Applying the post-digital strategy of anexact architecture to non-standard design practices within the challenging construction contexts

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ABSTRACT

New architectural forms offered by digital design approaches often appear incompatible with the prescribed precision and control in construction, especially in developing regions where advanced implementation means are limited. In response, this paper suggests working with design practice indeterminacy. Named ‘anexact architecture’, the post-digital design practice strategy presents a convergent diagram of seeking the feasible design solution space. It relies on the procedural parametric modelling to constantly integrate computation and humanisation, so that a rigorous built outcome is capable of accommodating project-specific idiosyncrasies and constraints. The demonstrator projects are discussed based on the combination of the Participatory Action Research method and the idea of anexact architecture. This paper aims to illustrate the peculiarity of anexact architecture and its ideology of treating design delivery uncertainties as essentials rather than negatives when practicing in a volatile construction context.

1. Introduction

1.1. Architects’ increasing agency

Past decades witnessed a dramatic expansion of digital applications in architecture, which has increased architects’ agency of project design and realisation. With digital tools at their disposal, today’s architects are no longer excited about the creation of unprecedented building forms. They are keen to adopt computation in bridging the virtual and the physical world, and linking architectural design with the matter, materials, and materialisation. This paradigm shift arguably conflicted with Alberti’s statement that ‘the design is the original, but the building is the copy’.

Architects, nowadays, can bypass the cut-off line separating conception and construction, and are increasingly designing and making at the same time (Carpo, 2011).

Architects’ increasing agency allows them to ‘search’ instead of ‘sort’ design solutions (Carpo, 2017). By going through cycles of trials and errors with digital simulations and prototyping technologies, digital architects may regain their authorial position within the design delivery process. Kolarevic refers to these architects as ‘information master builders’ (Kolarevic, 2003) since they are capable of altering design outputs for the sake of construction affordance. Like Brunelleschi invented a crane for the realisation of the cathedral’s dome, digital master builders are working closely with fabrication and construction parties to foster the progressive emergence of feasible design solutions.

1.2. The search for an expedient design practice strategy

Architectural design is a problem-solving process (Lawson, 1994) where the creation of a building form must adapt to the project-specific requirements and constraints in order to have practical meanings (Crolla, 2018). However, the socio-industrial and economic context may lead to indeterminacies, resulting in ill-defined design problems where additional requirements may arise at any time without standard design solutions (Hudson, 2010). This makes architectural design practice a pursuit of trade-offs since it must involve compromises made over certain aspects. Especially in developing regions where advanced fabrication means are not accessible, it could be challenging for architects to materialise design intentions posed using nearly-free digital tools. The authors argue that it is necessary for these architects to pragmatically overcome the dichotomy between universality and locality. They must root in the project-specific socio-industrial context so that the design delivery may benefit from the local construction system and supply chain.

In his doctoral thesis titled ‘Building Simplexity’, Crolla refers to Chinese architects who managed to work with local opportunities and construction affordance as ‘regional hackers’ (Crolla, 2018). These
architects, in order to materialise their non-standard design intentions, are willing to overstep the common professional boundaries, and to extend their authorship into the design development and crystallisation process with available digital means on hand. This pragmatic mindset of seeking expedient design practice strategies was theorised by Li as ‘make-the-most-of-it architecture’ (Li, 2008), which suggests young Chinese architects not make a fetish of design complexity but strategically bypass local restrictions. Chang uses the ‘third attitude’ to summarise an ideology that Chinese architects possess toward the idiosyncratically political, economic, social, and cultural matters (Chang, 2004). It emphasises flexibility in design practice and encourages architects to heuristically seek feasible design solutions using their inherited knowledge. Similarly in the digital domain, Xu and Yuan both mentioned that domestic digital practitioners should not simply combine the Western trend with local realities. Instead, they must absorb the volatilities emerging from a labour-intensive working condition so that the Western trend with local realities. Instead, they must absorb the volatilities emerging from a labour-intensive working condition so that an integration of low-tech and high-tech implementation can prevail (Xu, 2015; Yuan et al., 2013; Yuan, 2016).

Chinese architectural firms like Archi-Union, HHDFUN and Atelier cnS etc. have been adopting the expedient thinking meanwhile trying to make the most of what have been given to them in their design practice explorations. Taking the Rizhao Tourist Centre (Rizhao, China, 2012) as an example (Figure 1), the architects from HHDFUN carried out a fully computational design process to generate the master plan, the building geometries, and the non-standard building envelopes. The local fabricators, however, were not capable of producing the three dimensionally curved components needed for the building structure and the façade. Only manual fabrication techniques were available locally, leading the architects to explore alternatives by simplifying the building geometries using ruled surfaces and planar panels. Rather than holding on to their design ambition that might exceed the local construction affordability, these Chinese architects chose a pragmatic approach for design materialisation while largely achieving their original plan. With digital design tools at their disposal along the construction process, they have translated the non-standard form of Rizhao Tourist Centre into conventional annotation drawings so that the low-tech construction could stay within schedule and budget (Wang et al., 2012).

Beyond the scope of China’s construction context, architectural practices, such as Tehran-based CAAT Studio, Sao Paulo-based SUBdv, and Delhi-based Studio Symbiosis, also adopted a similar mindset in resolving the dilemma caused by the available design capacity and the implementation challenges. Having learnt from the above-mentioned pragmatic thinking and built cases, the authors developed a post-digital design practice strategy, namely ‘anexact architecture’, featuring parametric procedural modelling and heuristic settlement of materialisation uncertainties. The strategy encourages architects to exploit serendipities along the design delivery process, treat local organisational and technological barriers as an active component in searching for feasible design solutions. By combining anexact architecture with Participatory Action Research (PAR) method, the authors aim to discuss the strategy’s pragmatic meaning through three demonstrator projects.

2. Theory: anexact architecture

2.1. Project complexity in the post-digital era

The term “anexact” was originally introduced by Derrida. It essentially covers vague morphological types, which give rise to a pre-geometrical descriptive science (Derrida, 1989). Deleuze and Guattari described that “anexact” provides a different sense from the fixed, metric, and formal essences since it is neither exact which deals with ideal essences nor inexact like sensible things (Deleuze and Guattari, 1987). Anexact architecture situates in the post-digital context where the term refers to a state no longer sees information technology as new media, rather, it liberates ‘digital’ from its technological-scientific or media-theoretical senses (Cascone, 2000). Post-digital is more of a cultural rather than a paradigmatic shift like Modernism to post-Modernism (Cramer, 2015). Post-digital possesses an aesthetic perspective which rejects the conventional understanding of high-tech cleanliness but builds upon the upheaval of computation while seeking intersections with analogue systems.

This post-digital architectural design practice aims to increase the transparency of technology adopted by project parties insofar as they no longer deliberately display ‘digital’ as a working method (Bosia, 2016). By enhancing the synthesis of virtual and actual, post-digital architects can reach multiplicities more than solely design simulations and productions, and can further integrate with new and old crafts, materials, and technologies for collective intelligence (Colletti, 2016). Here, anexact architecture stands for the post-digital notion that addresses humanisation in computational design practices. Instead of celebrating digital capacity, it emphasises real-world matters and absorbs human impacts during design delivery.

As a post-digital design practice strategy, anexact architecture aims at moderating complexity per project-specific context. Mitchell has used the ratio of ‘added design content’ to ‘added construction content’ to describe project complexity in the digital age (Mitchell, 2004), which was further interpreted as the design effort needed to generate sufficient information for fabrication and construction operations. In an ideal CAD-CAM scenario, project complexity merely fluctuate since design content can be digitally and directly transformed into construction content. However, this is not common in developing regions where advanced fabrication means are beyond affordability. In response, anexact architecture relies on the authorial upheaval of post-digital architects who shall possess an expedient attitude in controlling project complexity. This strategy suggests architects to embrace contextual limitations while exploiting implementation serendipities with digital design flexibility. To harness project complexity in the post-digital age, the fundamental change is not simplifying building geometries but adopting a heuristic approach to absorb real-world matters into design delivery.

2.2. Characteristics of anexact architecture

Methodologically speaking, anexact architecture inherits its operating characteristics from the ‘vibrant object’ proposed by Crolla,
which builds on the open-endness nature of parametric procedural modelling to cope with the non-digital aspects of design materialisation (Crolla, 2018). On the one hand, ‘vibrancy’ refers to high levels of uncertainty caused by intricate design requirements and ill-defined design problems. The volatility of project materiality, material systems and materialisation can only be settled if the uncertainties are given room to re-interact with the design process. On the other hand, the idea of ‘objecticle’ represents an infinite number of variations (Deleuze, 1993) that can be addressed with rigorous algorithms. A parametric model creates a flexible continuum insofar as the methodology allows a late intervention of project-related matters and forces. Anexact architecture inherits the technical essence of vibrant objecticle of adopting parametric model, as it allows architects to work with mass variations and to gradually reduce project complexity. Ideologically, anexact architecture hinges on ‘fuzzy logic’ introduced by Zadeh (1999) to practice the ‘third attitude’ represented above. Fuzzy logic deals with human’s common-sense knowledge, such as verbal descriptions and qualitative analysis, which usually contains vagueness and indeterminacies (Gray, 2011). Building upon such epistemology, anexact architecture seeks the neutral territory between the exact discrete definitions offered by parametric model and the unmeasurable design intention expressed by humans. It helps architects to create a margin for unexpected matters and prepare them for ad-hoc adjustments.

Based on vibrant objecticle and fuzzy logic, anexact architecture is a strategy of set-based design. The set-based design was originally utilised by automobile manufacturer Toyota in dealing with communication ambiguity and design decision deferral (Ward et al., 1995). It illustrates a convergent diagram (Bernstein, 1998) where designers, at the beginning, explore multiplicities within a controlled range and gradually narrow design concepts as the project proceeds (Figure 2). With parametric procedural modelling, set-based design helps architects add design content accordingly per construction affordance. Also, design indeterminacies or implementation uncertainties can be described using a series of parent-children relations (Davis, 2013). Because of the mathematical precision offered by parametric objecticle and the flexibility endowed by fuzzy logic, anexact architecture is neither exact in dealing with fixed, metric essences, nor inexact merely concerning intangible matters. Instead, the set-based design practice strategy can be described as anexact-yet-rigorous. Anexact architecture looks for project-specific forces and matters, such as material resources, site restrictions, and local craftsmanship, to guide the convergence of design development. By regarding the built outcome as an intentional approximation of its initial design intent, post-digital architects are endowed with a progressive control of project complexity.

Due to some contextual constraints that may not be foreseeable at the early design phase, the strategy allows post-digital architects to defer design decisions until local affordability gains clarity. Especially in a labour-intensive construction context, a level of design ambiguity is a necessity to accommodate materialisation inconsistency and slippage. Hence, the authors suggest 5 characteristics of anexact architecture in achieving a convergent diagram:

1. Morphable intent: the idea comes from the embryological process where the genes of an embryo do not decide a final form but only guide its morphogenesis (DeLanda, 2002). The parametric model is the genes to a project's embryo, which allows emerging real-world material, materiality and materialisation matters to affect its physical form. The idea of morphable design intent implies design fuzziness and self-organisation around a pre-defined project topology.
2. Parametric ambiguity: the key operating characteristic inherited from vibrant objecticle, which determines the level of vibrancy that building form, structure, and programs may acquire. Gero refers that parametric flexibility is inherited from architects' experiences, from which they combine heterogeneous elements learned from similar design practices (Gero, 1990). Parametric ambiguity ensures the open-endedness, variability, and interactivity nature of post-digital architecture.
3. Incremental materiality: architects' increasing agency of design delivery allows them to defer design decisions so that they may establish a better understanding of construction affordance. This characteristic is meant to properly position design problems within a supply chain and progressively increase the clarity of real-world events that later become design-driven forces.
4. Technical bypassing: by working with CNC machinery, robotics, and virtual-actual interactive devices, post-digital architects may create a quasi-automated design delivery environment when facing a challenging construction context (Yuan and Yan, 2016). By directly transforming design content into construction operations, they can hack a conventional design-to-build system, to bypass representational difficulties.
5. Concentrating performance: the idea suggests architects hierarchise design ambition for the sake of implementing rationality. The characteristic ensures architects focus on rational design expectations within their field of interest and reduces the need for computational power so that parametric ambiguity is technically feasible.

These characteristics of anexact architecture suggest post-digital architects, instead of blindly pursuing universality, ought to wisely harness project complexity based on locality and project-specific peculiarities. Anexact architecture resists a transcendental design-to-build process but is deeply rooted in the socio-industrial context.

3. Method: combining PAR with anexact architecture

3.1. PAR in architecture

The research of architectural design practice is not quantifiable as in science and engineering due to its social attributes, the development of epistemology mainly relies on the interpretation of human actions (Swann, 2002). Here, the authors adopt Participatory Action Research (PAR) as a qualitative research method to investigate the practical meaning and operational feasibility of anexact architecture. PAR focuses on the social changes fostered by the collaboration between the investigator and the participants (MacDonald, 2012), as it produces knowledge and makes improvements in practice within a committed social context (McTaggart, 1994). PAR in architecture roots in pragmatism, therefore, the research of anexact architecture would acquire a positive result only if the case-by-case design practice experiment contributes to
real-world circumstances (Groot and Wang, 2002). Through a process of change and improving specific situations, investigators adopting PAR in architecture are capable of developing practice epistemology through reflection on past or ongoing actions and engaging in a continuous learning process (Herr, 2015). This qualitative research method emphasises the influences and active changes that the investigators and participants made to the process. The authors believe PAR aligns with post-digital architecture's social dimensions, where architectural activities not only encourage physical production but also produce practical knowledge that is beneficial to a broader context or dynamic human relations (Katoppo and Sudradjat, 2015).

Rather than a linear model of research like most scientific experiments, PAR presents a cyclical approach which works its way through iterations of ‘plan’, ‘act’, ‘observe’ and ‘reflect’ (Walter, 2009). PAR matches the back-and-forth nature of architecture design and is especially beneficial to parametric objective practice. Here, ‘plan’ aims to establish a design problem space and defined the genes for project development; ‘act’ implements the plan, converts digital to physical; ‘observe’ evaluates the act outcome, takes social and reality matters into consideration; and ‘reflect’ uses the knowledge gained to modify the plan, adjust design solutions accordingly. In the post-digital age, this cyclical process is effectively shortened thanks to computational simulation and prototyping. Architects' increasing agency of design delivery helps them to start early conversations with different project parties, absorb versatile requirements and restrictions into design explorations, and properly add design content for the project complexity's sake. Investigators who use PAR in architecture will go through cycles of adaptation and refinement, exclude inappropriate design intents, and optimise design problems before an idea is successfully realised. PAR matches the set-based design mode, as setbacks and crises that architects encountered are the elementary force driving the convergence towards a feasible design solution space.

3.2. Combine PAR with anexact architecture

In the previous argument, the authors imply that anexact architecture hinges on a convergent fashion of harnessing project complexity. To accommodate project intricacies, restrictions and indeterminacies, this post-digital design practice strategy relies on parametric procedural modelling to progressively integrate real-world matters. The heuristic and abductive nature of anexact architecture is in line with PAR's cyclical research model. Besides, PAR's goal of producing knowledge through social activities and epistemological developments matches the social dimension of anexact architecture. Based on Katoppo and Sudradjat’s method of combining PAR and design thinking (Katoppo and Sudradjat, 2015), the authors propose PAR as a research model umbrella for anexact architecture. As the human-centred social innovation fits well with PAR in architecture, anexact architecture’s 5 characteristics in set-based design can also incorporate PAR's 'plan-act-observe-reflect' loop. Hence, the authors believe that the combination of PAR and anexact architecture presents a mixed research method for post-digital architectural design practices, especially for those within the challenging construction contexts.

This mixed research method will involve both quantitative and qualitative approaches. Because not only the parametric model is the core for adding design content and generating information needed for construction operations, but also it is the key to the cyclical, convergent design activities. The gained knowledge, either observed from prototyping or unexpected on-site construction, will eventually reflect in the adjustment of design parameters. In addition, the unmeasurable factors brought by project participants, such as contractors' empirical knowledge of construction and stakeholders’ ad-hoc decisions, are crucial to the design delivery, and therefore can be addressed with parametric ambiguity. As a research method (Figure 3), the combination of PAR and anexact architecture can be applied across different projects, so that architects or investigators are capable of a better plan for harnessing project complexity.

This paper then uses three building projects, Yan Ancestral Hall, Yibin International Bamboo Products Trading Centre, and Aurora, in which the authors were the architectural designers and investigators. These projects are discussed in terms of the practical meaning of anexact architecture in realising non-standard buildings within challenging construction contexts. By adopting the mixed research method above, the authors, from one project to another, enhanced the ability to integrate accessible digital capacity with project-specific sociality, locality, and construction affordability.

4. Results: increased control of project complexity

4.1. Yan Ancestral Hall: a high-touch construction

In Yan Ancestral Hall (YAH), the authors aimed to investigate a contemporary representation of brick architecture with the given digital design capacity. The building locates in a remote village near Yulin, China. To blend a new design into the existing context, the authors decided to use locally available building materials and inherit a traditional architectural form. By combining digital design and local craftsmanship, YAH realised ripple-like patterns on the West façade imitating the Chinese character “Yan” (Figure 4).

4.1.1. Local construction idiosyncrasies

The peculiarity of local culture, the poor quality of building materials and the unskilled labour force were the major challenges to YAH's design delivery (Figure 5). Locally handmade clay bricks are used as the building material to increase the project's cost efficiency and architectural meaning. But the material impurity makes these bricks poor in their strength and shapes and may potentially result in construction deviation. Feng Shui, also known as Chinese geomancy, plays a decisive role in local architectural design practice. Including building orientation, entrance location, and crucial component dimensions are explicitly stipulated in this culture. Figure 4 right shows a Feng Shui tape measure where characters in black indicate misfortune, therefore they are prohibited in use. The human factor also added uncertainties to the project design and materialisation. Since the construction team was made of local villagers who were not professional contractors and lacked experience in non-standard practices, the authors had to cope with their knowledge and implementation competence.

These local construction idiosyncrasies have impacted the project complexity because they were not fully quantifiable. Especially for culture and human matters, a predefined design space must encompass a certain level of flexibility so that design content could be altered in a later project phase. Also, as YAH has adopted a path of high-touch design realisation, the authors optimised the parametric model to accommodate the conventional brick laying technique and human cognition.

4.1.2. On-site project simplification

The construction of YAH took place in a homestead where tender submission is not required. The authors, therefore, were able to work alongside local labours and communicate directly through the parametric model. All building components, from building envelope to interior structure, from upper roof to lower foundation, have been parametrically connected insofar as the authors created a morphable design intent (Figure 6). Parametric ambiguity ensured a PAR-based design practice. Some specific design contents, such as the overall brick amount and mortar thickness, could only be confirmed on-site due to the indeterminacy of high-touch construction. The authors relied on parametric procedural modelling to realise the cyclical research. By continuously observing and reflecting on the in-situ accidental events, the authors were able to progressively reduce design fluctuation and increase material clarity.

Unlike digital fabrication where added design content can be directly transformed into machine operations. Humans, however, will seek
commonalities and familiarities when they confront unfamiliar tasks. To provide the on-site labours with an articulate implementation logic, the authors simplified the West façade by changing its coursing from a ‘Stretcher bond’ to a ‘Flemish bond’, and only ‘stretchers’ were cut into 5 different lengths. By using ‘headers’ as a visual reference, the labours were able to keep track of the implementation sequence (Figure 7). In
addition to the planned design optimisations, impromptu adjustments made on-site also contributed to the successful design delivery. For example, given the major deviation (more than 200 mm) in the as-built foundation, the authors have made a last-second design adjustment based on the site survey, so that the following construction could make the best of the as-built conditions. The labours’ initiative also played a key role in reducing the negative influence of irregular bricks, ensuring a smooth pattern on the façade (Figure 8).

4.1.3. Project discussion

The successful realisation of YAH benefits from the designer’s increased agency of design materialisation, the back-and-forth negotiation between the digital and the physical, and the serendipities emerged from the local craftsmanship. The authors were able to combine the strategy of anexact architecture with the PAR-based design practice, achieve a pragmatic outcome by progressively harnessing project complexity. However, the major vibrancy of the project was not settled until a series of cyclical research have been carried out regarding project complexity. However, the major vibrancy of the project was not settled until a series of cyclical research have been carried out regarding project complexity. For example, the ‘plan’ and ‘act’ of the façade design modification can only take place after the ‘observe’ of construction errors and the ‘reflect’ from the site survey. This is due to the nature of a high-touch design delivery process where uncertainties can only be addressed during implementation. Even though the built outcome of YAH is satisfactory, deviations are spotted in more than half of the West facade (Figure 10). Hence, for a better control over project materialisation, design optimisations must engage with pre-construction matters.

4.2. Yibin International Bamboo Products Trading Centre: increased control over project complexity

Yibin International Bamboo Products Trading Centre (YIBPTC) is a multipurpose convention centre that locates in Yibin, Sichuan. Because people commonly see bamboo as banal materials and wrongfully associate it with temporary structures (Ngo, 2013), this building was designed as a showcase of permanent bamboo architecture in urban context. Bamboo’s cylindrically hollow shape and fibre composition promise its structural efficiency when used in construction, hence, recent design studies have been expanding the formal repertoire of bamboo architecture. By relying on the material’s bending property, experimental projects like ZCB Bamboo Pavilion (Hong Kong, China, 2018) (Crolla, 2017), INBAR Pavilion of the International Horticultural Exhibition (Beijing, China, 2019) (Laverde, 2022) and IBUKU green school (Bali, Indonesia, 2021) (Stathaki, 2021) illustrate the potential of using bamboo poles in non-standard design practices. YIBPTC contains a curved roof that is supported by bamboo trusses. Its exterior structure encompasses continuous bamboo vaults and the largest span of which is over 58 m (Figure 11). Having learnt from the design delivery experience of YAH, in this project, the authors further increased the control over project complexity.

4.2.1. Pre-construction design optimisation

The design of YIBPTC utilised the material properly for both structural and non-structural purposes. The two-story convention centre includes 5 exhibition halls that are symmetrically positioned in two wings. The building’s roof surface occupies more than 14,000 square metres area, sits on a hybrid two-way truss system. Having considered the non-standard truss components and the material imperfection, the authors decided to pursue a trade-off in structural design to avoid unpredictable deformations. Therefore, the spandrel-braced trusses along the building’s long direction were designed as hybrid structures. The top chords, verticals, and diagonals of the trusses are made from rectangular steel tubes, which also help to shape the roof geometry. The bottom chords of the trusses, which are arches only take tension and compression, are made from bamboo poles. There are 14 bamboo poles with an average radius of 50 mm in each arch. Figure 12 is an illustration of the multi-material spandrel-braced truss where the bamboo poles are bundled and mounted on the verticals to ensure the holistic integrity.

The realisation of the exterior bamboo vaults surrounding the building envelope was also challenging. Like YAH, the non-standard design of YIBPTC could be fully described with parametric models, allowing a morphable design intent with rigours ambiguity. Unlike the previous case, the design practice of YIBPTC was a commercial activity that involved various stakeholders. This has increased the level of indecision as extra design requirements might emerge at any time. Instead of working directly with fabricators and contractors, in this case, the authors must produce annotation drawings as part of the official submittals. Therefore, an early harnessing of the project complexity has been a necessity in the pre-construction phase because the non-linear bamboo components would be difficult to annotate with plans and sections. At the time, only manual bamboo craftsmanship was available. The local fabricators heat bent the bamboo structure components using nothing but a blowtorch and a customised guide (Figure 13 left). These handmade segments were then bundled and connected into arches on-site. When being lifted, the influence of gravity and bending force also caused unexpected deformation in bamboo components, making it challenging for the on-site assembly (Figure 13 right). With all the consideration of latent uncertainties, the authors simplified the design by only adopting singly curved vaults in the exterior bamboo structure. The pre-construction design optimisation allowed the project to firmly develop around the local constraints, secured an effective transition from the parametric model to planar drawings.

4.2.2. Increase construction rationalisation

The exterior bamboo structure contains 18 bamboo vaults, and each one encompasses 3 to 5 trusses depending on their span and width. Since these trusses are planar arches, the fabricators were able to position, bend, and connect bamboo segments into their designed shapes based on the guide curves drawn on the ground. The on-site prefabrication and assembly operations were instructed by the construction documents. Due to the excessive construction content needed and the latent construction deviations, the contractors were given implementation autonomy in

Figure 7. The simplified implementation logic.
order to meet a tight project schedule and to ensure an expedient material outcome. For example, the contractors have been allowed to adjust web members’ lengths so that they could accommodate accidental structural deformations.

The form of the exterior bamboo structure was controlled by parameters including the anchor positions, the highest point, and the curvature of each bamboo vault. Since 2D drawings were the sole communication channel between the design party and the implementors, the authors have kept these design variables adjustable until most of the concrete works were in place. The parametric model helped the authors to delay outputting construction content, and to absorb the material deformation and gravity matter to the greatest extent. It took no time to label all the structural joints and their coordinates, as well as to annotate the anchors’ locations based on the existing concrete piers (Figure 14). The entire construction of YIBPTC lasted less than a year under the pressure of the local government, fortunately, the use of digital tools allowed the design party to quickly respond to external design requirements.

4.2.3. Project discussion

Based on the ‘reflection’ on YAH, the authors were able to further increase the control over project complexity. By extending the strategy of anexact architecture into the pre-construction phase, the design party could involve material property and fabrication limitations in a PAR-based design exploration. During the on-site assembly of YIBPTC’s exterior bamboo structure, the authors delayed the final output of construction drawings until all indeterminacies have been settled. Also, since more project participants have joined the cyclical design research, the final design decisions, especially on the form of the non-standard bamboo structure, were the expedient results that made the most of the fabricators’ competence, the available resources, and the administrative demands. Compared to the previous case, early adoption of PAR and anexact architecture permitted several rounds of design optimisation, allowed the authors to pragmatically distribute complexity across different project phases and concentrate on the expressive building parts (Figure 15).
4.3. Aurora: a further extension of complexity control

The authors have adopted parametric models to maintain design flexibility, and by doing so, they could progressively exploit related constraints and opportunities so that rational solutions would emerge. However, digital capacity only benefited YAH and YIBPTC’s design processes due to the lack of advanced implementation means. To further demonstrate the architect’s increasing agency of design delivery, the authors investigated virtual-actual interactions upon the idea of post-digital design practice. Aurora (Zhang Jiakou, China, 2021) is a single-story residential architecture built for 2021 China’s Solar Decathlon Competition (SDC). The building was designed to illustrate the use of energy-efficient systems, environmentally friendly materials, and a BIM-based design delivery process (Figure 16). In this project, the authors have adopted a computationally enhanced workflow where digital capacity not only stimulated the design iterations but also contributed to the off-site fabrication, on-site construction and as-built evaluation.

4.3.1. Holographic design delivery

Per the transportation requirements, Aurora has been divided into 5 modules that were fabricated and partially assembled in an off-site factory. The BIM-based workflow has enabled a simultaneous design and making process where designers, fabricators, and contractors could work together. To better integrate the virtual design environment and the actual construction operations, the authors adopted Mixed Reality (MR) technology to assist Aurora’s design delivery. With head-mounted display HoloLens and MR software Fologram (Jahn and Wit, 2019), the implementation team firstly inspected potential fabrication deviations and...
system collisions via overlaying the digital model with the built modules. The technology helped with a high-touch in-situ construction of Aurora’s non-standard façades. The wall pattern is visualised via differentially flipped laminated bamboo panels. These panels were cut into various lengths and their flipping angles were restricted in 5 types including 0, 25, 40, 55, and 70°. Figure 17 illustrates the assembly details where the bamboo panels are vertically staggered on the wood keels with a 20 mm overlap. The shape of the façade pattern was driven by a control curve and the solar radiation simulation.

A holographic construction helps to reduce the tedious repetitive translation of parametric models and provides implementers with visual instructions instead of static drawings (Jahn et al., 2018). MR technology
relies on human tactile and vision to stimulate collaborative knowledge, then to resolve the complexity of a high-touch non-standard construction. In the case of Aurora, the authors adopted the maker-based 3D registration method to place the construction instructions in the implementers' line of sight. Several ArUco markers were placed on the construction site in case of a misalignment between the virtual and the actual. With a real-time parametric control, the implementors were able to fine-tune the holographic display to cope with the lighting condition as well as to make ad-hoc model adjustments. During the façade construction, implementers wearing HoloLens firstly have labelled angle types on the pre-installed wood keels so that the others could follow and simultaneously mount bamboo panels. Inspectors holding smart devices adopted MR to monitor the as-built condition along the process (Figure 18). Besides the construction of Aurora's non-standard façade, the implementors also used MR technology during the positioning and assembly of a roof structure (Figure 19). The authors have been able to refine the structure's parametric model based on the as-built condition, which helped the implementers to trim and re-drill the structural components accordingly.

4.3.2. An information feedback loop

Compared to the design delivery of YAH and YIBP, the authors carried out a quantifiable PAR-based design practice by adopting MR and 3D scan technology. With a laser scanner and handheld depth cameras, the inspectors have collected as-built data in point clouds, transformed it into mesh models then compared it with the initial design model to calculate construction deviations. For example, Figure 19 shows a recreated model based on point clouds and the as-built analysis of the South façade. The green area represents construction deviations that are less than 10 mm while the blue and red ones indicate geometric differences ranging from 10 to 50 mm (Figure 20). Such quantifiable observation and reflection helped to create an information feedback loop between the as-built condition and the parametric model, and by doing so, the authors could make the best of what had been in place. Based on the feedback data and corresponding design adjustments, the implementors, again with the help of holographic instructions, fixed the building parts with minor construction errors to further increase built quality.

4.3.3. Project discussion

Compared to the previous cases where the authors could only respond to the project-specific idiosyncrasies via design tools, the holographic construction of Aurora established direct interaction between the design intent, and the in-situ operations, and the as-built conditions. Not only did MR technology remove the redundant annotation work from the design delivery, but also it has allowed real-time design adjustments insofar as a PAR-based anexact architectural practice could apply more easily. MR technology further increased the architect's agency of design delivery. Especially for tasks like the high-touch construction of Aurora's non-standard façade and roof structure, such adoption of digital advances will inject humanisation into computation therefore the pursuit of zero-tolerance or zero-deviation is no longer of any relevance. Instead, the post-digital integration of materials, materiality, and materialisation will value the project locality and affordability.

In the case of Aurora, the authors were able to stretch their authorship across the design, construction, and as-built phase (Figure 21). The information feedback loop has facilitated a productive communication between the design party and the implementors so that they were given more time to resolve related design and construction problems. From one design-to-build process to another among the three demonstrator projects, the authors gradually enhanced their control over project complexity through, on the one hand applying the cyclical design research method to a broader project domain, and on the other hand utilising digital capacity in optimisation, fabrication, and construction.

5. Discussion: gained knowledge from PAR and anexact architecture

Unlike architects' initial interests in utilising computation to create new building forms that divested from the deconstructivist cult of fracture (Carpo, 2004), anexact architecture suggests using the digital capacity to alter the trajectory of a design-to-build process. This post-digital ideology is derived from the interaction between computation and humanisation, emphasises architects' increasing agency of design delivery. By relying on digital advances like parametric procedure modelling, VR/AR and CNC technologies, today's architects are capable of a better control over project complexity, carrying out a convergent search for feasible design solutions. The 5 operating characteristics of anexact architecture provide the essential approaches of integrating digital with locality and materiality, at the same time, ensuring the rationality of design materialisation. Based on the research method of combining anexact architecture with PAR, the authors use three non-standard projects to discuss the practical meaning of this post-digital set-based design strategy.

The knowledge is gained not only from the individual design practice but also from the improvement of complexity control across all three projects discussed above (Figure 22). From one case to another, the authors were getting better at appropriately distributing digital power, accommodating project-specific constraints, and making the most of available resources. The capacity for harnessing project complexity increased by stretching digital authorship into different project phases. In other words, it suggests several rounds of virtual-actual interactions and design iterations according to pre-construction concerns, construction volatilities, and as-built adjustments. Compared to the ideation of vibrant objectile, anexact architecture emphasises the expedient thinking that post-digital architects should possess rather than their capacity of manipulating designs.

In YAH, project locality was overshadowed by the employment of digital design means. Even though the authors, at the early design stage, have taken matters like human logic, the material and cultural peculiarities into consideration, it only reflected in the simplification of construction. Having learnt from the previous project, the authors harnessed YIBPTC's project complexity in separate stages. Structural

![Figure 17. Panel assembly details and design control parameters.](image-url)
components were firstly simplified for the sake of a manual bamboo fabrication process and the material behaviour indeterminacy. Then, the design of non-structural parts was kept flexible and given more room for geometric changes. The construction was eventually optimised by the authors to cope with administrative requirements and the demands for a high-touch construction. When it came to the design delivery of Aurora's non-standard façade and roof structure, the authors were able to take advantage of the emerging digital technologies and used them to further

Figure 18. Holographic construction and inspection.

Figure 19. MR-aided positioning and assembly of roof structure.

Figure 20. As-built analysis of South façade.
enhance the control. Not only did the authors optimise the non-standard design in the pre-construction phase, but they kept reducing virtual-actual differences by accordingly adjusting the on-going construction and the as-built condition. Such developments of anexact architecture suggest that, when practicing within the challenging construction contexts, post-digital architects must preserve space for knowledge growth. This will help them to articulate a strategy of balancing pros and cons. Anexact architecture presents a heuristic approach requiring architects to maintain design fuzziness, pragmatically bypass restrictions, make rational compromises, and eventually benefit from what is given to them.

This design practice strategy aims to stretch a schedule of freezing design decisions so that post-digital architects can go through design multiplicities within a controlled range. The convergence and the generation of new design ideas rely on their increasing agency of design delivery via digital means. To refine project complexity, they may prioritise design problems so that gradual changes can take place in order, and construction a proactive logical structure to increase the clarity of an arbitrary form. By working with parametric objectives, post-digital architects are capable of producing design and construction content at need. Post-digital architects may again work like Renaissance master builder who are able to properly position themselves within a supply chain of project design, development, and production.

6. Conclusions

The authors discuss the strategy of anexact architecture through the reflective design practice of three non-standard projects. From case to case, the authors enriched their knowledge of harnessing project complexity by combing a PAR-based design practice and anexact thinking. The development of expediency and pragmatism benefits from parametric procedural modelling, in which the authors were able to ‘plan’ design problems based on parametric relations, ‘act’ by going through design variations, ‘observe’ conflicts and opportunities that emerged from the contextual idiosyncrasies, and eventually ‘reflect’ on the design solutions. This back-and-forth design optimisation is deeply rooted in the project materiality and materialisation matters. As the project proceeds, the design delivery process will appear in a convergent fashion because, in each research cycle, the impractical design solutions will be excluded from the range of design objectives.

To conclude, anexact architecture advocates a heuristic problem-solving approach which requires architects to utilise available yet scalable design technology to mediate the transformation between a virtual image and its physical form. Rather than pursuing a seamless integration of information between the design and construction, this strategy relies on parametric design variations to absorb later-phase changes made to any plan. The design problems may appear fuzzy at first sight, yet they are mathematically rational and will continue to gain clarity as the project proceeds. Anexact architecture embraces the potential forces that can emerge from a local context and uses them to digitally adjust pre-defined design problems. This convergent process can articulate architects’ authorial positions within a specific project organisation and prevent them from front-loading all design decisions. Therefore, today’s post-digital architects are capable of accordingly harnessing project complexity based on local circumstances. The method illustrated in this paper of combining PAR and anexact architecture pursues a lean design development and materialisation approach. It hinges on the architect’s incremental perception of the project-specific constraints and opportunities, relies on available digital means to ensure flexibility during design delivery. The future study will further investigate the strategy of complexity control based on PAR and anexact architecture. Components such as human-machine collaboration, collective intelligence, and smart construction will be the focal points.

Declarations

Author contribution statement

Sining Wang: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Dandan Lin: Analyzed and interpreted the data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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