DESIGN PRACTICE COMPLEXITY IN THE POST-DIGITAL AGE

Theoretical discussion and comparative case study of non-standard building façades

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Abstract. This paper starts by introducing an expression proposed by William J. Mitchell measuring the “complexity” of a designed and constructed architectural project. After reviewing other interpretations of this term, as well as specific peculiarities from the building industry, the article expands this metric from an organisational and technological perspective. This is followed by the case studies of six non-standard façades whose process complexities are driven by their project-specific affordances. By comparing built projects of different architects and implementation environments, the paper suggests specific criteria for non-standard architectural designs. Application of acquired knowledge has the potential to help architects better control their project’s design and construction solution space.

Keywords. Project complexity; measurement; non-standard; China.

1. Introduction
Architecture practices are ill-structured problems, since the goals and the way of achieving corresponding solutions will be ambiguous at the outset of the task (Hudson, 2010). In order to solve practical design problems, architects, along with other project participants, must iteratively seek proper materialising solutions while constantly changing design descriptions. Rowe (1987) stated that it is impossible to either describe or solve ill-structured design problems with specific patterns because: 1) additional design requirements or constraints may emerge any time, 2) design problems and their solutions interact, and 3) there is no ultimate problem-solving method. Modernism’s strategies like “form follows function” intend to reduce such uncertainties and standardise the problem-solving approach. In doing so, architectural design is bounded to a safe zone where the financial risks and technological uncertainties are predictable. However, such method may be unfitting for the digital design experimentation frequently found in today’s more exploratory practices.

The boundaries of the design space are shaped by various requirements, involved project parties, and their project-specific interests. Lawson (2006) categorised design problems as internal and external constraints. The internal
Constraints are normally based on the client’s task brief, the architect’s design intentions and the users’ needs, while the external constraints describe conditions a design practice needs to accommodate and regulations it must follow. Both types of constraints affect the description of a designed form and its followed problem-solving processes thereby making up the complex nature of architectural practice. Hudson (2010) suggested a heuristic approach for resolving architectural design problems. Steps include describing the space of design problems, fragmenting larger problems to smaller pieces, and then exploring the appropriate options for each sub-problem while reducing the size of an overall design solution space. The mechanism for an architect adopting this approach focuses on his/her strategy of controlling the project complexity.

Such complexity becomes especially visible in today’s practice when it is dealing with the realisation of non-standard architecture in challenging building contexts typified by limited engineering, fabrication, or construction capacities. This paper discusses six non-standard façades facing such conditions. Their built forms demonstrate the value of adopted problem-solving strategies and complexity controls. Through studying these non-standard façades, higher-order knowledge is extracted that other architects can use when defining their digital design strategies when being faced with similar contexts.

2. A metric of complexity

Mitchell (2003) defined state descriptions as the explicit expressions of design information prior to any construction operation and referred to the steps of transforming a design’s state descriptions to its physical form as process descriptions. Carpo (2011) defined the Albertian paradigm as a linear state-to-process transformation where the designers are responsible for preparing annotation documents and the implementors then materialise whatever has been submitted to them. This paradigm has shifted in recent decades with CAD-CAM integration trying to eliminate the separation between design annotation and construction. Today, architects are increasingly designing and making at the same time (Carpo, 2011). Thus, the state-to-process transformation becomes more about using the same digital medium so that information can be explicitly interpreted at both ends. Mitchell (2003) used design content to describe the created database in a computer-aided design environment. Designers input strings of commands or use sequences of operations to define the design space. Transforming the digital bits of a design into data that drives the fabrication machines and instructs assemblies is defined as construction operations. The length of these operation sequences and its related built scale are referred to as construction content.

2.1. MITCHELL’S MEASUREMENT

Mitchell (2005) suggested a ratio to measure the complexity of a built project:

- “complexity” = added design content / added construction content

This expression introduces the relative positions of both design and construction, based on the project-specific conditions. The required quantity for additional
construction content is determined by a project’s particular design requirements while limited by the resources the project parties can access within the construction context to which they belong. Mitchell (2005) mentioned that this starting point for adding construction content relates to the supply chain for construction elements, meaning the minimum fabrication and assembly operations needed to realise the design. The proportion of these two operations may change from project to project.

The starting points for adding design and construction content are up to the capacity and the knowledge of each party involved in the project. Architects create the design problem space based on their past experiences and define it in modelling environments. Newly designed geometries can borrow elements from previous projects, such as a specific script for façade design, or can use component libraries embedded in digital design modellers. The competence of engineers and implementers also adds to the inherited content, including their provided solutions and corresponding industrial capacities.

2.2. OTHER EXPLANATIONS OF COMPLEXITY IN ARCHITECTURE
Lawson’s model indicates that for intricate design problems it is difficult to separate the requirements for additional design and construction content, especially given that the modes of collaboration between the designers and implementors may shift in today’s digital era (Lawson, 2006). Baccarini (1996) introduced two characteristics from complexity science when referring to the various interrelated parts in architecture: differentiation and interdependency. Both characteristics are discussed from the organisational and technological aspect in the architectural practice.

Organisational differentiation concerns the project roles, their correlated tasks, and the composition of the design itself. Baccarini (1996) defined the horizontal and vertical differentiation of organisational systems. The horizontal differentiation refers to the number of different units involved in the system such as the project parties and the component types of a building system, while the vertical differentiation means the depth of these differences, such as each party’s liability or the variate elements of the same type. The interactions between these differentiation are referred to the organisational interdependency, which integrates all the members in a system and affects the system as a whole.

Technological differentiation was described as the diversities in a task. This includes the inputs and outputs variations, the number of involved specialists, and the specific design and construction content needed to produce a building entity. Regarding the technological interdependency, Baccarini (1996) stated that the technological differentiation interacts within a network of practical tasks so that the operations carried out by different project specialists will influence the entire design solution space.

2.3. EXPANDING THE MEASUREMENTS
Mitchell’s ratio of added design content to added construction content introduced a fundamental idea to understanding the complexity of a built project. Its concepts can be used to evaluate projects accomplished in a lab environment,
where processes are usually well-structured and the design solution space clearly defined by the designers/researchers. There, one can assume, design inputs are directly transformed into construction operations. However, when introducing the organisational and technological complexity in real-world practices, this measurement lacks differentiation and must be further expanded. Mitchell’s approach appears too abstractive to allow for cross-comparative case studies. Hence, this study imports Baccarini’s interpretation of complexity, which Wood (2010) stated is valid to all dimensions in building practice, as the rationale to expand Mitchell’s measurement.

In terms of the organisational complexity, architects are commonly not the sole party to add design content. Instead, in building-scale practice, initial design information generated by the architects might be recreated by the consultants for contractual purposes; or be further developed by engineers for the sake of production requirements; or even be revised by contractors and fabricators due to a lack of constructability. Since an architect’s design contribution is determined by both the horizontal and vertical differentiation in the added design content, the organisational complexity concerning an architect’s project role can be described as:

\[ \sum \frac{\text{added design content}}{\text{architect’s state description}} \]

Since Mitchell (2005) mentioned construction operations that include fabrication and assembly operations, we can also divide the project complexity using these two aspects. According to Mitchell’s concept, the fabrication complexity can be addressed as the amount of information inputted to drive the machining or the manual making processes. The assembly complexity, likewise, refers to the ratio of the construction instructions to the on-site assembly actions. These two construction operations are normally carried out by different project parties. Thus, they can be discussed separately. The expression for technological complexity can be proposed as:

\[ \sum \left( \frac{\text{added fabrication design content}}{\text{fabrication operations}} \right) + \sum \left( \frac{\text{added assembly design content}}{\text{assembly operations}} \right) \]

This expansion of the measurements can be used to cross-compare architects’ design strategies and their responsibilities during the state-to-process transformations. Such comparisons may form the higher order knowledge that can be used in general to deal with uncertainties of the ill-structured architectural design problems.

3. Comparative case studies

Six built non-standard façade projects were studied as part of this research project. All were designed by Chinese designers facing both the opportunities offered by globally available computational tools and the restrictions from unevenly developed building technology in China. The projects include: 1) “Silk Wall” (SW) by Archi-Union, 2) “Yan Ancestral Hall” (YAH) by M.O.D.E.S, 3) “Arachne” by Archi-Solution Workshop, 4) “Art Gallery C1” (AG1) and 5) “Art Gallery C3” (AG3) of the “Foshan Art Village” by Atelier cnS, and 6) “Bird
Watching Tower” (BWT) by Tee-mu Studio (Figure 1). Their design solution spaces are discussed in response to internal and external constraints. To facilitated construction, all six façades were materialised by breaking down overall fluid geometry continuity in discretised elements.

Figure 1. From left to right: 1) “Silk Wall”, 2) “Yan Ancestral Hall”, 3) “Arachne”, 4) “Art Gallery C1”, 5) “Art Gallery C3”, and 6) “Bird Watching Tower”.

3.1. ORGANISATIONAL COMPLEXITY

The organisational complexity concerns the architect’s authorial role during the design-to-build process. Practicing outside a lab environment may increase the uncertainties in controlling both the input and output information. According to the measurement above, this notion is evaluated by the proportion of data generated by the architects to that used for materialising operations.

The first three cases follow a lab-experiment workflow where the architects’ state descriptions were directly transformed into construction operations. Archi-Union was both the client and the architect of the SW project, as part of the office’s renovation work. The advantages of such construction practice include the early confirmation of the material suppliers and implementors, a rational project schedule and the protection of the architect’s authority. The SW project was assembled with standard concrete blocks in 12 different horizontal rotations. Architect’s state description was directly used for the making of 6 brick layering guides and the generation of an assembly schedule. Thus, the ratio of the organisational complexity for the architect is close to 1.

Architects of the YAH project also operated at a high authorial position when compared with the SW project. The project is materialised in a rural Chinese village where the construction of homesteads requires less administrative regulations than urban building constructions. Hence, its façade construction proceeded without any conventional construction documents, meaning both the brick fabrication and assembly were carried out on-site by the contractors following the diagrams directly extracted from the architect’s digital model.

In the “Arachne” project, Archi-Solution Workshop joined the project only in the capacity of the material supplier. However, the firm bypassed administrative regulations and ended up designing the overall form and fabricating the components in-house. The façade system contains around 2800 different parts which were produced with homemade Fused Deposition Modelling (FDM) machines. These FDM platforms operate with G-code data streams to define its tooling paths, which the designers could directly translate from the components’ geometry definitions. All components adopted standard joint conditions so that the added design content for assembly operations was minimised.
The remaining three projects followed a conventional design-bid-build workflow in which the architects submitted traditional tender documents, even though most of this information was redundant from a construction perspective. In the case of AG1 and AG3, the architects of Atelier cnS produced façade construction drawings describing the tessellations of all four elevations. Such information, the state descriptions provided by the architects, did not contribute to any actual construction operations, except as the visual references. In the case of AG1, the façade component manufacturer recreated the mould geometries with a machine-specific software. Hence, the added design content from the manufacturer relates to the total number of mould types and the project’s level of non-standardisation affected the organisational complexity. The panel units on the AG3 are made of triangular sub-surfaces which were fabricated with a 2D plasma cutter. Compared with the AG1 project, such operation in the case of AG3 helped to maintain a relatively low-level organisational complexity, since the fabrication shop drawings were developed from the architects’ state descriptions of the unfolded component outlines.

The materialisation of the BWT project encountered the scenario where the Glass fibre Reinforced Plastic (GRP) manufacturers had to add a large amount of unexpected design content in order to materialise the architect’s formal requirements. This included the implementor’s effort of developing a production flow for the customised façade pieces. Also, due to the lack of 5-axis milling tools, the perforation design could not be precisely transformed from the architect’s digital model. Neither the manufacturers nor the on-site contractors were familiar with the designed geometries and some construction-related design decisions were made by them without the involvement of the designer. Hence, the organisational complicity is the highest for the architects in the BWT project compared to others.

If we cross-compare the organisational complexity for the architects among all six projects, one can notice that the influencing criteria include the project construction context, the administrative regulations, the architect’s project tasks, and the capacity of industrial fabrication. Figure 2 left shows a qualitative and relative result based on the measurement of an architect’s authorial role mentioned above. The smaller the ratio value gets, the more streamlined a state-to-process
transformation it represents. On the contrary, the greater the value becomes, the more redundant design content is added to the project. The organisational complexities were kept at low levels for the first three cases as the architect’s state descriptions were directly transformed to construction operations. Meanwhile, the next three cases have varied and relatively high organisational complexities concerning the challenges brought by additional design content and different fabrication environment.

3.2. THE TECHNOLOGICAL COMPLEXITY IN MATERIALISING SOLUTIONS

The contributors to a project’s design solution space are determined by the organisational complexity it has. These intricate relationships shape the boundaries of a design solution space, which not only responds to the raised design problems but also concerns the interest of each involved project role. The technological complexity, on the other hand, describes the interdependent connections between the construction operations carried out by related project roles. In the previous section, the paper defined such intricacy as the summation of fabrication and assembly complexities. Based on Mitchell’s idea, both notions refer to the ratio of inputted design data to the amount of physical operations it drives.

Figure 3 shows the photos of critical construction operations in each studied case. In the SW project (No.1 in Figure 3), the technological complexity is measured by the fabrication of customised tools and the assembly of the brick wall. Since the architect has chosen standard concrete blocks as construction materials, there was no specific effort needed for unit fabrication. Meanwhile, because human contractors could not directly use the information extracted from the parametric models, customised tools (the brick layering guides) were needed for the manual assembly. These guides were designed and directly CNC fabricated from metal within the office’s workshop. Thus, it added a little design and construction content to the fabrication operations. By using 6 different brick layering guides the contractors could easily create 12 variations on-site with the same procedure. This made the assembly difficulties in the SW project no higher than building a conventional brick wall. So, the total technological complexity stayed at a low-level.

A similar geometric requirement of the YAH project was realised by stacking bricks of different lengths (No.2 in Figure 3). The brick cutting operation was carried out on-site following a computer-generated schedule of unit types and brick amount counts. Therefore, the fabrication complexity was kept minimal since the information output was entirely based on a couple of lines of computer code. In order to reduce the assembly complexity, the architect adopted the Flemish bonding method as the bricks only variate in their long edges. In the façade, all headers are at the same relative positions, making it a reference grid for construction. The only design content added for the sake of assembly operations was the legend of the layering sequence of different stretchers. The diagram was generated using procedural modelling software grasshopper according to the desired pattern. Because all the fabrication was done manually, the fabrication complexity was a little higher than the SW project. Architects of the first two cases controlled
the complexity by referring design innovations to standard constructions - the SW project varied only in the unit rotations while the YAH project only changed the header lengths in certain areas.

The construction process of “Arachne” (No.3 in Figure 3) combines digital design-to-fabrication methods and labour-centric manual installation. The designer took on a multifaceted role during the project materialisation, including the material (polylactic acid plastic) purchase, the in-house FDM printing, and the post-production management. Therefore, Archi-Solution Workshop was the sole party controlling the fabrication complexity. Regardless of the incorporation of custom-built FDM printers, the digital design-to-fabrication of 2800 pieces was a streamlined process based on a grasshopper script connecting the Rhino modeller with a customised CAD/CAM controller. Nevertheless, the total fabrication complexity was relatively high because the large amount of post-production management of the 2800 unique elements. This included sorting, coating and shipping according to the different element types. Mass variation increased the difficulty of fabrication management which illustrates the idea that the fabrication complexity concerns the entire production life-cycle where the product’s non-standard characteristics may impact anytime. On the other hand, all unit assemblies use the same type of joints connecting with each part and with the structural fame behind. Therefore, the assembly complexity was maintained at a low level.

Projects AG1 and AG3 (No.4 and 5 in Figure 3) were constructed by one contractor team and adopted the same structural system. In both cases, the façade units were prefabricated off-site so that the entire installation process was possible within one month. There are six different panel types in the AG1 façades and eight types in the AG3 façades. Since both component assemblies were following the same type of instructions created by the architects, their assembly complexity is equal. However, the fabrication complexity of the AG1 project is higher than that in the AG3. As mentioned in the previous section, the GRP mould production led to extra design and construction content, thereby increasing the fabrication complexity and the total cost. Comparatively speaking, the materialisation of the AG3 façade was more straightforward. Eight panel types were made of five different planar elements which could be directly produced by plasma cutter, to then be folded and welded manually. The information for such fabrication operations was directly developed from the architect’s drawings.
The materialisation of the BWT project (No.6 in Figure 3) illustrates a higher level of technological complexity than the other studied cases. The non-Euclidean geometry has led to the uneven subdivisions of the façade units and the non-standard perforations. The architect’s state descriptions only explained the desired form and the documents fulfilling the requirements asked by the clients and legislators, but these were barely transformed to direct construction operations. Each façade unit is made of two doubly curved GRP surfaces and is enforced with a series of single curved steel ribs inside. These design contents were added by the facade consultant from the scratch. The design of waffle scaffoldings for moulding the GRP components and the recreation of façade perforations also increased the total fabrication complexity. Due to the fabrication deviations, the related assembly drawings could not be fully transformed into assembly operations. Hence, some on-site adjustments and improvisations had to be carried out by the contractors to ensure the built outcome.

Figure 2 right describes a qualitative comparison on technological complexities between the six façade cases based on the above discussion. The value in the chart does not have practical implications and can be scaled up or down proportionally, but its relative relationships indicates some general understandings of materialising non-standard architecture within this context. Comparing with the diagram on the left, we can learn that the technological complexity relates to an architect’s authorial role, concerns the additional design information. Standardising construction or basing the work on inherited knowledge from the previous projects may help to reduce the risk of invalid solutions since each party is familiar with the design problems.

4. Extracted higher-order knowledge
Li (2008) introduced the design ideology of “make-the-most-of-it,” describing an attitude that some Chinese architects adopt to cope with the constraints in the developing construction context while maximising the design problem-solving. Regarding all six façade cases, such expedient notion means the balance between the architect’s formal requirements, the façade’s materiality and the corresponding implementations. From the previous discussion, we learn that the project complexity raises when redundant information exists in the state-to-process transformation. This is determined by the project-specific administrative conditions, the architect’s project role, and the design-related construction affordance. A developing construction environment may increase the uncertainty of these factors, which cannot be easily bypassed with a certain problem-solving approach due to the interdependent relationship between the organisational and technological complexity. Hence, it requires the architects, when pursuing the idea of “making-the-most-of-it”, to adjust the design solution space so that its state-to-process transformation is controllable.

When architects have a higher level of authority within the project team, i.e., in the first three projects, the generation of design problems can be directly connected to the implementation resources at hand. In such mode, the project’s technological complexity is at a dominant position, influencing the feasibility of a defined design solution space. The architects are suggested to be aware of the inherited starting
points for adding design and construction content. By controlling the amount of added design content, the projects can be realised with expected outcomes. The uncertainty of the organisational complexity matters when the architects must obey the administrative regulations. In the AG1 and AG3 projects, the uneven project complexity occurred due to the different production setups between the cutting of planar steel parts and the moulding of GRP components. In this manner, the key to a guaranteed feasible solution space is to ensure the design is in accordance with the capacity of implementors. Since the workflow requires additional inputs from other project parties, the architects are suggested to increase the reusability of their state descriptions.

A top-down problem-solving approach can be risky in the developing construction context. The high level of project complexity in the BWT project was due to the fabricators lacking experience in precisely producing the doubly curved surfaces and locating non-identical openings. Such implementation uncertainties jeopardise the entire state-to-process transformation and therefore must be contained. Instead, a bottom-up approach for defining the design solution space ensures more predictable built outcomes.

5. Conclusion
This paper studies six non-standard façade projects built in the China’s developing construction contexts and compares them from two perspectives: the organisational complexity evaluating an architect’s design contribution and the technological complexity describing the materialisation difficulties. Applying such measurements to the case evaluation indicates the defined design solution spaces in response to the ill-structured architectural design problems. Mitchell’s metric to discuss the process complexity of a built solution is expanded. The knowledge gained from the case comparisons can be brought back to the generation of problem-solving strategies. These strategies can be based on the architect’s awareness of the upcoming constraints and the project-specific affordance, or they can benefit from his/her enhanced control flexibility by using computational tools.

References
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