	Modifying design concepts is inconvenient, and designers tend to reduce the frequency of design change.
Design process and design decision are efficient.	Design process is time-consuming and expensive.
Previous model versions cannot be reserved.	Various versions of a design are produced by the different various digital modeling systems.
The design thinking is based on the mathematical logic approach to problem solving.	The design thinking is based on the need to find a modeling system capable of solving the problem at hand, and tends to be a function of intuition and/or experience.

conventional CAD/CAM without BIM. In first case study, designers adopted the parametric approach using one 3-D modeling software based on a one modeling system, as shown in Figure 18. The fact that all operations could be performed using a single 3-D modeling software meant that making changes in any of the interlinked steps would lead to modifications in all of the other steps, automatically, without the need to revisit each step. However, the system was constantly renewed, such that older versions of the design were not easily reserved.

Parametric design enables designers to define relationships between design objects in order to link all of the design steps through programming and coding. This approach emphasizes the need to establish rules for the resolution of design problems, rather than solving design problems directly. Thus, designers are able to ensure that the design process resolves all arising problems before outputting final drawings and physical objects for fabrication.

In the second case study, designers adopted a variety of software programs to deal with different design objectives. This can be attributed to the fact that early 3-D software programs were just developed for specific purposes that did not completely consider various and complex design problems which were required to be resolved. These software programs are operable only on specific modeling systems, such that designers must spend much time on converting their work to be compatible with other modeling systems, as shown in Figure 19. The design model which was through the software conversion was more or less different from the original one; moreover, it affected designers' decision making by reducing the execution of modifying prototype.

The characteristics of the two design methods are outlined in Table 1.

6. Conclusion

In the conventional CAD/CAM approach to design, every aspect must be edited manually; however, parametric modeling makes contextual adjustments automatically via high-level user controls. A parametric design approach enables the integration of the entire design process using a single modeling system, thereby integrating the design and manufacturing processes. This agrees that

Burry [2] referred to understand this way of thinking and designing it is helpful to consider algorithms for architectural design in broader sense.

In the *seeing-moving-seeing* model, Schön and Wiggins [19] described design as an iterative process. Parametric design meets this ideal by integrating the design concept, design development, and detail design of the design process into a modeling system, thereby removing many of the limitations facing designers using traditional design processes in sequence when designing. The parametric design approach enables designers to overcome previous limitations with regard to the use of digital tools by facilitating the modification of design concepts and forms. This approach facilitates designers to reach the fluency of creative thinking [23], which are more in line with the creative process [24,26].

Parametric design resolves some of the problems in the conventional CAD/CAM techniques; however, it cannot replace all of conventional design methods. The parametric design process is initially very time-consuming, particularly for inexperienced designers, such that basic design projects would gain negligible benefits from the use of such a system. The design thinking of parametric design focuses on the definition of elements, a process based on mathematical logic. As such, this approach is ideally suited to the design of projects that involve repetition of a large number of the same or similar objects, especially the form in math geometry. The usefulness of this approach lies in its integration of relevant design elements within a single large database. In recent years, more and more works based on the parametric design process were completed. They have formed a new design style with the maturity of parametric design. However, there is no limitation for design results. The design forms should not be blocked from a particular design mode.

7. Limitations

This study is subject to two important limitations. First, the design scale of the two selected cases was not entirely equal. However, they both focused on the concept of free-form design. They followed a similar design process using similar digital design media. Secondly, it was difficult to obtain the necessary amount of research data as the selected cases were already completed, allowing only for the collection of retrospective data. In the future, useful results might be obtained from tracking design cases as they progress. This research could serve as reference for subsequent studies in which the choice of design theme, objectives, tools, and background of designers could be controlled in an experiment setting.

Disclosure statement

No potential conflict of interest was reported by the authors.

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