博士論文

EMPIRICAL RESEARCH ON INTEGRATED DESIGN-BUILD PROCESS FOR ARCHITECTURE THROUGH ROBOTIC TECTONICS PEDAGOGY

ロボットテクトニクス教育手法による統合型建築デザイン構築プロセスに関する実証研究

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EMPIRICAL RESEARCH ON INTEGRATED DESIGN-BUILD PROCESS FOR ARCHITECTURE THROUGH ROBOTIC TECTONICS PEDAGOGY

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Preface

This thesis research was performed at the Department of Architecture, the University of Kitakyushu. This thesis presents a study on the empirical research on integrated design-build process for architecture through robotic tectonics pedagogy. This study focused on tectonic thinking from its concept and development in architecture practice, how it manipulated and influenced architectural design through technology evolution process, and with the advanced technology, such as computational design and robotics construction, continuously intervened to architectural design process, how the tectonic thinking enables the integrated design-build process for architecture and the advanced design creation, and the corresponding pedagogical workflow to dissemination.

Acknowledgements

This work could not have been completed without the support, guidance, and help of many people and institutions, for providing data and insights, for which I am very grateful.

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EMPIRICAL RESEARCH ON INTEGRATED DESIGN-BUILD PROCESS FOR ARCHITECTURE THROUGH ROBOTIC TECTONICS PEDAGOGY

Abstract

Robotic tectonics as an emerging automation construction technology has been introduced into the architectural profession for more than a decade, advancing sustainability initiatives in the architecture, engineering, and construction industry, increasing the quality of building construction as well as solving the labor-shortage consumption increasing problems. Over the years, avant-garde architects have explored the feasibility of this new technic and design paradigm through the integration of newly-developed digital design software into advanced automated construction practices. This robotic digital workflow continues to push designers to re-think the complete architecture process (from design conception to physical construction) and guides the building industry towards more precise, efficient, and sustainable development.

However, the innovative workflow of Robotic Tectonics has merely accepted as a new emerged technique instead of a newly developed design methodology and theory for advanced architectural design, most of architects and students are barely know, interested, and understand its working mechanism and workflows for inspiration of architectural design. Therefore, in this study, through the literature review of 'tectonic' and deductive theory studies, inductive design practice of workshop experiments, and quantitative investment of teaching questionnaires, the author plans to use mixed-method strategy, exploring the hypothesis of Robotic Tectonic as Cross-interactive workflow for design inspiration.

Through this study, we aim to introduce a new didactic pedagogical approach that is reliant on the principles of robotic tectonics and is defined through linear development in four distinct, developmental stages (based on information gleaned

from four "Robotic Tectonics" workshops and various other rich teaching practices). This pedagogical framework provides interdisciplinary knowledge to architecture students and enables them to use advanced digital tools such as robots for automated construction, laying the groundwork for the discovery of new and complex building processes that will redefine architecture in the near future.

Keywords: robotic tectonics; advanced architectural design; architectural education; construction automation; workshops; pedagogical approach

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1.1. Introduction

This chapter intends to construct the initial background for the research project and form a first delineation of thematic and instrumental approaches. As a starting point, a research background is described and analyzed below, with revealing the current development situation of architecture, engineering, and construction (AEC) industry, and corresponding conditions of architectural design method, came out the critical wonder of introducing robotic technology in the architectural design procedures. By revealing the industry condition, the research objective of identifying a new ideal design approach that combines the advanced technology and architectural tectonics cultures is proposed and intended to be analyzed and answered. Trough define the research questions into three aspects of theory development, practice experiments and Pedagogical dissemination, the framework of this research is draw out.

1.2. Research background

1.2.1. AEC Industry conditions

At the end of the 20th century, the construction industry broke through the limits of traditional construction methods. The "Egan Report" (1998) commissioned by the British government showed the information that was still popular at that time, which was an important milestone. Architectural design and the construction industry have been fundamentally reformed: (1) The construction industry is divided into numerous small firms; (2) Building regulations and institutional systems with local characteristics are formed; (3) Bidding prices have become cheaper to encourage Bidding, rather than preventing cost overruns and litigation, is an extremely low investment for real estate. The research results in 1999 have been widely cited until now, in which the downward trend in building construction efficiency was compared with the potential growth of benefits and value in other economic sectors driven by technology. That means risk aversion, low investment and low returns. However, until now there is no clear way to improve it to a large extent. Therefore, the same impediments to change has always been an excuse for traditional models of practice to resist the economic imperative of advancement (Shelden, 2020).

In order to maintain productivity and economic growth, every country attaches great importance to production efficiency. With limited natural resources available for exploitation, only through the development of advanced technologies can sustainable economic and social development be achieved. In addition, the aging population and declining birthrate have also affected the development of the country, which is also one of the reasons for technological upgrading. Approximately half of the country's total investment is spent on urban industrial construction, including housing and other infrastructure and other supporting facilities, which shows that the industrial sector is one of the industries with important national strategic significance. However, according to statistics, the production efficiency of the global construction industry has shown a clear downward trend in recent decades (see Fig. 1). , and capital investment is low compared with other industries. This is because the obvious shortage of labor (related to aging), the large consumption of raw materials and

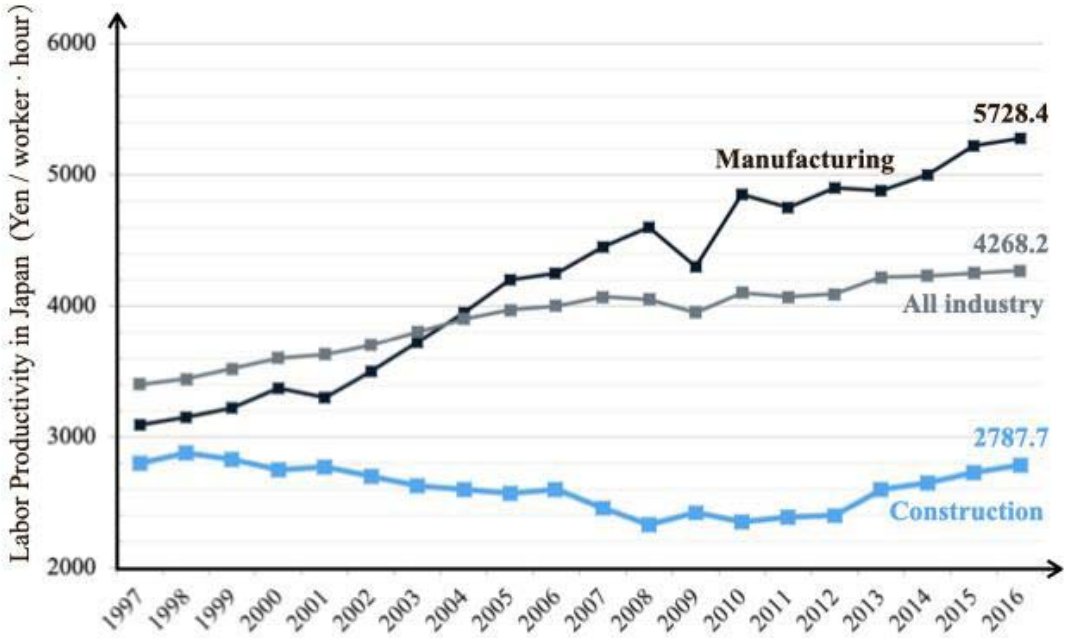


Fig. 1 - Labor productivity in industry generally, and especially in the manufacturing industry is continuously rising; labor productivity in construction has been decreasing for decades.
image based on(Allmon, Haas, Borcherding, Goodrum, & management, 2000).

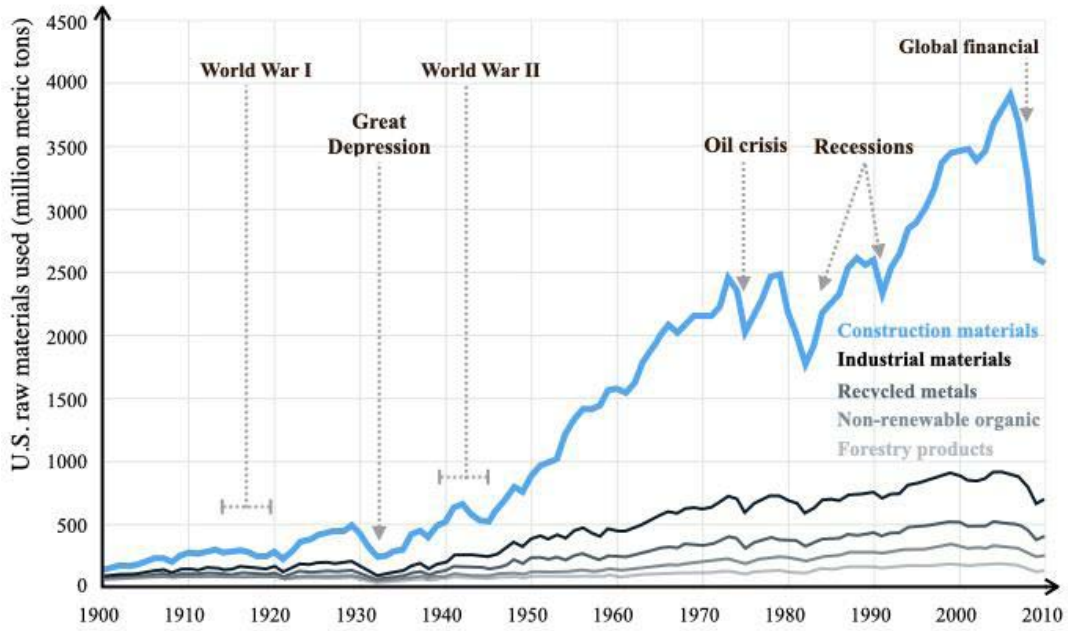


Fig. 2 - Raw material consumption (short tons) in the United States 1900–1995.
Image based on (Matos, 1979).

energy (see Fig. 2), the hard work and the harsh environment have led to low interest among young people in the construction industry. In addition, problems such as the defect rate of construction products, making ends meet, and the inefficiency of investment management strategies these be related to sub-par human conditions or to technological inadequacies—as well as a low interest in the construction sectors shown by younger (Linner, 2013) have become increasingly prominent. The technical performance under the conventional construction mode may have reached the limit of application (Bock & Linner, 2015a).

The trend of promoting economic growth by reducing labor input and realizing technological changes is intensifying. This is also the law of natural social development, especially in highly developed countries. German macroeconomic economist Borch-Supin proposed a solution to improve the situation. He believes that by increasing the capital intensity of human capital, using intelligent technologies such as machines to make up for the lack of productivity and achieve economic growth (Börsch-Supan, Erlinghagen, Hank, Jürges, & Wagner, 2009). The concepts such as “Industry 4.0” (Jopp, 2013) or “Cognitive Factory” (Zäh et al., 2009) have been proposed, indicating that a highly automated and flexible manufacturing system (often referred to as the “fourth industrial revolution”) is undergoing Become a strategic goal of all countries. These robot systems that can work autonomously, move flexibly, and can realize linkage and collaboration through a distributed layout through the network will become the "workforce" of the manufacturing industry. They can run uninterrupted 24 hours a day with stable productivity and near real-time, producing more complex and customized building products. This will bring "new life" to an industry that has been stagnant for decades.

Compared with other industries, innovation in the construction industry has been progressing very slowly. The main reasons are as follows: (1) Building products usually need to meet many performance requirements and have a long service life cycle; (2) There are many types of product sizes and materials; (3) The structural changes within or between products are complex; (4) New The product development cycle is long and the cost is high; (5) The construction industry has a complex work chain and it is difficult to popularize new technologies. Nevertheless, some leading scientists, researchers in universities or R&D departments have been working hard to

break through these bottlenecks. They established innovative enterprises through joint government agencies, and always insisted on trying to apply new technologies and new workflows, that is, the introduction of "building automation" (Bock, 2015). , which has made a huge contribution to promoting changes in the entire industry. It can be traced back to the 1970s when Japan applied industrialized processing and manufacturing to the prefabrication of modular houses. Subsequently, in 1991, the first construction project that fully applied the "building automation" technology was completed in Japan (Bock & Linner, 2017).

However, for years, automation technologies such as robotic systems have been employed exclusively by industrial manufacturers, but recently, avant-garde architects have begun to explore using this technology as a tool for architectural tectonics that could be introduced into professional practice, successfully revealed the potential of combining the most frontier advanced technology with the pursuit of humanities and art into architectural design method under the core concept of architectural tectonics practice. As a kind of cultural inheritance, the tectonic tradition was incepted and had its peak in connection to the master-builder tradition in architecture where the design was carried out on the building site as a direct response to materials and structure. Since then, the building industry has become increasingly complex and this has confronted the tectonic tradition with a number of challenges.

First, industrialization has weakened the link between design and implementation (Beim, 2004). There are usually two situations: (1) Through the industrial production of building components, a large number of building construction work is transferred from construction sites to factories, thereby ensuring low-cost or high-efficiency building components. (2) Through the introduction of a bidding system, the construction of the project will be tendered after the design is completed, which makes architects and engineers have to choose from existing building components. Secondly, engineers who strictly follow scientific norms and architects who try to create works of art that conform to the current situation often disagree with each other. That means it is difficult for them to working closely together in the process, so that the creative ability of tectonic architecture and its expression effect were limited making it difficult to achieve the design to real materiality. In addition, the diversified forms of the construction industry are also one of the reasons for the inertia of the

construction industry, such as free competition and obtaining qualified workers through division of labor. The competition between the design team and the industry makes the technical capabilities of the industry cheaper, resulting in a higher price ratio for choosing existing products from the shelves. Because they do not have enough sales market, the replacement speed of new products in the industry is slow (Schmidt & Kirkegaard, 2006).

As every technological upgrade process, there's a shifting period between the conventional technology and the advanced technology, same in the AEC field. With the swarm of BIM, computational design, digital fabrication and robotic constructions, a new design and building culture is emerging. An overlay of S-curves (Foster, 1988) can be used to describe the relation between the stagnation and technical limits of one technology (conventional AEC technology) and the initiation, development and growth of new strategies and technologies (future advanced AEC technology), which are at the beginning inferior to the existing technology but gain in importance, performance, and adoption rate over time (Fig. 3).

In the past 20 years, with the development of sophisticated digital technology, computers have been changing architectural practices (A. J. B. Picon, Switzeland: Birkhauser, 2010). Beginning in the early 1990s, Columbia University's paperless studio applied computer technology to word processing and accounting, creating conditions for the widespread use of computers in design practice. In 1998, Greg Lynn published the Animate Form manifesto, which involved the infinite possibilities of geometric exploration in the eyes of digital designers, which was extremely influential (Lynn & Kelly, 1999). Although some people have raised objections to the content of his manifesto, Patrik Schumacher's "parametricism" still focuses on the production of tables (Schumacher, 2011). Manipulating complex geometric shapes and generating creative new forms seems to be one of the few successful cases where digital culture is widely used in the construction industry.

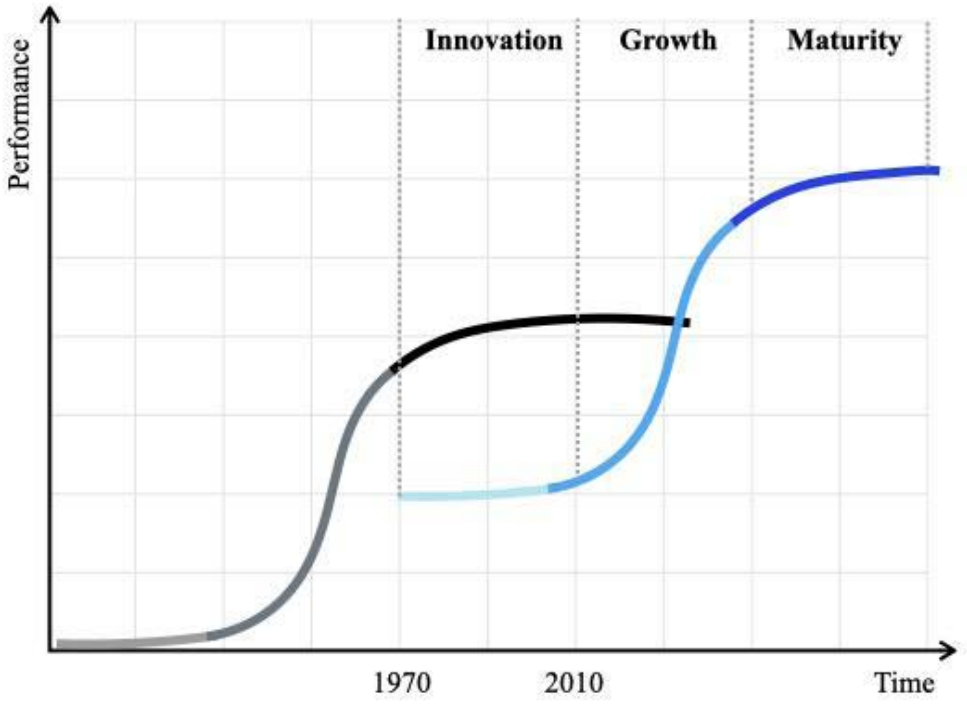


Fig. 3 - Foster's (1986) S-curves applied to AEC industry.

Image based on (Bock & Linner, 2015a).

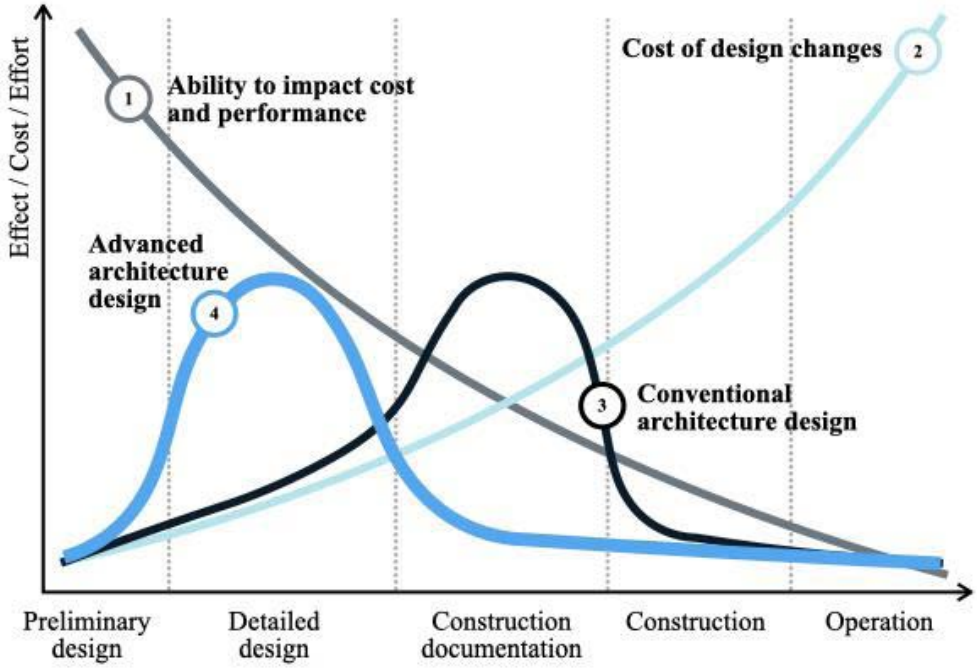


Fig. 4 - MacLeamy's curve which advocate shifting design effort forward in the project, frontloading it, in order to archive high efficiency design.

(MacLeamy, Design, Construction, & Operation, 2004; Matos, 1979)

However, in recent years, research on the impact of digital culture on architecture has gradually turned to focus on construction. From school laboratories to professional construction companies, various computer numerical control machine tools (such as lathes, milling machines, 3D printers) are widely used, which means the rapid rise of digital manufacturing. Pioneer architects in the field of architecture such as Fabio Gramazio and Matthias Kohler have done a number of pioneering experiments using robotic arms at the Swiss Institute of Technology in Zurich. The possibility of the application of robotics in the construction industry (Gramazio & Kohler, 2008b). On the basis of these studies, many schools have also begun to build experimental platforms for robotic manipulators. Researchers also generally believe that digital manufacturing represents the direction of architectural transformation under the influence of digital culture (Caneparo & Cerrato, 2014).

As Antoine Picon emphasized above, a bunch of advanced technology applied into AEC industry has enlighten a digital future for architectural design field, the combination of parametric design tools, design and multi data simulation, automated construction and robotics, the most advanced technologies start to shifts the conventional design methods to the next efficient design workflows. This brings the opportunity to fully realize MacLeamy's curve which advocate shifting design effort forward in the project, frontloading it, in order to archive high efficiency design process and high-performance architecture eventually (Fig. 4). Following the pavement contributed from the avant-garde architects, like Fabio Gramazio and Matthias Kohler in Zurich, and the demonstration of developing a workflow that challenged the current limitations of computational digital fabrication in design and construction, we believe the relevance of Advanced Architectural Design method with Robotic Tectonics is growing (advancing mostly in unstructured environments such as research labs and universities), and it may have the potential to serve as the catalyst for the automation of construction across the diverse architectural field (A. Picon, 2018; Ursprung, 2018).

1.2.2. Advanced Architectural Design

Based on the continuous expansion and innovation of construction industry technology (an illustration of the AEC technology ecosystem could been seen Fig. 5),

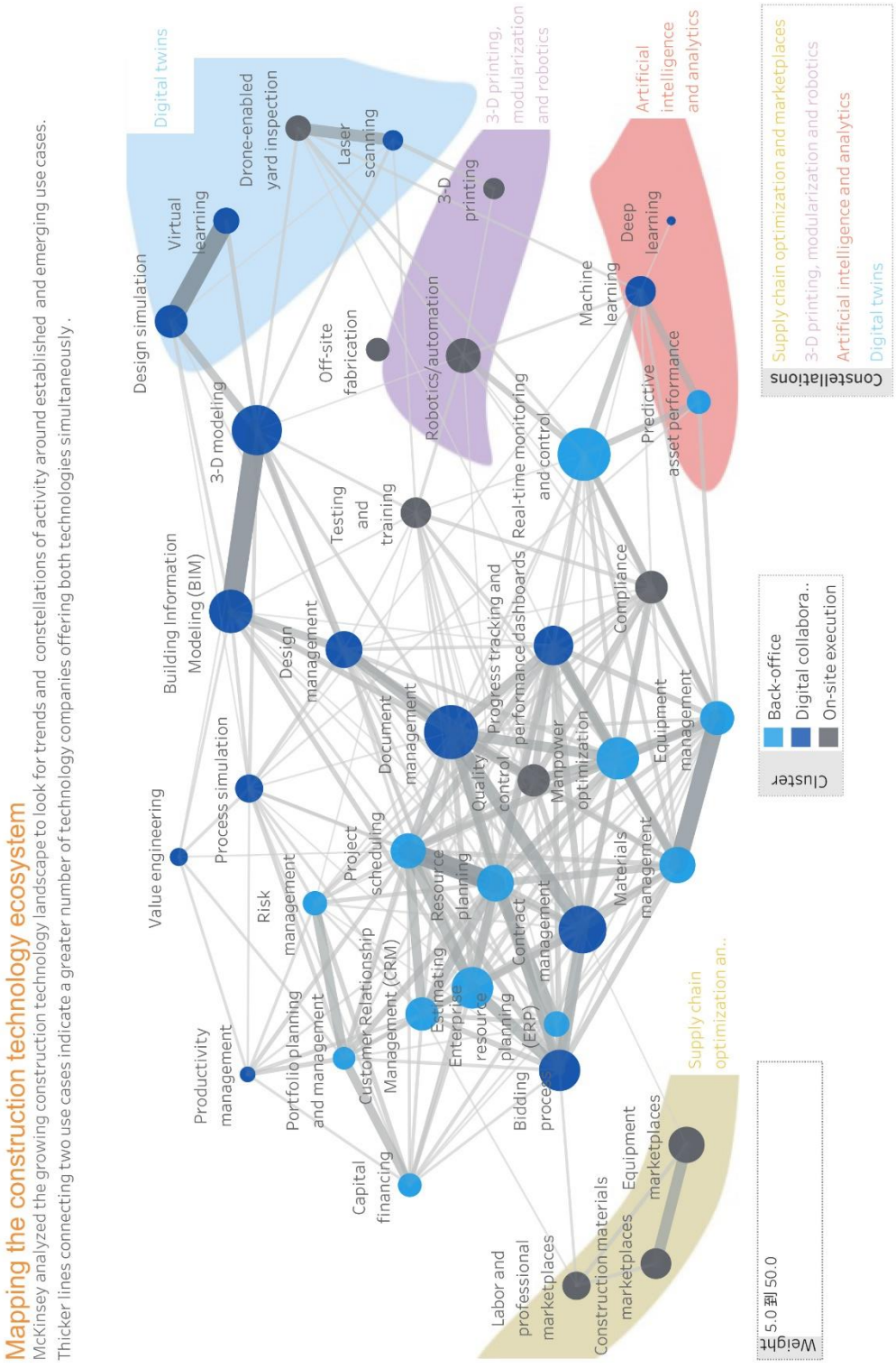


Fig. 5 - Mapping the constrution technology ecosystem. Sources: McKinsey Startup and Investment Landscape Analytics, Pitch Book, Capital IQ.

Image based on (Blanco, Mullin, Pandya, Parsons, & Ribeirinho, 2018).

Advanced Architectural Design is the blending of the most advanced construction materials and building techniques with outside-the-box visions of the way to define a structure and fabricate it to integrate the inside space and the outside, and all the time making a useful and usable space within a shell that is connected to the surroundings. Within contemporary architectural design a significant shift in emphasis can be detected – a move away from an architecture based primarily on visual concerns towards an architecture justified by its performance. Structural, constructional, economic, environmental and other parameters – concerns that were once relegated to a secondary level – have now become primary, and are being embraced as positive inputs into the design process from the outset. Architecture is now preoccupied less with style and appearance, and increasingly with material processes and performance. It is as though a new architectural design sensibility has emerged.

But how exactly might we theorize this new sensibility? Some of the avant-garde architectural schools established courses on Advanced Architectural Design tracks this new development from its origins in materialist philosophies to its implications within the field of design. It draws upon biomimetics and other aspects of scientific thinking, such as theories of emergence and swarm intelligence, that are informing recent developments in contemporary design thinking. It goes on to consider the role of computation in this development, from new scripting techniques to fabrication technologies, and from terrestrial concerns to new robotic technologies being envisaged by NASA for application on the Moon. Advanced Architectural Design engages emerging methods of design and fabrication through architectural design to speculate upon future modes of architectural practice, enhanced construction methods, and material culture within the built environment.

Architecture and its design practices are critical in addressing contemporary challenges; architectural specificity is the result of transdisciplinary cooperation; architecture's future agency lies in the discipline's capacity to mobilize realities across different scales and time frames. These ideas are explored through innovations in representational tools and the embrace of new probationary artifacts, inviting architects and students to shift away from the specialized mastery of specific scales towards methods of "interscalarity." By aligning new models of response to new architectural modes of practice, these Advanced Architectural Design tools strive to

empower future practitioners in the face of unknown future scenarios.

Digital workflows and computational design

Digital technology as a new capability is transforming the designed organization and hierarchy from autonomous processes to collective work processes. The historical position of the designer as the sole creator has begun to shake, gradually being replaced by a semi-autonomous, algorithm-driven design workflow deeply embedded in the collective digital communication infrastructure. Under these opportunities and risks, more severe challenges have been brought to the architecture discipline, and higher requirements have been raised. The main challenge is to design the possible role in this process. Due to changes in technology and design, the AEC industry is in a state of constant change. For example, from the perspective of new production economics, some financial incentives are implemented to improve efficiency in a simplified form and the automation of labor-intensive processes (Marble, 2012).

The integration of building information modeling (BIM) platforms and digital simulations, as well as increased access to data in the form of building performance, enables contemporary architects to collaborate with others to develop workflows during design and construction. In addition to design intent and process, workflow now occupies an expanded field in architectural practice, merging digital design operations with architectural activities, project delivery, and post-occupancy scenarios in virtual and actual formats. (Garber, 2017).

Many architects have been able to establish a coordinated and collaborative relationship between architectural design and current technology. For example, the demand for individual customization of construction products has increased while the volume of conventional large-scale modular production has decreased. And the machine replaces a large number of workers working linearly on the assembly line to produce individual parts. In this way, only a few workers with certain professional knowledge are needed on the assembly line, and the free changes of multiple parts can be completed through easy programming of the hardware. Therefore, the current workflow is particularly suitable for effectively customizing a variety of different solutions to specific building performance requirements. This is different from the traditional way of working in the 1990s. The design team can use 3D modeling and

simulation tools to develop building solutions that meet various standards, including shape, performance, material and energy use, and cost. Now, it is possible to control design decisions such as location and direction, a large number of considerations and accessibility early in the design process, and smoothly link them with downstream tasks, such as material selection and the manufacture of structural or building components . Design decisions such as siting and orientation, bulk considerations and accessibility can now be controlled very early in the design process and linked to downstream activities such as material selection and the fabrication of structural or architectural components. Although the formal variation could always be numerically controlled, it can be directly connected to a highly specific criteria which would creatively drive design decisions from now to the future.

New Design-to-Construction Processes

“Architects think constructively; that is, the principles they apply are conceived in generative terms. The notion of design as computation captures this constructive attitude and indicates, at the same time, basic possibilities for utilizing the generative power of computers in design education” (Flemming & Media in the Computer Era, 1990). This means that architectural design can be seen as a form of calculation, a process of transforming the initial idea into the final building by applying continuous operations. (González & D’Acunto, 2016).

Computers have not only changed the way we design objects, from furniture to buildings. More and more experiments have proved that it will more or less affect the process of producing artifacts of various scales to a certain extent. In other words, the relationship between a new design and manufacturing is being redefined. More broadly, it should be a relationship between new thinking and manufacturing. Because the relationship between thinking and creation is an important foundation for all cultural creation activities. The close connection between thinking, production and culture is one of the essential courses. The main theories put forward by German architects revolve around "technical and structural art style" on this key issue, and provide bold and enlightening ideas (Semper, 2004).

Researchers from the University of Oxford proposed in a recent study that most construction activities can already be computerized (Frey, Osborne, & change, 2017).

Although the digital continuity between design and manufacturing does not yet exist, and some people even want to know whether this continuity will be fully realized, countless machines and processes working day after day to achieve this goal will surely promote It becomes a reality (Caneparo & Cerrato, 2014). Therefore, we should start by completely changing our design culture, first using current technology and then considering how to use it for the next digital wave. Architects should not only be like music producers but focus on developing new construction methods themselves. They should also use digital technology more extensively, learn and accumulate experience in various practices of building construction, and continue to improve and form these results in the application of subsequent projects (Sinclair, 2017).

Pedagogy of Advanced Architecture Design

The revolution of information and computer technology and the accompanying advancement of digital technology have changed the traditional background of architecture as a profession and education (Breen, 2004). Advanced digital technology has provided architects with new capabilities and has begun to replace traditional design techniques. Obviously, various computing tools can achieve efficiency, control and intelligence. These methods are increasingly seen as essential to architectural practice.

In the 21st century, architecture education has witnessed the growth of digital technology involved in design studio courses. These various computer-assisted drawing, enumeration, modeling and analysis techniques have not only become the key teaching nodes of the design studio but have also begun to shape the overall curriculum structure of architectural education. Traditional architectural education tools are mainly based on 2D sketches and physical 3D models. This situation has changed in the 1990s. According to an experiment in architectural education, at least in the last three years of the education program, computer technology has been involved in the education process to replace traditional teaching tools (Angélil, 2003). At present, integrating complete digital teaching has become a major topic for educators and researchers. Their main goal is to use computer applications as design tools and improve students' skills and abilities.

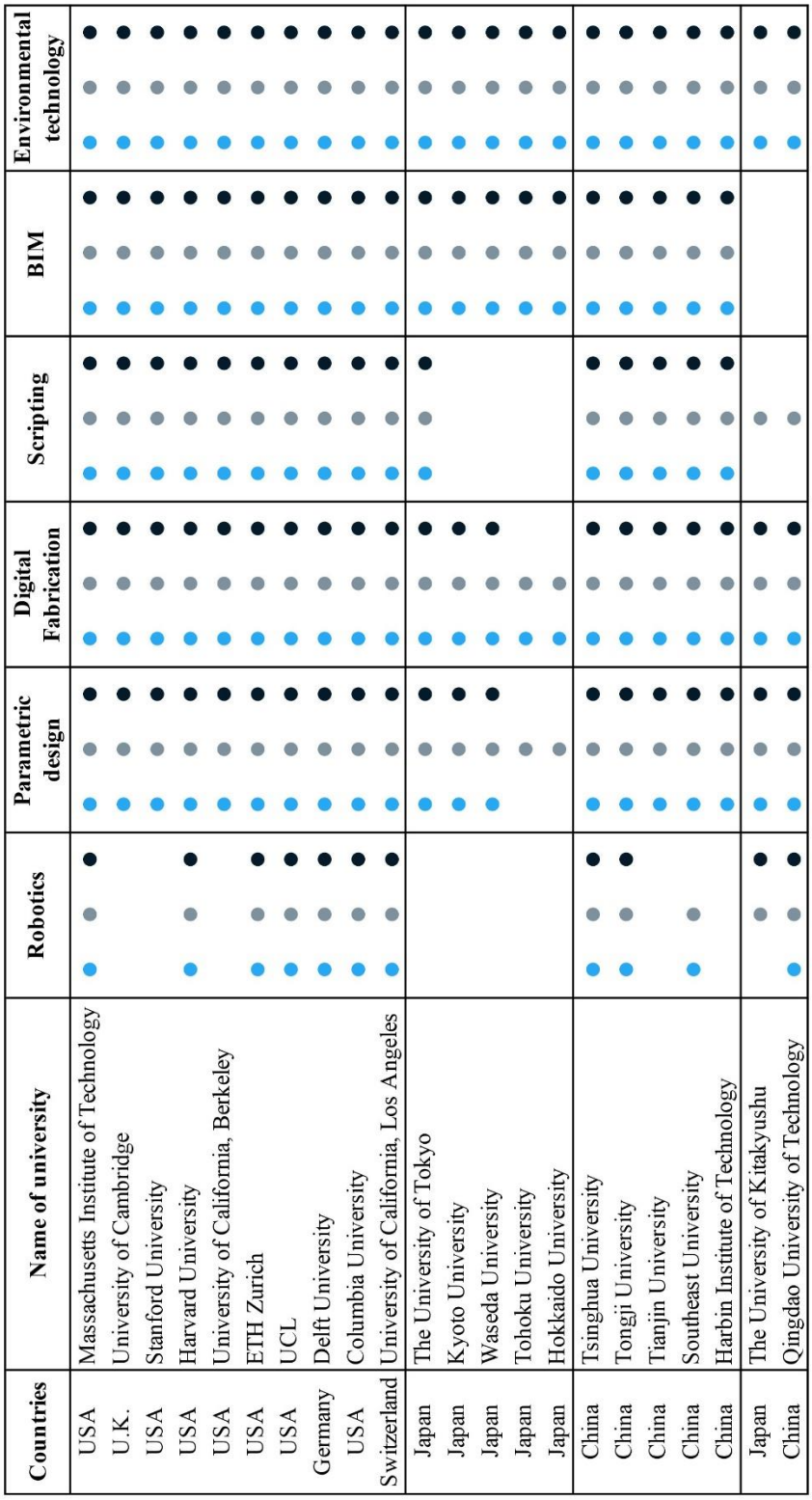
A study by Andia believes that the use of digital technology in architectural

schools is an effective way to modernize architectural practice (Schenk & Education, 2005). She further pointed out that computer applications can have an impact on the skills, education and professionalism of practitioners and students (Andia, 2002). In addition, the combination of traditional design methods and digital technology can effectively expand the possibilities of architectural practice. For example, some architectural schools are using computer applications to enrich students' imagination of architectural design and enhance the actual effect of their works.

Furthermore, architectural schools are becoming laboratories for various digital design media, and the architectural studio itself has become a space to examine the role of various digital tools in architectural design. Students have increasing tendencies toward digital applications and are becoming more skilled and involved in using various design media in their design processes, which, in turn, could eventually change the AEC industry developing trends as future practitioners.

In order to better understand the current situation and future trends in Advanced Architectural Design education, an investment of architectural design courses is made. A sample of top 20 international architectural schools are chosen, in order to state the contemporary architectural education status. The sample is chosen according to Quacquarelli Symonds (QS) World University Ranking by Subject (2020) and Times Higher Education University Ranking (2020). Then it is summarized to the common top 10 schools in both ranking systems. Also, in order to understand Japan and China situations, top 5 schools from both countries are added to the survey list. Finally, the University of Kitakyushu and Qingdao University of Technology which two collaboration schools on this research is included as well.

The matrix (see in Table. 1) is analyzed to investigate the current status of architectural education through examining the intensity of integrated and stand-alone courses, their category as well as their phase of teaching. The concept of Advanced Architectural Design in these top schools is mainly consisted of computer applications, digital fabrication, and performance simulation. The courses are operated in various formats, such as workshops, curriculums, and studios. From the matrix table, we could easily found that top architectural schools are all dived into the swarm of advanced digital technologies applied into AEC sector, they has all kinds of pedagogy methods developed from workshop to curriculum, and majority of them has induced Robotics



Countries	Name of university	Robotics	Parametric design	Digital Fabrication	Scripting	BIM	Environmental technology
USA	Massachusetts Institute of Technology	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
U.K.	University of Cambridge	● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
USA	Stanford University	● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
USA	Harvard University	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
USA	University of California, Berkeley	● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
USA	ETH Zurich	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
USA	UCL	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
Germany	Delft University	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
USA	Columbia University	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
Switzerland	University of California, Los Angeles	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
Japan	The University of Tokyo		● ● ●	● ● ●	● ●	● ● ●	● ● ●
Japan	Kyoto University		● ● ●	● ● ●		● ● ●	● ● ●
Japan	Waseda University		● ● ●	● ● ●		● ● ●	● ● ●
Japan	Tohoku University					● ● ●	● ● ●
Japan	Hokkaido University		● ● ●	● ● ●		● ● ●	● ● ●
China	Tsinghua University	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
China	Tongji University	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
China	Tianjin University		● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
China	Southeast University	● ●	● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
China	Harbin Institute of Technology		● ● ●	● ● ●	● ● ●	● ● ●	● ● ●
Japan	The University of Kitakyushu	● ●	● ● ●	● ● ●			● ● ●
China	Qingdao University of Technology	● ● ●	● ● ●	● ● ●	● ●		● ● ●

Note: ● means the technique / method is involved in the curriculum; ● means there is a working Studio that studies the technology / method; ● means the technique / method is widely used in the workshop.

Table 1 - Matrix investigation of top 10 Architectural Schools worldwide and top 5 Japan and China's Architectural Schools courses status for Advanced Architectural Design.

Technology into their pedagogical system both for teaching and future researching. Japan's top architectural schools shows slow development in the field of scripting and robotics application in architecture, while China's schools are developing fast towards these new emerging technologies.

For the two schools who collaborate on this research, compared with those top schools, although there's no impeccable didactic mechanism focus on Advanced Architectural Design, but have experimented different possibilities to introduce the

emerging concepts and skills to their students, such as using various kinds of workshops to bring intensive collaborations from industry avant-gardes to creative education.

As a response to the current demands of industry and architectural logic, the way buildings are designed, built, and operated needs to change (Bock & Linner, 2015b). The relationship between architects and robotic technology seems to raise challenges that have triggered a cultural shift in architectural pedagogy to encourage adaption to the building industry's demands (Yablonina, Prado, Baharlou, Schwinn, & Menges, 2017). Many institutes and universities have explored advanced robotic automation practices and organized similar research efforts over the past few decades (Leach, 2009). In fact, the top twenty architectural universities in the world have all offered courses or workshops related to robot-based architectural design, encouraging a wide range and highly advanced robotic skills such as digital design, programming, and construction of structural assemblies (Bechthold, 2010). However, only 10% of architectural universities offer relevant courses in China, and half of them do not provide the necessary facilities (Wei-Guo, 2016b). Without proper facilities, though the teaching framework and content of each course are valuable, practical application and project completion cannot yet be explored at a satisfactory level (Wei-Guo, 2016a).

Therefore we have dedicated ourselves to the development of this new pedagogical approach and tested its administration through the completion of various forms of courses in the attempt to explore how robotic tectonics improves architectural education for sustainability (Karslı & Özker, 2014). These pedagogical results represent the complete workflow of robotic tectonics, which can be

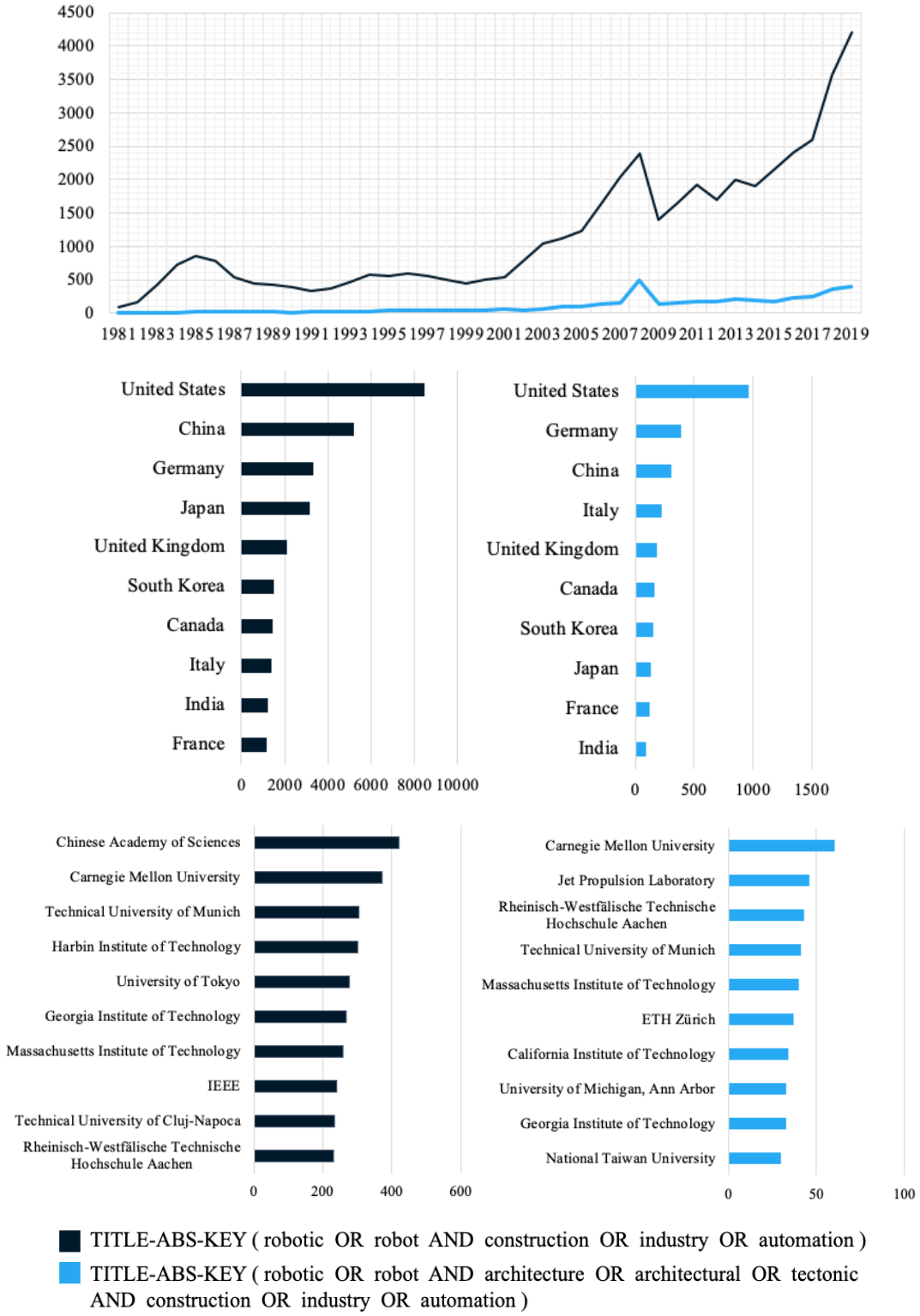


Fig. 6 - Investigation of literature collation on existed researches by using approximate string matching.

summarized as a compendium of four distinct stages ranging from digital design to fabrication. Each stage has its unique contributions to sustainability, while the overall system operates as a paradigm shift in architectural education to maximize its impact on the AEC industry. This workflow proves that using robotic tectonics in education could contribute to the underpinning of sustainable development in architectural practice and nurture innovation in future architects who are going to be closely tied to the building industry for decades to come.

In order to better understand the research progress, the author made an investigation of literature collation on existed researches by using approximate string matching. The extraction of literature data is derived from Elsevier's Scopus which is the largest abstract and citation database of peer-reviewed literature. In Scopus databases, the search conditions were limited to the abstract or title or keywords that limited containing "robotic or robot" and "construction or industry or automation" and limited to the relevant subject areas of "Engineering", "Society", "Environment", "Math", "Materials" and "Arts". Then, the "architecture or architectural or tectonic" was further added as a second limited content to compare and understand the research trends more closely related to this study direction.

To ensure the scientific, objectivity and accuracy of the literature analysis, the search results are deduplicated, and irrelevant entries such as journal conference call for papers, volume headlines, topic research, post-reading, overseas newsletters, news reports, no authors, etc. The retrieval time started from 1981 to 2019 at the earliest. A total of 45,961 articles were searched in the first screening. Of these, only 4116 articles matched the second additional search criteria.

As can be seen from Figure 6, during the research period, although the number of related literature publications has generally shown a growth trend worldwide, it is still in the exploration stage. The research literature before 2000 is scarce, and then after some years of research, some preliminary results were obtained between 2005 and 2008, and the research showed a rapid upward trend. Subsequently, more and more countries began to pay attention to the future development of the robot industry, promulgated various support policies and included the robot industry in the country's important strategic development direction. Then, in the process of the transition from the traditional labor production mode to the intelligent and automated mode, related

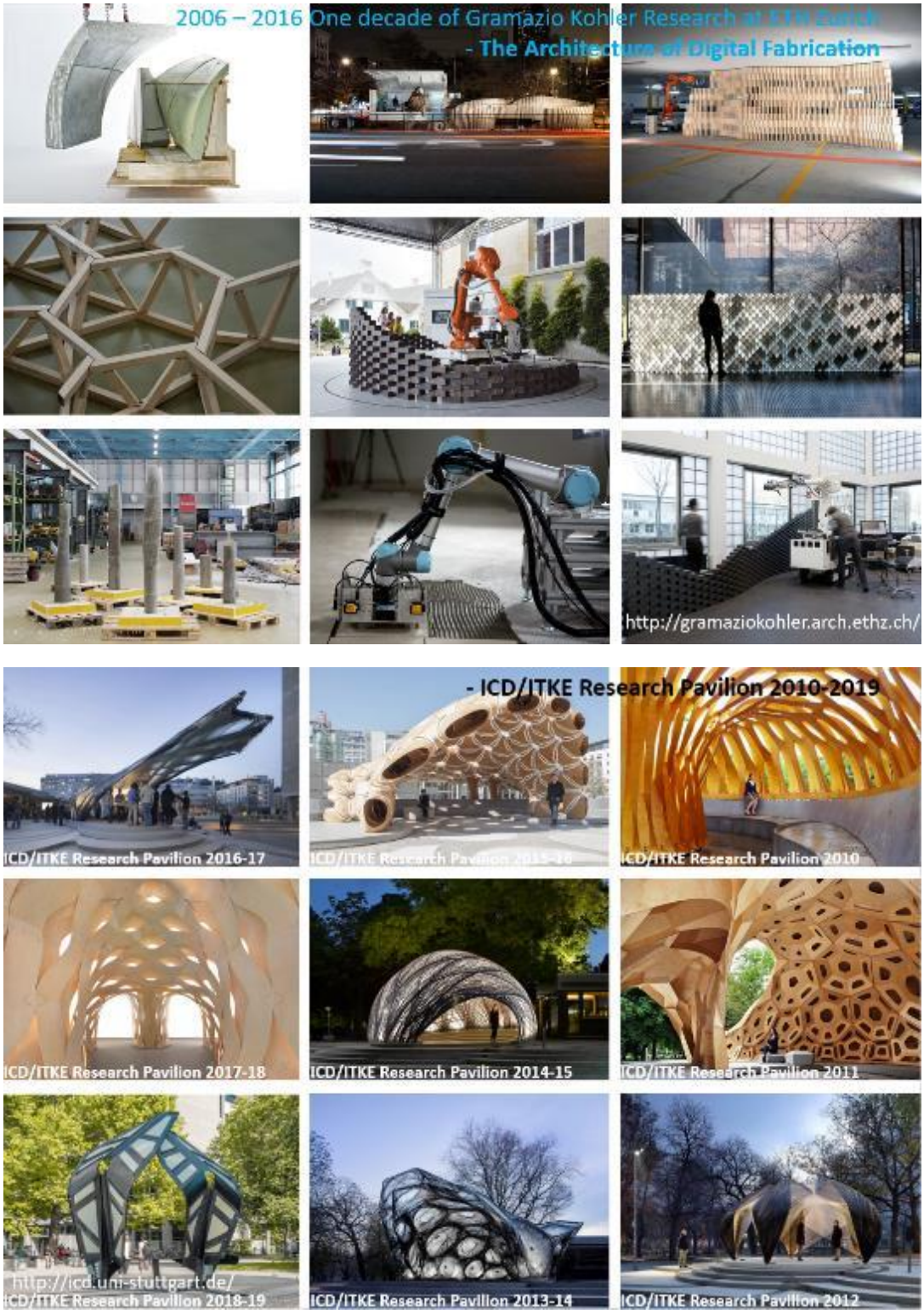


Fig. 7 - Collection of robot-based building projects from Fabio Gramazio and Matthias Kohler of ETH and Achim Menges's work from ICD Stuttgart Design.

(source from official website)

research entered the bottleneck stage of slow development. It was only in recent years that a large number of research results began to emerge again. However, the number of robot research in the sub-field of robotic tectonic has dropped from about 20% to about 12% of the industry-wide category from 2000 to 2019, indicating that the research of robots in the field of construction is still in the preliminary stage, and the research progress is quite slow.

From the point of view of the country to which the literature belongs, most of the top ten countries with more literature in the field of robot construction are developed countries, and the leading ones are the United States, China, Germany, and Japan. Focusing on the sub-field of robotic tectonic, China and Japan have fallen in the ranking. In particular, Japan, which has a leading technological level, dropped to eighth place. Among the relevant research units in this field, almost all the universities appear are among the top schools in the world. Therefore, as an indispensable aspect of the robot construction industry, robotic tectonic is concerned by many developed countries and advanced educational institutions and has a continuous growth research trend. Due to the difficulty of cross-professional co-ordination and the theoretical methods and techniques involving pioneers, it is extremely experienced in the absence of conditions, more arduous exploration and practice are required.

1.2.3. The Robotic Touch on Architectural Design

Fabio Gramazio and Matthias Kohler from ETH published their book *The Robotic Touch: HOW ROBOTS CHANGE ARCHITECTURE* In 2014. For the first time, it provides a comprehensive analysis of the substantive and constructive aspects of robot-based construction projects and proposes the impact of the continuous use of robots on architectural design. Combined with the work of Achim Menges of ICD Stuttgart shown in Figure 7.

Robots play important and multiple roles from architectural design to construction. As the relationship between building materials and data is getting closer, digital information can not only provide information for design and planning, so robots can be used to develop new building materials. Robotic Touch records thirty research projects on construction robots from ETH Zurich, including various methods and

concepts related to the use of robots in construction (Kohler, Gramazio, & Willmann, 2014). So far, the possibility of using robots in construction is still being explored continuously.

Among the existing traditional practitioners, architects are not only the potential victims most likely to be suppressed or criticized, but also the pioneer leaders who are most likely to lead the industry in a better direction. In fact, in the process of continuous learning and practice of receiving creative thinking training, architects have created a large number of new intellectual property rights in design, including new concepts, new inventions and new methods, which have unique value and significance. Their thinking process is generated from a set of unique conditions (culture, economy, nature, information and policies) of a specific built environment. And these conditions have gone through the repeated process of analysis, testing, optimization and updating. Not only can it comprehensively deal with the coordination issues between resources, funds, personnel, and technology, but it can also achieve sustainable interaction between nature and human culture (Shelden, 2020).

Nowadays, in order to avoid risks in the AEC department, most of the project manufacturing data is generated digitally, while the manufacturing and construction process is still traditional methods, that is, through manual methods and conventional materials used a century ago. Fortunately, the AEC department is undergoing a major transformation to provide structural innovation, visually harmonious or striking, and environmentally sustainable modern buildings. The use of robots has evolved from novelty to multiple applications involving new materials, construction methods and digital tools.

According to the US Bureau of Labor Statistics (2), "The employment of masonry workers is expected to increase by 15% from 2014 to 2024, which is much faster than the average growth rate for all occupations." This shows that the robot has been recognized in the construction industry, and one of the common uses is for bricklaying work. Although, this growth largely depends on many factors including the global economy, investment in civilian infrastructure, and new government plans. There are already specialized masonry robots that can map the individual placement of bricks to the three-dimensional layout of the structure being built. With the help of grinding,

cutting and milling functions, each brick can be customized on-site and treated with a construction adhesive to perfectly fit its target location. The use of robots can increase construction speed, consistency and structural integrity, thereby increasing the strength and thermal efficiency of buildings. Some studies have shown that it also helps to release the design potential of this common architectural element: it can create complex structures with spatial arrangements and undulating surfaces, giving new life to the oldest and most widely used buildings.

In fact, there are still many uncertainties in the future of digital manufacturing. Although the use of robot technology has been able to mature the workshop and the prefabrication of parts, it is still unknown whether the construction process can be completed directly on the outdoor construction site. This is because the cost of robotic equipment is currently high, the outdoor environment adaptability is poorer than that of conventional operating equipment, and there are some hidden safety hazards. The main reason for the uncertainty is that the vision of digital manufacturing can only be fully realized through professional reorganization and workflow reset. Realizing this reason, many digital designers dream of building a new world. In this world, there is almost no intermediary between the computer-aided hands and the manufacturing and assembly of the various components of the project. From this perspective, the designer's John Ruskin will be given the role of a craftsman, who has ideal views on the construction of medieval cathedrals (L. Spuybroek, 2016). However, whether this process is sustainable, whether there will be new possibilities, whether there will be new industries and forms of industry cooperation are key issues. Rather than simply letting the architect control the entire process from design to manufacturing (Caneparo & Cerrato, 2014).

However, the use of robots cannot be simply regarded as a shift from manual bricklaying to digital manufacturing. The emergence of new materials compatible with additive manufacturing is an opportunity to change traditional AEC practices. The improved materials are deposited through a flexible robotic manufacturing platform, and a large number of simulations are performed using computational design and machine learning. These will serve as technical support for the new way of digital construction. Some studies have shown that pioneers are already exploring the use of robotics to create new materials, so that regional materials can be reused to achieve

construction site printing. For example, materials such as carbon fiber or glass fiber, bioplastics, laminated wood, etc. can be quickly cured into high-performance concrete with optimized slump, flow characteristics and curing properties. Combined with the research and development of these materials, robot construction technology can be applied to construction activities in specific locations, such as the exploration of new planetary living environments.

Therefore, the challenges and opportunities related to the application of digital architecture and robot construction are extensive and worthy of study. Robot construction technology does not simply replace the problem of slow, labor-intensive traditional technology. They are not only closely related to the tools and materials used, but also the efficiency of the use of robotics far exceeds the traditional methods used in the assembly process and requires greater freedom in parameter design and structure formation. This requires architects to unite materials scientists, engineers and other professionals to carry out in-depth cooperation and innovative activities (Yang, 2017).

1.3. Purpose of this study

1.3.1. Problem framing and research motivation

Although there's some attempt to develop and introduce Robotic Tectonics workflow into architectural design process, but most of times it is merely accepted as a new emerged technique instead of a newly developed design methodology and theory for advanced architectural design, most of architects and students are barely know, interested, or understand its working mechanism and workflows for inspiration of architectural design. Which considered to be the main problem we should focus on in this study.

Frank Gehry has always believed that the work of an architect does not end with the end of the design. In his words: "The client hires us and expects that we are going to be parental through the whole process to make sure that they get the building they want for the price they want to pay. I believe that far too many architects have ceded their responsibility to less interested parties, which results in compromises in design or budget over-runs. I have spent 40 years building my architecture practice to be the Master Builder for my clients and I opened my tech company up to other architects to help them realize the same benefits for their clients."

The process of building buildings has not always served clients or architecture. A design has to go through thousands of hands before it is built. The design intent has to flow through engineers, consultants, project managers and contractors, who are all adding their own information to the documents. Along that path, there are many places where the information can be misinterpreted, misaligned and generally messed up. If the documentation of the design is not well coordinated, it can result in a lot of wasted time and money (Gehry, Lloyd, & Shelden, 2020). Therefore, how to deal with the complex delivery process of rich-information from the origin of design to the finial construction achievement, is a cross-interactive practical problems the architects are facing today.

Besides the practical and technical problems, architectural design is a combination of technology and humanity and culture, how to integrate this new

technic development into architectural theory, so that the architects and designers could accept this Robotic Tectonics concept theoretically and philosophically in order to manipulate flexibly in their own practices. This would be identified as the theoretical problems we are facing in this study.

Furthermore, architectural practices have tightly combined with architectural education, due to the tradition of the master-apprentice system, many practical architects are usually or intended to participate educational activities, such as previous mentioned Fabio Gramazio and Matthias Kohler from ETH, Achim Menges from ICD Stuttgart, or Frank Gehry, Zaha Hadid, Thom Mayne, etc. Usually, in architecture field, the education and practice are mutually reinforcing each other, therefore, how to redefine a didactive approach towards future architectural education would be the finial problems for this study.

1.3.2. Research objective

As a result of the above initial problems, the objectives of the research project are twofold. This study attempts to contribute to the architectural theory and its sustainable development direction of man-machine cooperation and multi-disciplinary interaction, and to identify, exemplify, explore and put forward specific instrumental design methods and patterns under this theoretical standpoint.

At the theoretical level, our goal is to identify and develop the theoretical and methodological framework for such an approach. The expected framework is based on a series of illustrative propositions rather than in the form of guidelines or design principles. The purpose of this is to create an open and predictable theoretical model of adaptability for the existing architectural orientation and its contribution to what is considered to be a structural architectural orientation. This is a response to current trends and related questions.

At the practical level, the goal is to develop and develop a series of specific methods and models to test and demonstrate potential specific methods in order to achieve the goal of robotic tectonics in theory. These experimental models are considered to be both demonstrators and experimental explorers. The purpose of this

paper is not to limit or automate creative and often elusive architectural design processes. Instead, it attempts to support methods and models for the development of environmentally sustainable buildings based on a broad but human-robot oriented approach at the theoretical and application levels.

Objective: Explore Ideal architectural design method based on the concept of robotic tectonics, to support a contemporary architectural tectonic practice.

The goal of this research is to improve the practitioners' ability to create architectural tectonics. Within the scope of the study, the purpose of this research project is to enhance the understanding of how tectonics is practiced in contemporary times. Although it does not attempt to reveal every possible way to carry out tectonics practice, the purpose is to understand the characteristics of tectonics practice, which should reveal what promotes or hinders tectonics practice while combining with current emerging technologies. Here, emphasis is placed on collaboration between architects and engineers in other disciplines, as well as new technical tools. In addition, the goal of the study is to understand the relationship between practitioners and available technical tools, thus clarifying the extent to which digitization has potential for tectonics practice, as argued in the writings of digital tectonics.

This understanding should be used as a model for discussing the practice of tectonics in contemporary practice. Similarly, this understanding should be used as a strategy for creating tectonics in a contemporary context, by recognizing what promotes or hinders structural practice, and therefore hopes that participants who are involved in architecture and are interested in creative tectonics will be able to apply the lessons learned to their own practice. Finally, when the goal is to support construction practices by developing design tools, the resulting knowledge should also be able to be used in program development.

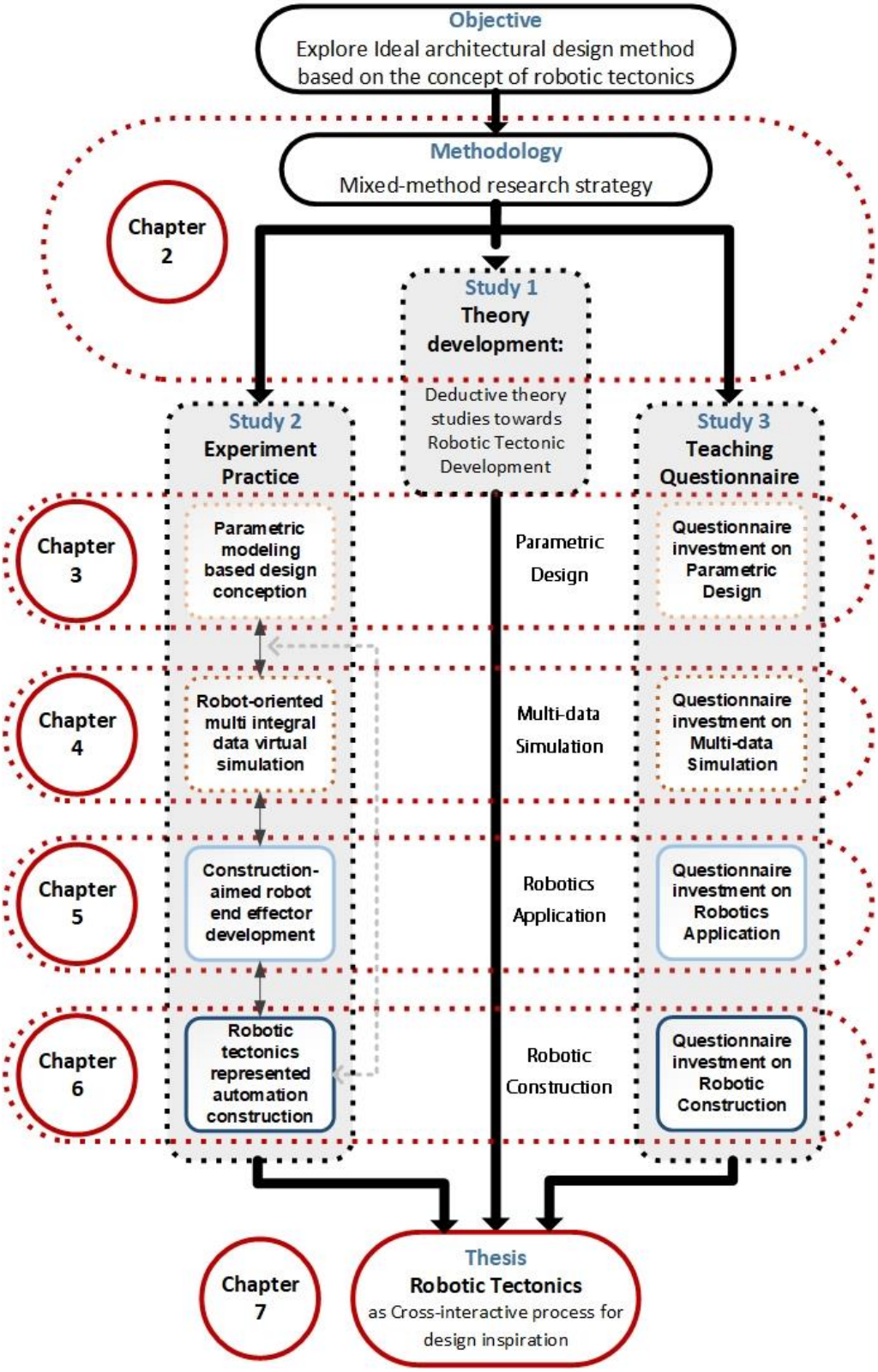


Fig. 8 - Research framework of this study.

1.3.3. Framework of research

With the research objective, it is possible to formulate the research question that is operational as well as a number of auxiliary questions that can shed light on the various aspects of the research question.

What principle and mechanism of introducing robotics technology for programing, computing, visualization, simulation and automation application that enables an advanced creative architectural tectonic practice?

Auxiliary questions:

Theoretical background - How can tectonic thinking be applied as a critical lens to guide architectural design in contemporary society?

- What is the concept of tectonics?
- How is the concept of tectonics in the digital era understood?
- How can the introduction of robotics application for programing, computing, visualization, simulation, rationalization and automation application enhance the understanding of the concept of tectonics and influence the practice of tectonics?

The tectonic practice - How can tectonic thinking be applied as a practice to conduct design process with advanced technology?

- What characterizes a tectonic practice?
- What enables and obstructs a tectonic practice?
- How did the individual actors involved in the integrated process, cooperation between operation and inspiration, and the design tools used enable or obstruct a tectonic practice?

Pedagogical tectonic dissemination - How can tectonic thinking be applied as didactical means to disseminate a critical understanding of advanced architectural design?

- What mechanism enables and obstructs a tectonic pedagogy?
- What degree is tectonic thinking influences architectural design pedagogy?
- How can the introduction of advanced technology for tectonic practice enhance the understanding of tectonic thinking and disseminate as a didactic workflow?

Based on above research questions, and the mixed methodology strategy, the research framework of this study is planned as follow (see figure 8):

The first part is consisted by chapter 1 and 2, described the research background and purpose of the study, by introducing the AEC industry conditions, current development of advanced technologies, the introduce of robotics technology, and its influences for integrated design-build process and architectural design method, framing research question and objective, choosing research methodology and propose thesis hypothesis.

The second part is theory development of tectonic thinking, form the initial ideas of tectonic concept, to the concept of digital tectonics, and finally the emerging of robotic tectonics. The deductive theory studies towards the concept of Robotic Tectonics is developed, then it is tested and applied to the pedagogical approach for the future sustainable architectural education.

The third part is the combination of the inductive practice experiments, introducing the mechanism of the four stages of Robotic Tectonics workflow, and how each stage applied to influence architectural design method. 8 workshop teaching experiments and practices are demonstrated in this part.

The fourth part is questionnaires survey analysis for the pedagogy efforts, 135 students who participated the curriculum of digital construction methods are volunteer to sharing their feedbacks for this pedagogical questionnaire survey. A comparison between before and after class for the understanding of the topic is analyzed, and specific analysis for each 4 pedagogical stage is unfolded.

The finial part is conclusions, summarized the above studies from theory,

practice, and pedagogy approaches, three study paths, drawn the comprehensive image of the concept of Robotic Tectonics, and the imagination of the future developments.

Chapter 2. Methodology and Theoretical approach on Robotic Tectonics for advanced architecture integrated design-build process

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2.1. Introduction

This chapter intends to clarify for the approach to research taken within the thesis by elaborating on an architectural research methodology that is based on the objective of the thesis.

Through three fields study of Deductive theory studies, Inductive design experiments, and Quantitative analysis on teaching feedbacks, a mixed-method of research strategy is applied in this thesis. By doing so, a clear research response towards the hypothesis of Robotic Tectonics as Cross-interactive workflow for design inspiration is developed step by step. The three fields of research questions are unfolded in parallel to the theme of the study, which is evolving around how we think and understand architecture practice, it ought to be relevant to several aspects of the profession.

Following this methodology, the first study area of deductive theory studies is unfolded in the ensuing paragraph. By reviewing the historical development for the concept of Tectonic, through study of Carl Bötticher, Gottfried Semper, Kenneth Frampton, Neil Leach and other architectural theorist's works, a clear roadmap of tectonic concept development is drawn out. Combined with the advanced technology application and construction automation developing trends, a new dynamic understanding for the concept of Tectonic is revealed, Robotic Tectonics as a Cross-interactive workflow for design inspiration is deductively defined.

2.2. Methodology

To investigate this research question, the research methodology is designed. The word method has its origins in Greek and means to choose a path. In the following, this chosen path is discussed and described.

2.2.1. Mixed-method research strategy

The research problems in these three fields are carried out in parallel. Since the theme of this study revolves around how we think and understand architectural practice and education, the theme should be related to several aspects of the major. This is the basis of the tripartite approach to the subject, and this structure promotes contact with the three kinds of thinking. The first question to guide deductive thinking: how can constructive thinking keep pace with the times and constantly inspire practice? The second question points to an application mindset: how do you apply it at creation time? The third is similar to the spread of educational meta-thinking: how to obtain recognition and corresponding thinking?

Following this principle, this study adopts three different research methods after three sub-problems. Therefore, this research has embarked on a research path that is not limited to the use of quantitative or qualitative data, which is the characteristic of the mixed-method research strategy (Creswell & Clark, 2017). The purpose of the mixed research approach is to establish a more subtle understanding of the subject and to increase the breadth of the survey. The aim is not to build knowledge that is always applicable, but to explore a topic from a different perspective, which will appear one-sided and lack nuances if dealt with in only one way. Hybrid approach strategies are thought to balance weaknesses because these methods will complement each other.

This research includes three studies related to three sub-research problems: theoretical research, designed experiment and teaching. The structure of the methodology follows an inductive hybrid approach, as shown in the illustration on the left. At the conceptual level, the research design follows Charles Sanders Peirce''s description of reasoning in scientific methodology: “Its reasoning should not form a

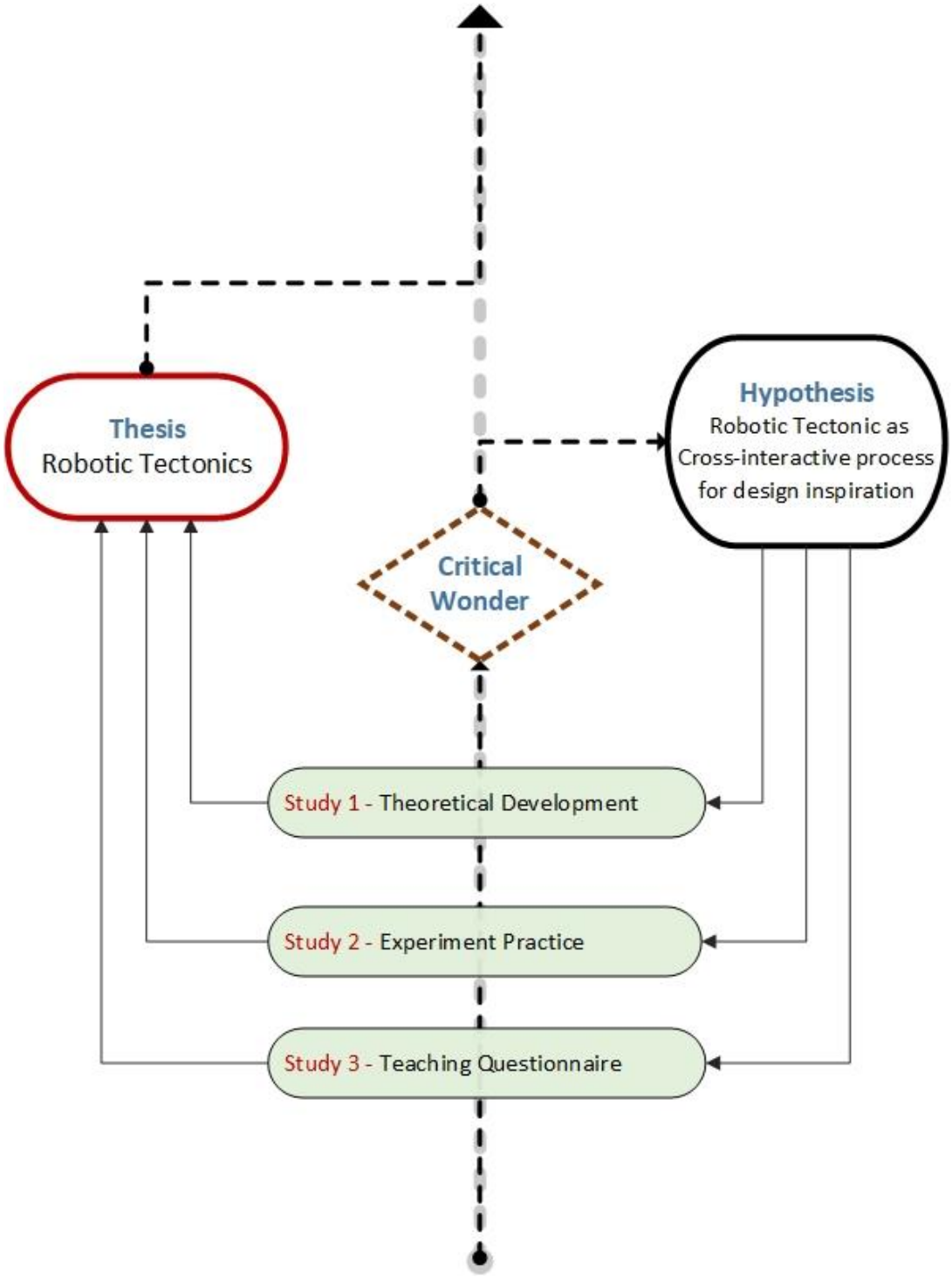

Fig. 9 - Model of the abductive mixed-method research strategy applied in the study.

chain which is no stronger than its weakest link, but a cable whose fibers may be ever so slender, provided they are sufficiently numerous and intimately connected" (Peirce, 1868). In this way, this study intends to think about the development of building automation in three levels: acceptance, application, and dissemination.

The project started from a critical wonder of the robotic represented advanced technology emerging within the architectural design workflow and the week relationship between them. This established a hypothesis for qualifying these relationships, a lens, or an attitude to the robotics application developed from the theories of tectonics called Robotic Tectonics. This hypothesis includes a theoretical development and is ongoing through the whole study. The subject of Robotic Tectonics is then approached through three studies in parallel, exploring an analytical deduction, to acceptance, a design experimental to apply and a teaching approach to disseminate the hypothesis. Repeatedly during the process, the attention is returned to the wonder, questioning whether the state of the argument provides new and satisfactory insights (fig. 9). Consequently, the three studies are interlinked and the course in one study will influence and inspire the progression of the two others resulting in the concluding argument becoming a synthesis of the whole study.

Epistemology in the research strategy of abductive mixed method

Considering the research strategies of three kinds of thinking and mixed methods embedded in the research problem, no single epistemology can span the whole research. Therefore, the study seems to fall somewhere between the three epistemological traditions, so an important part of the project is to determine how to combine them to improve the credibility of the research. Each epistemological tradition exists in all parts of the study, but the intensity is different. The rough distinction is that study 1 (theoretical research) tends to philosophical hermeneutics, study 2 (designed experiments) tends to pragmatism, and study 3 (teaching questionnaire) tends to empirical analysis. Having said that, because the three sub-studies are related to each other on topics, develop in parallel, and based on each other's knowledge, it is not enough to strictly divide the three epistemology, just like general research, and it will not provide enough framework for understanding this research.

2.2.2. Questionnaire design and its analysis

To explore the students' perceptions of the proposed pedagogical approach of robotic tectonics and obtain their feedback on teaching effectiveness. This study conducted a questionnaire survey of 135 students in the third grade of architecture major who participated in my course of robotic tectonic. The survey was undertaken using an on-line, self-administered questionnaire, comprising a range of closed and open-ended questions. The survey achieved even representation of males (n = 14) and females (n = 13). Of the 135 survey respondents, the ratio of males (n = 80, accounting for 59.26%) and females (n = 55, accounting for 40.74%) almost reached 3: 2, which is similar to the current gender ratio of architecture major in universities.

The response period of the questionnaire is divided into two stages, including before and after attending the course. From the questions before the course selection, we learned about the students' existing relevant knowledge and skill experience, as well as the initial attitude towards robotic tectonic. Among them, the responses of questions about existing experience are divided into four options (including never touched / heard of but never tried to use / understand and occasionally try to use / fully understand and master) and the numbers "1 to 4" are used as corresponding value labels for data analysis. (Fig.10 & Table 2) The results show that most of the students heard but never tried (49.6%) to use or occasionally use (41.5%) the knowledge and skills about parametric design (mean=2.47, Std.D =0.656). The majority of students over 80% never touched or heard of but never tried to use robotic simulation skills (mean=1.97, Std.D=0.680), applied tools (mean=1.64, Std.D=0.676), or any practice of robotic construction (mean=1.81, Std.D=0.768). Moreover, the result of Cronbach's alpha test is 0.821, reflecting the strong internal consistency of this series of questions, which means that students have little difference in cognitive level and technical ability before attending the course. Thus, excluding the basis influencing factors of inconsistent ability, so the questionnaire feedback information from selected students after participating in this course has more reference value.

In this study, the interaction relationships between some key points in the data of the questionnaire are also explored, so as to targeted optimize the teaching methods and practice process from the perspective of students.

In the questionnaire question setting, the same matrix questions are set for each stage, and the performance is quantified within the range of suitable options. There are two series of questions organized into 6 subscales were answered after participating in each stage dedicated to workflow feedback and content understanding of the concept "tectonic" in three aspects of advanced architectural design.

Questions related with workflow mechanism:

Q1. The degree of participation in each stage

Q2. The difficulty degree of each stage to the overall workflow

Q3. The importance of each stage to the overall workflow

Questions related with tectonic understanding

Q4. The degree of understanding “Tectonics lays in the interaction between material and construction”

Q5. The degree of understanding “Tectonics means clear and logic structure”

Q6. The degree of understanding “Tectonics represents performative architecture”

In the quantitative analysis process, effective statistical analysis methods were used, including Pearson correlation coefficient and linear regression analysis method.

Cronbach’s alpha

Cronbach’s alpha developed by Lee Cronbach in 1951. It is a convenient test used to estimate the reliability, or internal consistency, of a composite score. Theoretically, Cronbach’s alpha results are between 0 and 1.0. The general rule of thumb is that a Cronbach’s alpha of 0.7 and above is good, 0.8 and above is better, and 0.9 and above is best. The formula is as follows:

$$\alpha = \frac{n}{n-1}\left(1 - \frac{\sum_{i=1}^{n} {S_i}^2}{S^2}\right); \quad S^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})}{n}$$

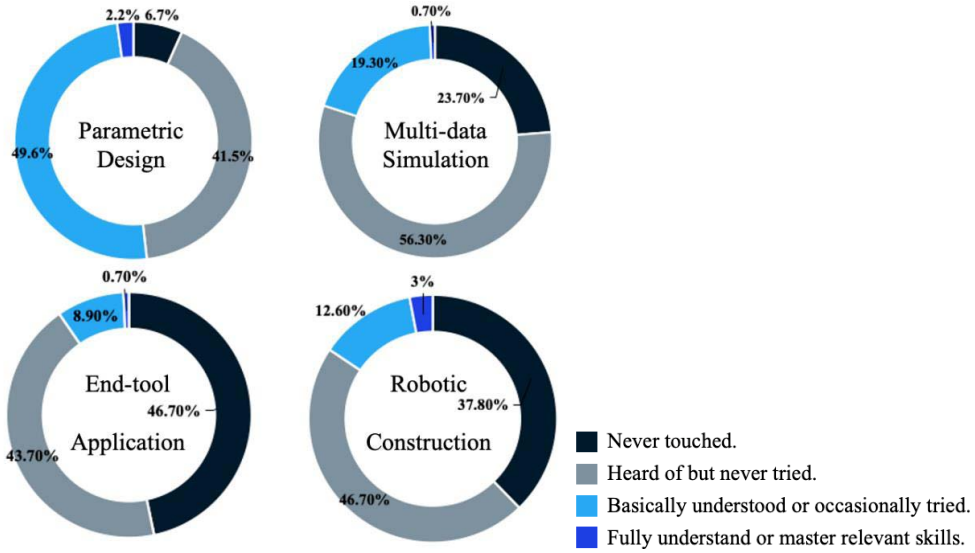

Fig. 10 Students' existing knowledge and skill experience analysis before attending the course*Table The empirical results of the number and proportion of students*

Items of choices	Parametic Design	Multi-data Simulation	End-tool Application	Robotic Construction
Never touched	9 (6.7%)	32 (23.7%)	63 (46.7%)	51(37.8%)
Heard of but never tried	56 (41.5%)	76 (56.3%)	59 (43.7%)	63 (46.7%)
Basically understood or occasionally tried	67 49.6%)	26 (19.3%)	12 (8.9%)	17 (12.6%)
Fully understand or master relevant skills	3 (2.2%)	1 (0.7%)	1 (0.7%)	4 (3.0%)

Items of experience before atending the	Mean	Standard deviation	Number of participants	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Parametic Design	2.47	0.656	135	0.503	0.833
Multi-data Simulation	1.97	0.680	135	0.761	0.719
End-tool Application	1.64	0.676	135	0.646	0.773
Robotic construction	1.81	0.768	135	0.677	0.759

Summary of internal consistency	Grand mean	Number of options	F-test	Significance level	Cronbach's alpha
	1.97	4	77.874	0.000	0.821

Table 2 *The internal consistency assessment by Cronbach's method(Notes: (1) Value label: 1= "Never touched"; 2= "Heard of but never tried"; 3= "Basically understood or occasionally tried"; 4="Fully understand or master relevant skills". (2) In Cronbach's alpha tests, a score of more than 0.7 is usually acceptable.)*

where:

N = the number of test samples S_i^2= the i^{th} sample variance. S^2 = the total variance. x_i= value of i^{th} sample. $\bar{x}$= the mean value of samples.

Pearson correlation coefficient

Pearson correlation coefficient method is widely used in the sciences, which is measures linear correlation relationship between two variables (X or Y) based on the covariance. It gives information about the magnitude of the association, or correlation, as well as the direction of the relationship through a calculated value expressed between -1.0 and 1.0. Generally, a coefficient value is near ± 1.0 or over ± 0.9 said to be a perfect correlation, lies between ± 0.5 and ± 0.9 said to be a strong correlation, followed by medium correlation (± 0.3 to ± 0.49), small correlation (below ± 0.29) and no correlation when the value is zero. The formula is as follows:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \cdot \sigma_Y} = \frac{E(X-\bar{X})(Y-\bar{Y})}{\sigma_X \cdot \sigma_Y}$$

where:

$cov(X,Y)$ = the covariance of X and Y. σ_X/σ_Y= the standard deviation of X or Y. $\bar{X}/\bar{Y}$ = the mean value of X or Y.

Then, Data were determined by the one-way analysis of variance (ANOVA), as well as obtained the results of the T-test and F-text to make sure all models are good at explaining patterns in data. In statistical analysis, the frequency description is used to clearly display the frequency or count of the occurrences of values within a particular group or interval by listing primary statistical parameters including mean, median, mode, standard deviation, variance, range, minimum, maximum and numbers of samples.

The present descriptive-analytic and quantitative research were conducted based on the information collected through questionnaires and from existing quantitative records. The collected data were analyzed by SPSS. The sample size of 135 people was computed by using the Cochran formula.

Three questions about the attitude answering with four levels were also asked after attending the course, and the results were comparative analyzed as intuitive feedback on the course effect.

The present descriptive-analytic and quantitative research were conducted based on the information collected through questionnaires and from existing quantitative records. The collected data of questionnaires were processed and analyzed by SPSS (version 26, IBM, Armonk, NY, USA) and Excel (Microsoft 365).

2.2.3. Hypothesis of Robotic Tectonic as Cross-interactive workflow for design inspiration

The research on design thinking about the definition, mechanism and process of design creativity is still a mystery, but it is the central interest in the field of design cognition and computing theory. Many studies try to understand the cognitive process behind the creative behavior of human designers, so they discuss the ability of computer imitation and enhancing the creativity of designers. Recently, we have begun to realize that changing existing and stereotyped choices is the key to the pursuit of creativity (Hofstadter, 1986). On the one hand, strategies for changing from different angles include various ways to expand knowledge boundaries. (Gero, 1996; Sosa & Gero, 2004), identify new problems instead of solving existing ones (M. Csikszentmihalyi, 1988; Simon, 1988), produce something that we didn't think of at the beginning of the project, and as we go through the process from novice to expert to creator, we work in different ways (Gardner, 1988; Y. J. D. S. Liu, 2000). On the other hand, creativity also belongs to the relationship between the personal level and the social and cultural level of thinking (M. J. H. Csikszentmihalyi, New York, 1997). Therefore, in addition to individual creativity, knowing how to make changes in the field of knowledge at social and cultural boundaries is another important direction to address creativity. (Y.-T. Liu & Lim, 2006).

In the period of extensive social changes such as industrialization, postwar, digitization and the recent environmental crisis, the attention to structural theory seems to have regained momentum. According to Marie Frier Hvejsel this say

something about the essence of tectonic theory: "*…throughout architectural history, tectonic theory has revolved around the question of outlining the meaningful development of architecture in relation to its physical, technological, and societal context, necessarily also addressing the more general - yet very delicate - question of architectural quality*" (Hvejsel, 2018). Is tectonics a means by which architects and scholars try to promote the architectural culture of their time and find meaning in the contemporary building industry and society?

Within this theoretical development it is the intention to unfold a tectonic thinking with the emerging technology application trends in architectural design practice. However, a success technology innovation is based on the widespread acceptance, where education plays an important role, but in the current architectural education, there is barely no professional courses focused on this. The need to find a framework to integrate the robotic tectonics workflow with architectural curriculum is increasing. Therefore, it became mandatory to integrating and testing of the complete robotic tectonics' workflow into architectural curriculum. While advanced digital technologies of programing, computing, simulation, automated construction and robotics technology introduced into architectural design process, an interdisciplinary interactive need is rising, asking architects to have cross disciplinary knowledge to over control the entire design to build workflow. But simultaneously revealing the potential of bring cross-interactive into the design workflow that offering creative inspirations to architectural practices.

2.3. Theory development towards Robotic Tectonic

To understand the impact of emerging technologies on structural tradition, it is necessary to understand the meaning of the concept of tectonics. Therefore, the purpose of this part is to analyze the tectonics concepts in historical and traditional works before robotics influenced the term. In the following paragraphs, we will take this understanding as the background to analyze today's understanding of the concept of tectonics.

The term of 'tectonic' is closely connected to the professional title of the architect because the word architect is a contraction of *archi* and *tekton*, *archi* meaning master and the Greek *tekton* meaning carpenter or builder. The Greek *tikto* refers to produce and describes a simultaneous existence of art and technology. The term tectonic thus refers to objects without distinguishing between the fields of art and technology, and to the process of creating these objects.

The term tectonics is rooted in the Greek conception of the creation of artisan objects, and it was only later used in the field of architecture. Carl Bötticher and Gottfried Samper were the first people in modern architectural history to use tectonics as a term. Their writings on tectonics are very influential, in part because most architectural publications prior to Bötticher and Semper were manuals for creating styles and architectural orders. Bötticher introduced the difference between the core form of structure and the form of decorative art. (Boetticher, 1844). With these concepts, he defined tectonics in architecture as the meaningful relationship between the core form of architecture and the art form, thus calling on the facade of the building to clearly express the structural principles rather than being regarded as a separate concern.

Samper is aptly called the father of modern tectonics. He based his understanding of architecture on the study of the tradition of primitive architecture, and concluded that knot is the beginning of the fence, and the weaving of the tent fence is the beginning of architecture. This understanding contrasts sharply with Laugill's view that the original cabin is an imitation of nature. Instead, Semper introduced four elements of architecture; earthwork, hearth, roof and enclosure

(Semper, 1989), and he believes that these elements are derived from their materials and that each element has its own technology. Human beings are eager to create patterns and pictures to regulate their world, which is the main reason behind architecture, but the structural relationship between materials, functions and technology affects expression.

In the era of modernism, works on tectonics have been criticized. Alois Riegl as the architectural theorist, believes that tectonics understands architectural expression as determined by materials, thus neglecting human beings-- this is a misinterpretation of Semper's intention (Mallgrave, 1996). In spite of this, some writers are still interested in tectonics. Edward Sekler distinguishes the concepts of structure, architecture and construction. According to Sekler, structure and construction are part of the field of engineers. On the contrary, tectonics is the field of architects, which focuses on expressing structure and construction through details and joints (Sekler, 1964). This decorative understanding of tectonics must be said to be a greatly simplified version of the concept of tectonics described by Semper and Bötticher. Carlos Vallhonrat believes that great architectural works can be seen as conscious expressions of structure and architecture, while others simply copy the former. For example, Louis Strauss-Kahn's double arches (holes) are architectural responses to buildings in earthquake areas, but are often copied to areas where there are no earthquakes (Vallhonrat, 1988, 2000).

Kenneth Frampton (Kenneth Frampton) is the most influential writer on the topic of tectonics in modern times, his interest in tectonics began with his attention to the modernist tabula rasa method. He used Semper’s concept of tectonics as the starting point for critical evaluation of modernist architecture that ignores context (K. Frampton, 1982, 1990). Later, he described the sporadic continuation of the tectonic tradition and defined tectonics as the poetics of construction (K. Frampton et al., 1995).

The purpose of study the development of concepts of tectonic here is not to choose one definition or understanding of the construct, but not to choose another. Instead, the aim is to expand this concept by identifying many methods that are structural concepts, so that the impact of emerging technologies on each method can be discussed.

Fig. 11 - Botticher was the first to address the role of tectonics in architecture believing that there were two main elements: the nuclear inner structure and the outer cladding.
(Photo of Galleria Vittorio Emanuele in 1890, Source: https://pin.it/2JLl2MX)

2.3.1. The evolution of Tectonics in Architecture

Within tectonics, there are great diversity in the understanding of this concept. This different approach is particularly evident when examining the historical works on tectonics of the two founders of tectonics, Bötticher and Samper, who are the founders of the architectural movement. Bötticher shows a structural understanding of the concept, while Semper focuses on the material aspects of the concept.

Carl Bötticher – tectonics is a relationship between expression and building principles

In the 1840s, the tectonic movement was undergoing a reflection on the continuous development of "absolute" knowledge of philosophy and science from the blind struggle of primitive people for survival to religion as an intermediate stage. They tried hard to interpret art and architecture as meaningful activities. Therefore, it is considered as a trend of thought against the Enlightenment. Carl Bötticher (1806-1889) published a series of works on tectonic from 1840 to 1852, sparking a new round of discussion. In his works, his main idea is to actively interfere with the natural and human order. In this process, architecture is no longer considered a finite world, but becomes a dynamic infinite world. Architects should start from balancing the interaction between society and nature, rather than conceiving an architectural form in advance. This means that the concept of tectonic cannot be limited to the tectonic itself (Hale, 2000), it has its own internal logic and knowledge base requirements such as function, structure, etc.

Bötticher's viewpoint inherited and deepened the historical construction theory put forward by his teacher Schinkel. While satisfying the function, we should further consider how to make the architecture a work of artistic value. He pointed out that the technique of artistic symbolism should be applied and believed that the decoration of ancient Greece is a good reference. Just like the Greeks, architects should develop a contemporary architectural expression that reflects a given material and technological environment. Therefore, based on his imagination of aesthetics in the late 18th century, he used composition and art forms to shape it. Not only that, Bötticher is also very interested in the role of decorations. By carefully studying the

decoration of the two architectural styles, Greek and Gothic, he discovered that the art form-also known as Hülle, because it conceals the structure-is closely connected to the core form. This is the mysterious power that sublimates this art form into a cultural carrier. Therefore, it is more than just surface decoration. To illustrate the relationship between art form and core form, Bötticher systematically demonstrated how to symbolically embody the complex mechanical nature of Greek temples in decoration.

Bötticher also thought that the structure should connected with decoration, ontology and performance, which is an innovative way of thinking for tectonic theory. He wrote that "all the decorative features in structural components are perceptible proofs of their own function, appearance development, transition, theory and connection." Art is the basis for connecting them into an organic whole. In Bötticher's construction theory, the cast-iron structure is also discussed in detail, “For instance, Bötticher interpreted the Doric cyma, a double-curvature molding that is applied at transitional points in the paradigm of a temple, as a symbol for load and support, a seam within the structure signifying the notions of upright-standing and free-finishing. The curvature of the molding varied, depending on the intensity of the load that was thus symbolically expressed.” (Mallgrave, 1996) That is considered to "lay an important foundation for a complete artistic and industrial theme."

At the same time, Bötticher did provide detailed advices to contemporary architects on how to create structures in practice: (1) The social needs of functions should determine the horizontal size of the building-the scope of the plan. (2) Determine the specifications of the vertical support and roof profile, and the type and material of the roof depend on the climate, material availability and social needs. (3) The relationship between roof and support and the resulting closure, void, light and shadow, material and color combination constitute the characteristics of the architectural space (Schwarzer, 1993). When all parts (structural as well as decorative) of the building are bound together like this, Bötticher calls the architecture tectonic – and thus rejects the idea of applying a decorative façade to a building with another principle. Although those suggestions for construction practice are more or less unreasonable, he should not ignore his important contribution to the main idea of how to use structural principles to create architectural expressions. Because what

he wants to express is the importance of an attitude to understand construction practice from a more open perspective, rather than just give detailed instructions on how to carry out construction practice using tectonics.

Gottfried Semper – tectonics is how different materials provide different expressions

Since 1860, the German theorist Gottfried Semper (1803-1879) also devoted himself to redefining "Tectonics". Inspired by Bötticher, Semper shifted from “quasi-materialism to a symbolic interpretation of art forms” (Mallgrave, 1996). He has developed his understanding of decoration in the broadest style of work in the fields of technology, construction art and practical aesthetics. He boldly assumed that the origin of architecture did not lie in the pillars and lintels in Greece, or even the need to add a roof to the pillars and lintels. He believes that tectonics begins with the production of cloth and clothing. Starting from weaving baskets, primitive humans learned how to weave branches into walls and then plug the gaps with dirt. From pottery, they learned how to make tiles and bricks. Therefore, the origin of architecture is not so much related to mythology and archeology as it is related to anthropology. This is a thorough reflection on the origin of architecture, which aroused extensive discussion at the time.

Semper‘s concept is different from Carl Bötticher in that Gottfried Semper believes that building materials need to be taken into account in architectural expression. In the "Style in the Technical and Tectonic" (English version, published in 2004), he emphasized the "principle of surface decoration". He believed that the epidermis is the most direct delimiter of space and will obscure the internal structure. Therefore, the essence of the building lies in the skin material covering the surface, rather than the internal supporting structure. Moreover, he further proposed that the contemporary skin is an extension of the cladding. Whether it is cladding or skin, they are not only a bunch of materials and different colors, their construction method is also one of the elements that can convey the architect's design concept. Semper advocated learning from the ancients and using classical and traditional color decorations. (Gottfried, 1860)

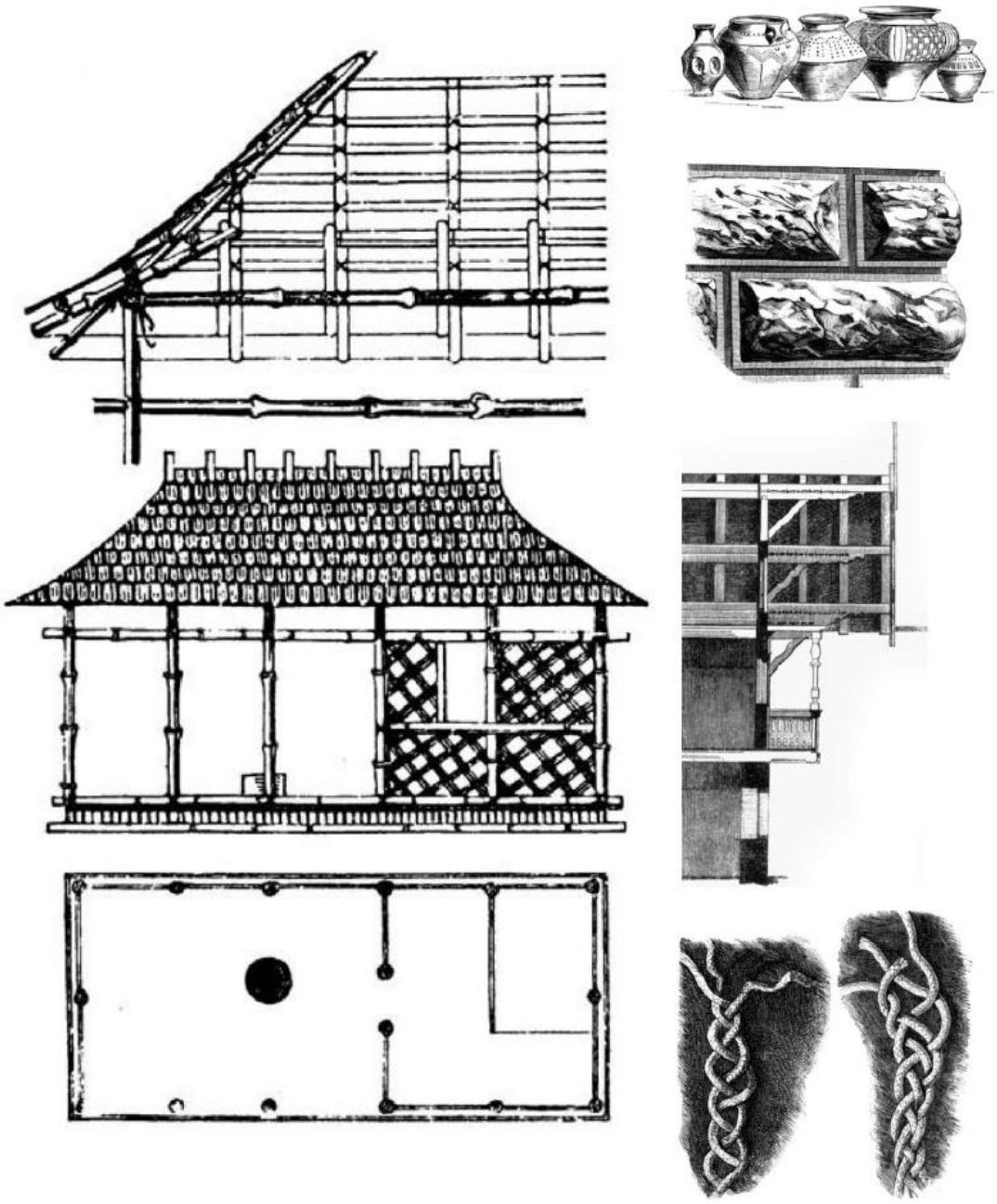

Fig. 12 - Gottfried Semper was inspired by the Carribian Hut that with its light frame construction contrasted the heavy stone or brick building that surrounded him in Europe.

Gottfried Semper understood architecture as consisting of four elements connected to the four primary artisan traditions. Ceramics was used for the hearth, masonry was used for heavy stereotomic bases and loadbearing walls, carpentry was used for roofs and the tectonic frame, textiles were used for the enclosure and lightweight room dividers. (Image source: https://pin.it/3JcSo0x)

In the book of "The Four Elements of Architecture" (English version, published in 1989), Semper further developed his thoughts on these four elements. He believes that the roof should not only be understood as a roof, but also as an element made of a frame composed of many rigid (wooden) parts. These elements are easy to understand from the Carribean Cabin (see Fig. 12). Here, not only the roof but also the walls of the cottage are made of wooden elements (roof elements). The hearth was treated as a circular figure in the plan, while the mound was reduced to a minimum and kept only as a stone carrying the wooden pillars-the wall was not a woven motive, but a woven textile surface. For Semper, these four elements are not important. The two most important elements are the hearth (the moral element of architecture) and the enclosure structure of woven textiles. In contrast, load-bearing structures and mounds are only secondary elements and are used to support the main elements of the architecture. (Gottfried, 1989)

Here, decoration is seen as a way to impose commands on architectural objects to create an orderly microcosm. He retains the four elements of architecture and its connection with the craftsman tradition but is now able to incorporate human desires for decoration into the understanding of architectural expressions. In this way, the new technology of industrial production creates new possibilities for decoration, but it cannot be regarded as the only effect on the expression, just as the use of an axe itself cannot explain the expression of the original cabin. Therefore, Semper believes that the main reason for creating handicraft traditions and expanding architectural expressions is to symbolically create order and meaning in a chaotic world. The pragmatic reason for the construction was the need for a safety fence that is not affected by the climate, but in Semper’s view, if you don’t consider the technical and symbolic meaning of the building at the same time, you cannot understand the building.

In addition, Gottfried Semper's pursuit of style is broader. He conducted a comprehensive analysis of the prerequisites of the style, in order to better understand what developed the architectural style as a whole, and not only consider the peaks in the architectural history. This led him to conduct anthropological research, in which he studied the architectural culture of primitive culture to understand the causes of various styles. He believes that style should be governed by historical function, cultural

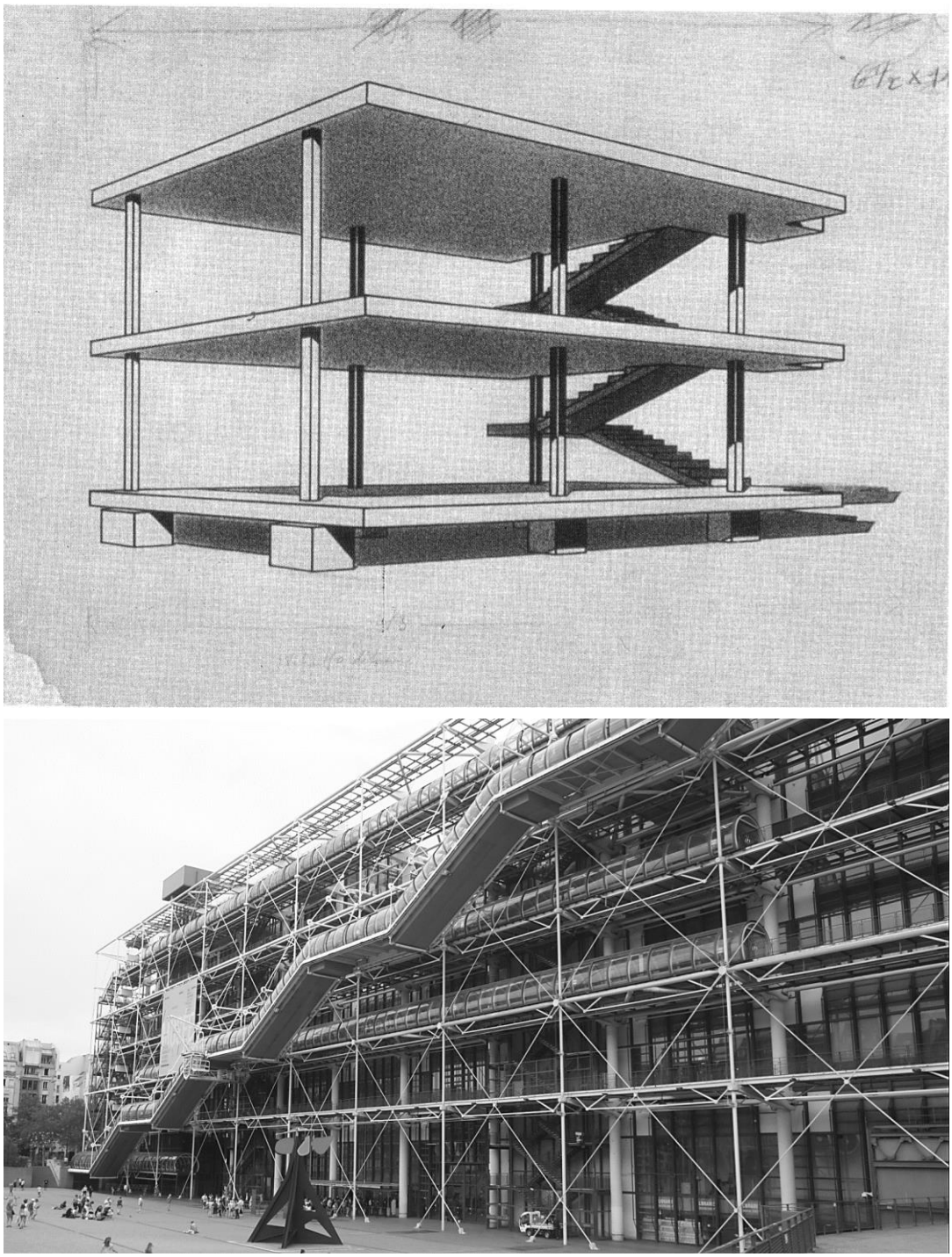

Fig. 13 - Perspective view of the Dom-ino system, 1914.

Image from Le Corbusier & Pierre Jeanneret (Corbusier, Jeanneret, Stonorov, Boesiger, & Bill, 1929). Centre Pompidou in Paris by Richard Rogers and Renzo Piano (1977) designed with its structure exposure as the visual expression of the building. (Photo by author self)

affinity, creative free will and the inherent attributes of each medium. Therefore, in order to divert the art discussion of the 19th century from historicism, aestheticism, and materialism, Semper developed a complex style change in Der Stil based on a careful study of specific objects and a deep understanding of cultural diversity Picture.

Therefore, the important contribution to tectonics made by Gottfried Semper is to show how the expression of these materials is constrained by materials and technology. Although Semper's basic stance on tectonics is obviously different from that of Bötticher, they both have an immeasurable positive impact on future generations.

Modernism –Structure is the truth hidden under the expression of architecture, Tectonics is creating an oasis of order and material.

The reduced understanding of architecture was highly criticized in the Post-modern era. First of all, the discussion is internal, because modernism is criticized for not achieving its goals-for example, Reyner Banham criticizes modernism for not creating real machine-age architecture (Banham, 1980). Secondly, architects and writers began to discuss the goals of modernism and look for inspiration for new paradigms in other historical times and fields. New ideas have emerged from the criticism of barren, background-free modernism and context concepts, resulting in the importance of cultural concepts that continue through history and the importance of meaning in architecture (Nesbitt, 1996).

"Finally, it will be a delight to talk of ARCHITECTURE after so many grain-stores, workshops, machines and sky-scrapers. ARCHITECTURE is a thing of art, a phenomenon of the emotions, lying outside questions of construction and beyond them. The purpose of construction is TO MAKE THINGS HOLD TOGETHER; of architecture TO MOVE US." (CORBUSIER, 1977).

What connects the works of tectonics as an architectural movement is that their understanding of architecture is not only a rational and sheltered commodity, but also an aesthetic choice between styles. In the works on the concept of tectonics, the general understanding of the role of architecture is that the cultural role of architecture transcends a single built building.

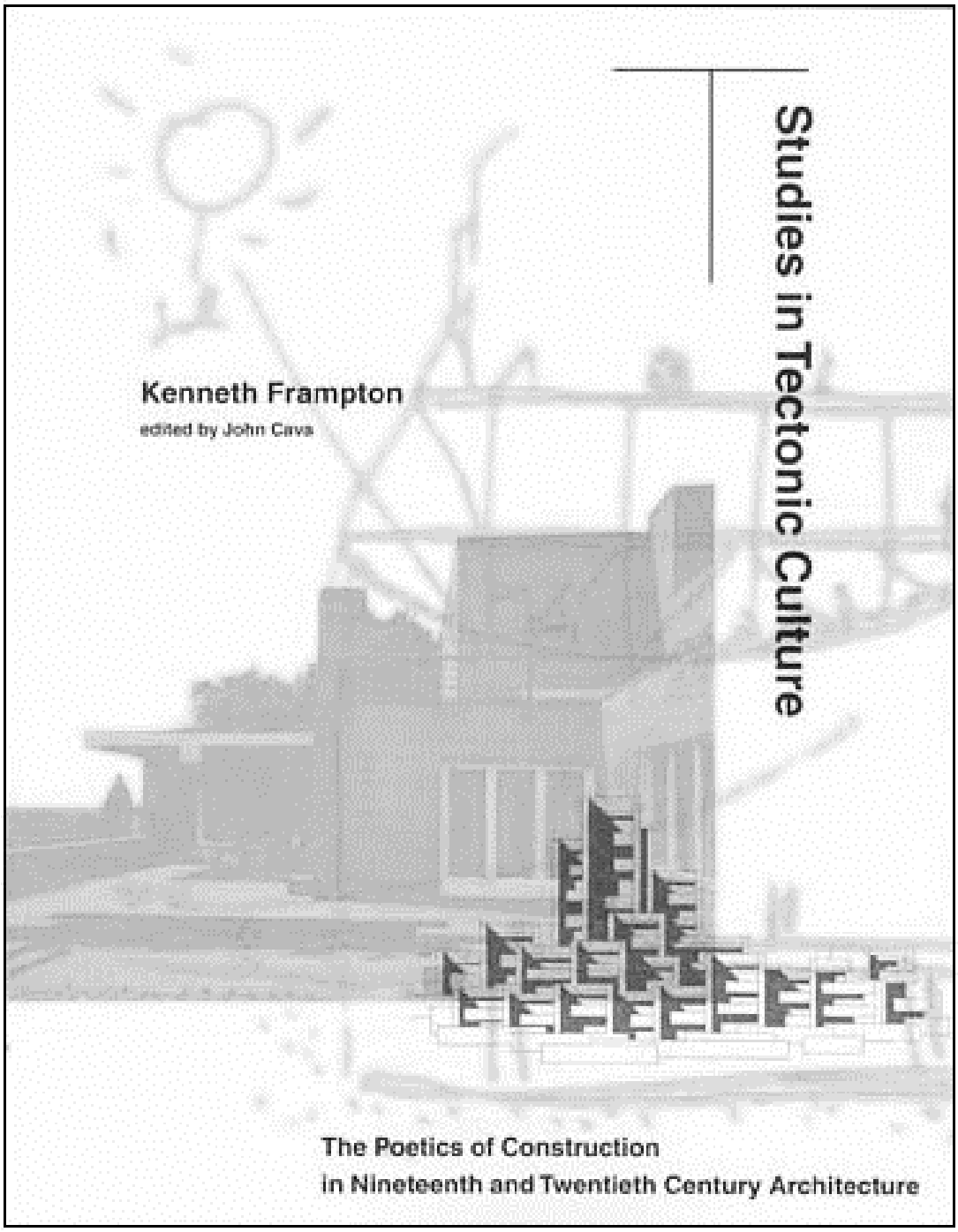

Fig. 14 - Kenneth Frampton in his book Studies in Tectonic Culture described the sporadic continuation of the tectonic tradition and defined tectonics as the poetics of construction/
(Image source: https://pin.it/30dH8uZ)

As Gaston Bachelard said, dreams, fears and desires always exist in buildings, and walls, moats and fences have another meaning than bridges, windows and doors (Bachelard, 1964). From the point of view that architecture is not just a rational effort, works on tectonics often take the form of defending the symbolic aspects, artistic views and other seemingly irrational aspects of architecture. In this case, the writing of tectonics often takes the form of defending the symbolic aspects, artistic views and other seemingly unreasonable aspects of architecture. These articles argue that irrationality in architecture plays an important role in our culture because it creates an oasis of order in an otherwise chaotic world. In architecture, this leads to the understanding that every detail should be relevant to the building, and vice versa. Therefore, architecture is an architectural work about the creation of material poetry, in which there is an inherent logic that follows rules that are completely different from the effects that can be measured by economy and science.

Since the concept of space was introduced into the modern understanding of architecture, works on architecture tend to pay attention to the experience created by spatiality (K. Frampton et al., 1995). The architectural view of tectonic maintains the prevalence of architectural material level. Neither the understanding of spatiality nor the understanding of materiality can be left out when dealing with and creating architecture. However, from a structural point of view, the means to create such a profound experience should include attention to material, architecture, and construction technology.

Frampton - reintroducing tectonics as the poetics of construction

“The tectonic emphasis is an important part of the postmodern critique of a sterile, debased modernism and of superficial postmodern historicism. Some architects construct a narrative through material and detail.” (Nesbitt, 1996).

In Kenneth Frampton’s book “Studies in Tectonic Culture – The Poetics of Construction in Nineteenth and Twentieth Century Architecture” He began to look for the remains of our architectural culture, which he called tectonics in one word. “For all its marginality, tectonic culture still possesses a vestigially resistant core, particularly as this is manifest in its proclivity for the tactile.” (K. Frampton et al., 1995).

Frampton describes his theoretical starting point as Semper's work, but Bötticher's concept can also be found in Frampton's thought. As a result, Frampton used two concepts, ontology and representation, that resonated with Bötticher's core form and art form, as well as the symbolic and technical aspects of Semper's architecture. "The concept of layered transitional space as it appears in traditional Japanese architecture may be related indirectly to the distinction that Semper draws between the symbolic and technical aspects of construction, a distinction that I have attempted to relate to the representational and ontological aspect of tectonic form: the difference, that is, between the skin that re-presents the composite character of the construction and the core of the building that is simultaneously both its fundamental structure and its substance. This difference finds a more articulated reflection in the distinction that Semper draws between the ontological nature of the earthwork, frame, and roof and the more representational, symbolic nature of the hearth and the infill wall. In my view, this dichotomy must be constantly rearticulated in the creation of architectural form, since each building type, technique, topography, and temporal circumstance brings about a different cultural condition." (K. Frampton et al., 1995).

Therefore, Frampton connects the concepts of ontology and representation with Semper's architectural elements, and points out how Semper understands the elements of fireplaces and walls as symbolic aspects of architecture. Frampton believes that the wall in the form of lightweight filled walls essentially represents the essence of architecture, and the function of this element is to clarify and strengthen the understanding of architecture.

"It is characteristic for our secular age that we should overlook the cosmic associations evoked by these dialogically opposed modes of construction; that is to say the affinity of the frame for the immateriality of sky and the propensity of mass form not only to gravitate toward the earth but also to dissolve in its substance." (K. Frampton et al., 1995).

Tectonics in the digital era: shifting, transforming, and adapting

On the basis of the tectonic theories laid by Karl Bötticher, Gottfried Semper and others, these theories have been further developed over time in order to be able to

better be applied under the conditions of contemporary society. However, this "transformation, adaptation and above all the reduction of and simplification of an extremely ambitious theory of tectonics was in fact ineluctable." (Oechslin & Widder, 2002). Despite its shifting, its transforming, and its adapting, architectural tectonics remains a central tenet of both the study of architecture and the practice of its design and construction. Based on these architectural thought theories, the architecture courses set up for students can have a positive impact on the built environment that supports our lives and work in the foreseeable future.

Through the digitalization process, the relationship between form, structure, and material properties can now be clearly communicated and coordinated through digital media. The products of architecture are not only buildings and spaces. Architecture is also the development of new knowledge, new organization and new technology (should be all technical issues). The development of technology is very important to the architecture itself and the society as a whole, because it draws a boundary between the possible and the impossible, and it is the structural mechanism of our architectural culture. The available technology affects the language of the architecture, and changes to the architecture language should also affect the technology. However, in today's construction industry, there is a lack of new technology development. This not only increases the building price, but also limits the language of the building.

The concern with technology in connection to architecture can be found in the writings on architectural tectonics by writers such as Eduard Sekler (1965), Vittorio Gregotti (1983), Marco Frascari (1984), Kenneth Frampton (1995) and Anne Beim (1999). Using tectonics as the theoretical framework for discussing architecture is to strike a balance between two extremes. That is, by pointing out the conditions of architectural expression (according to purpose, materials and technology), it rejects the idea of architecture as a free art and rejects the expression of architecture. It is believed that architecture only satisfies needs by pointing out the cultural significance of architecture. Books on architectural construction usually regard the product of the building as the building of the building, while the maker of the structure is considered to be a limited number of architects, whose ability to create structures is mainly explained by talents. However, the framework of tectonics is outrageous, because

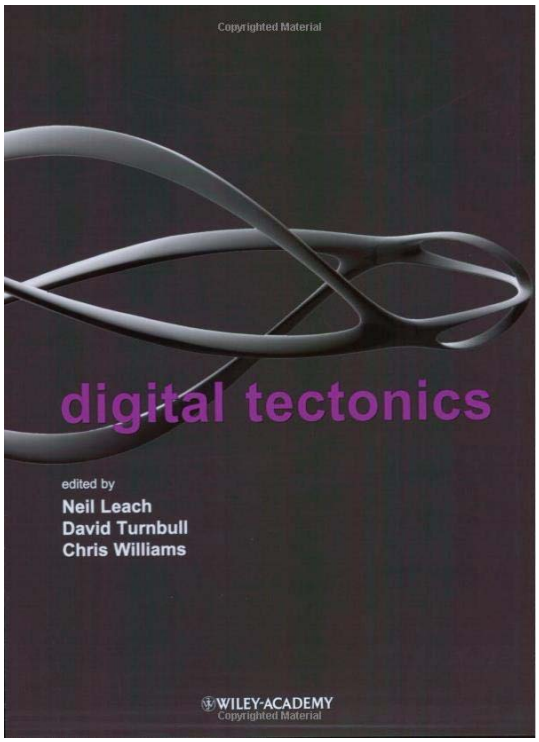

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Fig. 15 - Digital Tectonics by Neal Leach (Leach et al., 2004).

NOX water pavilion Waterland Neeltje Jans, Zeeland, 1994 (source: FRAC Centre)

through tectonics, architects can transform from passive technology consumers to key users and developers, and thus act as change agents. Therefore, the tectonics has always been an important framework for describing and evaluating the architecture (Schmidt & Kirkegaard, 2006).

Recently, Paolo Tombesi, a professional writer in construction technology, conducted research on structural architecture from an economic perspective. Tombesi not only introduced tectonics from the structure of buildings, but also from the perspective of the long-term influence of the construction industry and this point of view, he believed that the role of an architect as a change agent is not limited to his own architectural design. The category also plays an important role in the wider social field. Therefore, the buildings we are talking about are not only actually constructed buildings, but may also be the driving force for the development of new technologies. (Tombesi, 2005).

2.3.2. New developments of Tectonics with Emerging Technology

To solve the digital process of design and construction, Wade Mitchell first proposed that the basic elements and processes of classic digital construction are very different or even opposite. He proposed the idea of 'antitectonics' to expand the boundaries of classic design and constructional thinking for the digital age of architecture (Mitchell, Inouye, & Blumenthal, 2003). B Bernard Cache believes that due to the emerging industrial development at that time, Semper is considering solutions that can be used in construction production. Nowadays, in the digital age, computers also provide possibilities for new production methods and solutions. With the development and progress of technology, we can use various new materials and production processes. Considering that information is also a substance (Cache, 2002). In addition, Neal Leach studied the digital exploration of the United Nations Studio, FOA, d ECOi, etc., and distinguished between the static form of classic construction and the dynamic form of emerging digital tectonics (Leach et al., 2004).

Digital tectonics research has noticed from different angles that the traditional architectural methodology related to digital technology has undergone tremendous changes in the 20th century. In order to transform these changes into theoretical

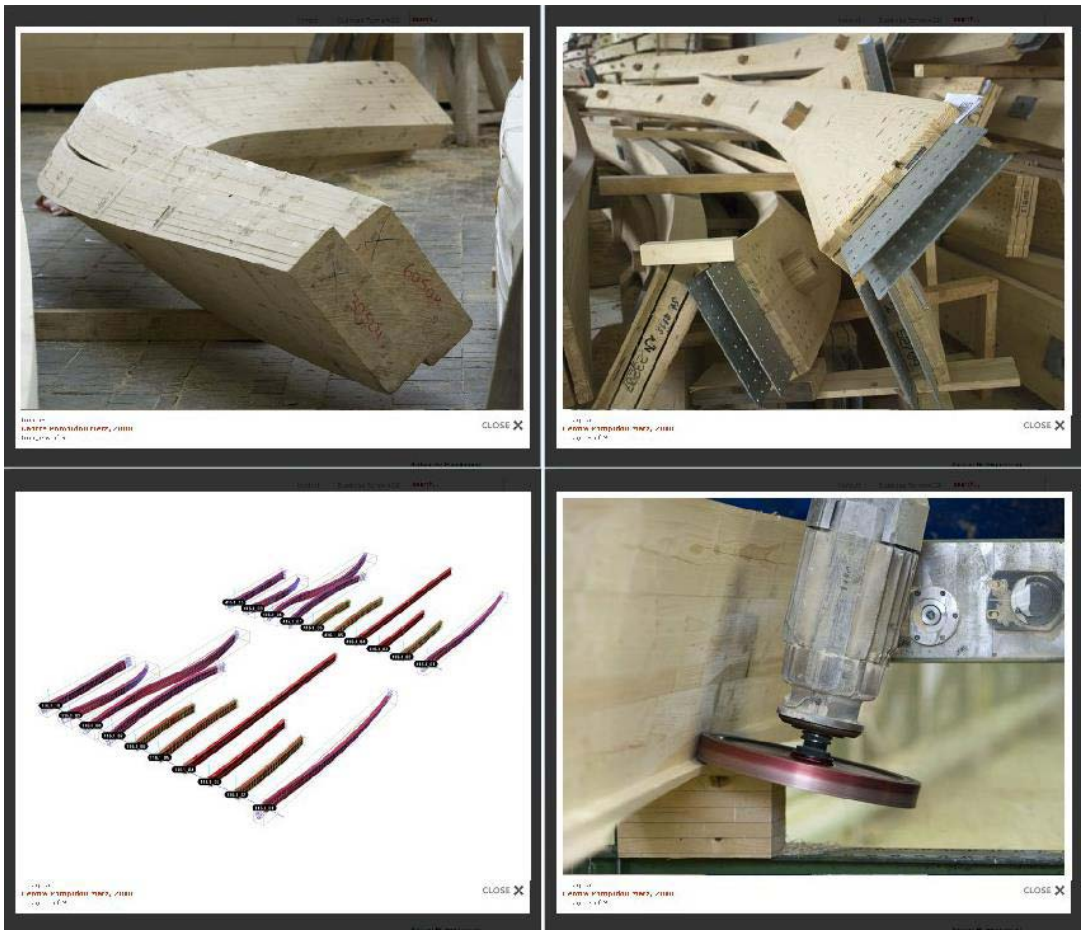

Fig. 16 - Shigeru Ban designed the roof for the Centre Pompidou in Metz, with 18,000 linear metres timber beams be individually digital-fabricated.

Source from Design to Production: http://www.designtoproduction.ch/en/

methods, we may ask questions like this, for example, could classical structural analysis be directly applied to digital design or construction processes that rely heavily on non-classical digital technologies? If so, are there some new factors that could be integrated into the classic structure for further deduction and development? If not, what kind of new digital tectonics theory or method should we propose to replace the classic construction thought, on the premise that the traditional tectonics thought is already an important part of the history of architecture. In other words, is it necessary to propose a new tectonics logic framework that could systematically fully integrate numbers and classic architectural elements to promote the exploration and development of digital tectonics' theory in the field of architecture?

Since the 1990s, a wide range of digital tectonics have been used as part of new media to aid the design process. The digital process based on the design and construction process is different from traditional architectural thinking. Many features of the digital environment, such as dynamic manipulation process, immateriality and zero gravity state, are gradually changing the design and construction process or method of buildings. Multidimensional and digital technologies (such as 3-D modeling software, generating systems or algorithms and CAD or CAM manufacturing) have also contributed to this change. On the one hand, although some parts of the definition of analytical factors should be further adjusted and expanded, the concepts of classical tectonics still apply to digital design. On the other hand, some key phenomena of tectonic thinking involved in digital projects are far beyond the scope of classical tectonic science. The classic tectonic factor is no longer sufficient. Therefore, the digital tectonics should be derived from the architectural practice of the 20th century. The new digital tectonics elements must coexist with the classic tectonics elements and can reflect the reality of the current tectonics' considerations in the digital tectonics.

Liu Yutong and Lin Chu's research concluded through virtual case analysis and research that the digital phenomena that need to be involved in the selected case include the following new features: (1) digital projects use dynamic processes to derive design concepts, such as animation and animation . Deformation during the molding process or even during the deformation process. (2) The immateriality in the digital and virtual environment is derived from the concept of matter by incorporating

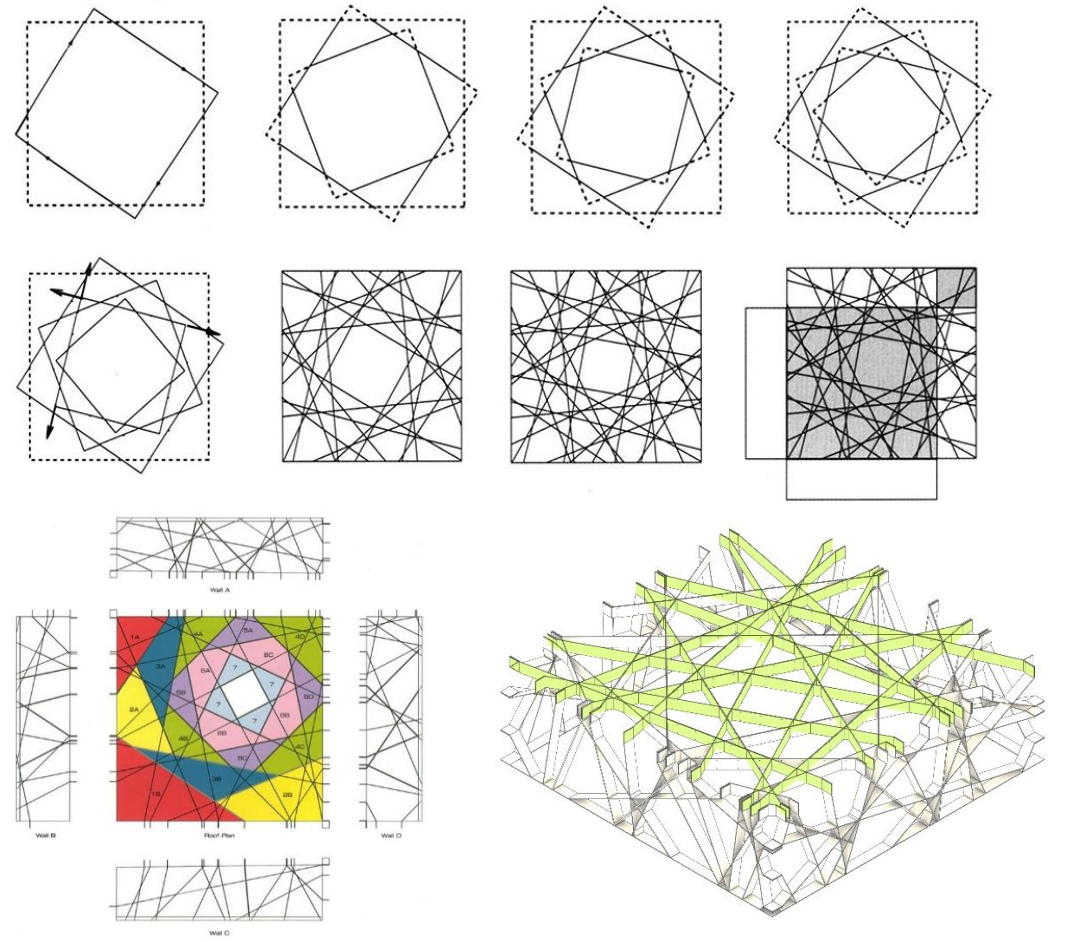

Fig. 17 - The Serpentine Gallery Pavilion 2002 by Toyo Ito and Cecil Balmond, appeared to be an extremely complex random pattern derive from an algorithm of a cube that expanded as it rotated. Source: www.serpentinegalleries.org

digital information units into the architectural form, and functions as a new substance. Therefore, information becomes a new type of building surface material. (3) Computer software such as generation systems/algorithms is used to assist the formal evolution process in the early stages of design. The designer enters some parameters and runs the generation system/algorithm to automatically generate various design forms, and then the designer selects them to suit their requirements. Finally, a new design process appeared before the construction phase. Designers use CAD/CAM manufacturing techniques such as rapid prototyping (RP), computer numerical control (CNC) and 3-D scanning to explore new assembly methods. It includes the precise production, manufacturing, testing and assembly process of digital design components for linear and free-form geometric figures (Y.-T. Liu & Lim, 2006).

Therefore, the new structure is not only a challenge to the old building tradition and technology, but also a question of the integration process. Digital tectonics is a new way of thinking about architecture, which is the clear logical result of the mixing process. The deeper meaning of architecture and tectonics remains the same-it should still reveal the truth about the building and its surroundings. The definition of construction by Bötticher, Semper, Sekler and Frampton is no longer sufficient as a contemporary theory to support the whole system of digital tectonics. The integrated form-finding process should be added in it as an important aspect. In addition, the digital tectonics described by comparing keywords ignores the relationship between structure and material. The interaction between buildings and materials is an important aspect of revealing the authenticity of loading forces and material properties. Therefore, the digital tectonics should be a combination of material and structure, clear and logical structure, and execution tectonics. Only this can fully explain the meaning of architecture.(Andersson & Kirkegaard, 2006).

Algorithmic tectonics

In the design cooperation of the Serpentine Gallery Pavilion project in 2002, the two architects Toyo Ito (1941) and Cecil Balmond (1943) jointly proposed two ideas to form an absolute box: one is a very simple concept based on structural thinking; another flat roof composed of random crossing lines and supported only by external wall lines. They finally chose the second idea, and Balmond found a simple algorithm to get the seemingly chaotic lines.

“Propose an algorithm: half to a third of adjacent sides of the square. The 1/2 to 1/3 rule traces four lines in the original square that do not meet. (Choose the half point instead of each side, the trace 1/2 to 1/2 closes back on itself like a billiard ball bouncing perfectly around a square enclosure.) The half to a third rule forces one to go out of the original square to create a new square so that the rule, the algorithm, may continue. Continue for six cycles and a primary structure is obtained. Then if these lines are all extended, a pattern of many crossings results. Some are primary for load bearing, some will serve as bracings to secondary and the rest will be a binding motif of the random across the surface of the box typology” Cecil Balmond.

However, Toyo Ito believes that the algorithmic approach is a good thinking tool. It can have greater freedom and the ability to randomly generate spatial shapes, which can make up for the lack of imagination of architects. Through algorithmic methods, unpredictable complexity and mixed situations can be created, which can still be calculated and managed. Ito believes that in the 20th century, we should not have only one solution to a problem. When the scope of the constraints is expanded or the number of variable elements is increased, more and more abundant changes will appear. But at this time, a relatively correct and appropriate solution can be obtained by further narrowing the scope of the restricted conditions and discarding some inapplicable possibilities. Computers make this possible, and it is now easier to analyze complex network-like structures. The spatial movement of the serpentine kitchen (imagined, calculated, manufactured and assembled in a tight time frame through digital technology) provides spatial cues that are essentially different from our past habits. Therefore, algorithms will also be very important in the thinking stage of future architecture activities of tectonics, which is what Ito tells us: in the future, it is likely that we will need to learn how to talk about a new type of rationality.

Moreover, Ito believes that in the field of architecture, you cannot avoid turning open concepts into architectural forms through materialization and communication with society. Architecture always involves the separation of interior and exterior, the selection of details, and materials. In order to get rid of the constraints, he hopes to turn to the computer, trying to make the boundary between the inside and the outside as blurred as possible, but "it is impossible to completely eliminate this distinction, because it will mean leaving the field of architecture." Toto Ito (Ferré, 2004).

From Digital Tectonics to Robotic Tectonics: New Design-to-Construction Workflow

Nowadays, we are entering a period of seismic change around the way the world revolves. Disruptive technologies driven by technological advancements, generational and political change are core drivers.

The transition from computer-aided design (CAD) to building information modeling (BIM) and later to the digital ecosystem will be more advanced than the transition from drawings to CAD. Obviously, our architects are constantly adapting to the changes of the times, and the buildings designed have won wide acclaim around the world. But recently, although the client is very satisfied with the work in the design stage, his satisfaction with the actual architectural works after completion and delivery has decreased. This is because under the convenient Internet conditions, customers can quickly acquire some relevant professional knowledge and can clearly know the results they want, so that they have been setting higher expectations for the building. As a result, professionals can no longer work side-by-side with processes that have been hundreds of years old. When web-based alternatives can now provide immediate advice and information, they can no longer confidently make their own claims based on face-to-face as professionals in the transaction process. (Sinclair, 2017).

Practical architecture requires attention to both product and process(Deutsch, 2017). It is time for us to adopt new workflows and use more innovative energy in building design to solve customer concerns now. They emphasize the importance of workflow and the need to correct the balance between the architect as producer and director. For hundreds of years, drawings have been the lifeblood of architects' creative process and the main means of exchanging information. The industry is struggling to deal with the impact of new technologies, just as the art world has accepted new art forms , such as the way in Douglas Gordon's "24 Hours of Mind"(Gordon, 1993) , rather than more traditional the painting and sculpture form. CAD extends the status quo and revolves around the simulation process. Digital tools, such as BIM or robotics, will change the rules of the game. It can be used from the beginning. The process becomes an indispensable part of creating, developing and improving product maturity. Immersive technology can better convey design

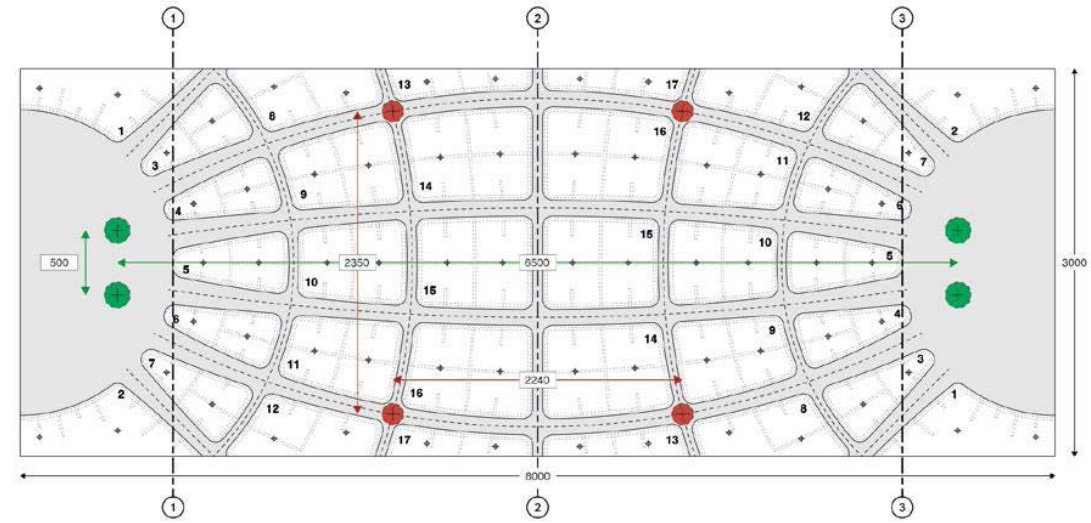

Fig. 18 - LIGHTWEIGHT CONCRETE CEILING - Additive fabrication of concrete elements by robots, Graz University of Technology (Hansemann et al., 2020).

suggestions to customers. New software tools allow us to perform 3D coordination as the design is gradually fixed.

The transition to digital workflow will take a long time to complete this major cultural change. For centuries, architects have been acting like chief conductors, responsible for guiding and coordinating various design professional teams from initial sketches to comprehensive construction drawings. Also assist the contractor in the later design service work during the construction process. Now, architects need to adapt to their role in the new work environment and recognize the fundamental changes that are taking place around us driven by many new digital opportunities. For example, BIM can provide full-process services, from modeling and collaboration in the early design stage to operation management in the later completion stage, which can substantially improve the quality of completed projects.

Researcher (Richard, 2017) realized that the contributors to this issue acknowledge the rapid shift away from simple notions of sharing and storing information to the development of workflows that effectively connect project information (including geometry and data) and analyze is together are sowing the seeds for the future. Most methods are customized research and development for realizing new specific functions. Although they are slowly automating many aspects of the design process. So, the workflow that connects different software tools together is crucial. Those new systems are no longer developed by software personnel only but are structured by multiple disciplines, though they need a relatively slowly design process for automating many aspects. For example, the connection between the 3D geometry used by architects and engineering analysis software will be automated, allowing for faster and more effective design iterations. The tools used include relational databases, visual scripting processes, plug-ins, algorithms, optimization engines, different coding and scripting processes, generating components, and feedback from custom computing tools.

What is worth looking forward to is that the game-changing era of real-time design iteration will soon come. These new systems will provide relevant architects and engineers with instant feedback from visual simulation, so that many interlocking tools and software can be used at any stage to adjust and optimize the architectural design at any time. In these new digital design ecosystems, any pre-production or post-

production steps that affect real-time information will have a shorter shelf life. So as to achieve the purpose of quickly improving the design quality and reducing the design cost. For example, adjust the wall structure at the same time and receive instant feedback from the environmental analysis software to ensure that the environmental results of the project are achieved, or directly insert the engineering software to optimize the geometry of the cladding or structural components. In addition, an ecological environment simulation system can be added to integrate environmental data such as building physical environmental conditions, material costs, and even carbon emissions into the control platform to optimize the performance of various indicators of the simulated building in real time. It can not only eliminate the adverse effects of environmental problems on the construction site on the building in advance, but also ensure the introduction of the green building concept to the greatest extent. Workflows will transition **from being multidisciplinary to interdisciplinary**: a bigger cultural shift than we imagine.

2.3.3. Pedagogical approach of Robotic Tectonics for advanced architectural design

In modern times, the pursuit of sustainability requires systematic and balanced development between environmental, sociocultural and economic efforts ("2005 World Summit Outcome," 2005; Capra & Luisi, 2014; Healey & Shaw, 1993; Porritt, 2005). Sustainability, productivity, and improved economic efficiency can be more readily achieved with the help of sophisticated technology (Ayres, Turton, & Casten, 2007; Chang, Leung, Wu, & Yuan, 2003; Du Pisani, 2006; Mokyr, 2010). The architecture, engineering, and construction (AEC) industry is one of the key components of the sustainability movement, (BCG, 2016; Parliament) and it is currently faced with the a myriad of challenges such as rapid changes in digital technology and shifting societal values (Statistics, 2019). Likely, automation will be the catalyst that will accelerate the building industry from traditional, inefficient, and labor-intensive practices toward the opportunity to build more efficiently, accurately, and creatively (Chen, García de Soto, & Adey, 2018; García de Soto et al., 2018). Along with the emergence of digitalization, virtual production, and computational analysis in the past 50 years, programmable robotics has greatly expanded the field of automation to make it smarter, more flexible, and more versatile (P. F. Yuan, Leach, & Menges, 2018; P. F. Yuan, Meng, & Devadass, 2014). These qualities suggest that it could similarly cater to the building industry in the current digital age (Austern, Capeluto, & Grobman, 2018; Leach & Yuan, 2018). It is not farfetched to regard computer programming and architectural construction as reliant upon each other and to see their reciprocity as fundamental to architectural practice (Leach & Xu, 2006; P. Yuan, 2016). In such a manner, the industrial robot may become both a symbol of, and a primary tool for, a profound reformation of the discipline (Gramazio & Kohler, 2008a). So, with the interdisciplinary requirements and technical difficulty of robotic tectonics, how can we integrate it into architectural education in a simple and understandable way that could allow students to master the necessary skillset while addressing the critical challenge of sustainable development in architecture? As a response to this challenge, we are pushing to establish a novel workflow that can act as a model for a digitally-focused pedagogy and define it within a sustainable

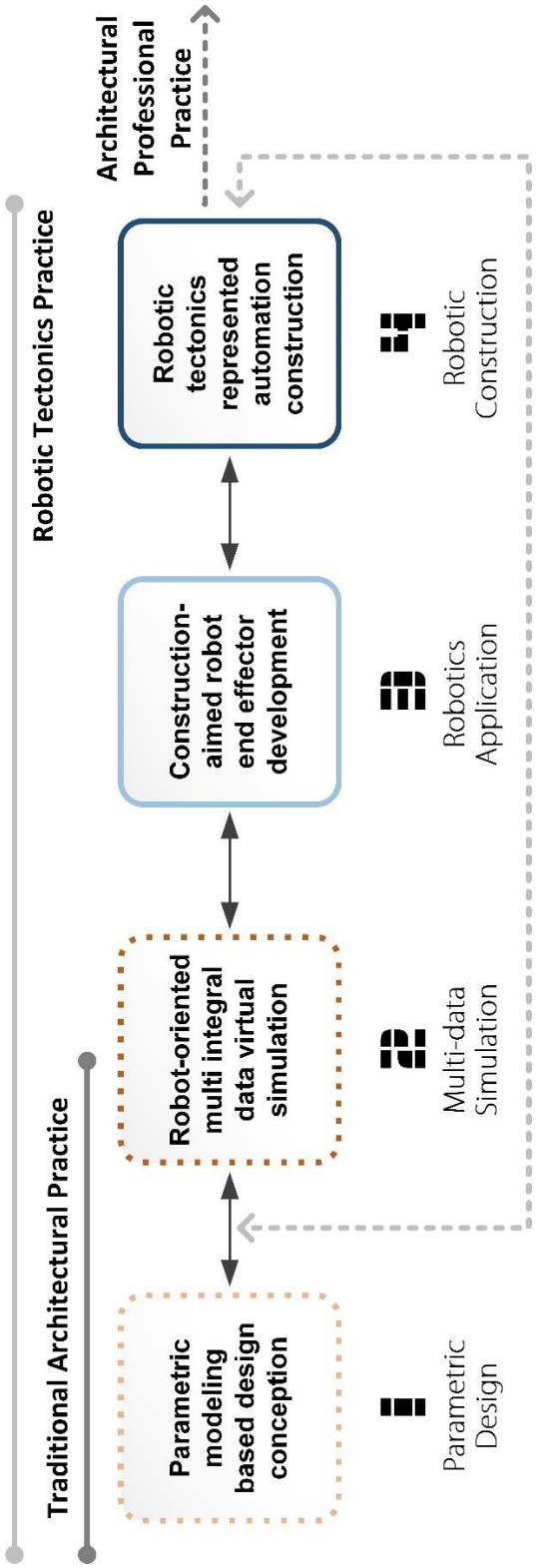

Fig. 19 - Diagram of the robotic tectonics workflow

framework that combines advanced robotic technology and architectural tectonics. We intend to focus on construction techniques driven by robotics in order to significantly improve material, structural, energetic, and procedural efficiency, all while promoting the aesthetic innovation emblematic of an architectural education. In this linear model, we aim to test the integration of a variety of interdisciplinary techniques in the early design stages, which we believe will aid in the advancement of sustainable development. (Bejan, 2015; Mavromatidis, 2015, 2018, 2019).

Education is of utmost importance for the future of sustainable development, especially in the field of architecture (Fien & Tilbury, 2002). It is a key factor in the reorientation of the construction industry toward a system of more responsible buildings and cities (Porras Álvarez, Lee, Park, & Rieh, 2016). The daunting task is finding a way to provide the necessary knowledge to future professionals which will empower them to deal with impending environmental issues through the integration of novel design methodologies and technology (Rahman, 2010). In order to better address sustainability through development of creativity and technical skills, it is necessary to reconsider the current implementation of sustainable design methods at the educational level (Altomonte), 2012).

Since its induction in 2016, DAMlab (digital architecture & manufacturing laboratory) has established an experimental teaching platform exploring a myriad of digital tools including 3 KUKA robots (KR120R2700, KR60R2100, KR9R1100) and various CNC machines. Since then, we have hosted several workshops focused on the topic of robotic tectonics. From these last three years of teaching practices, a prominent didactic pedagogical approach has emerged. This new pedagogy is a fully comprehensive robotic tectonic workflow, but it is more easily understood through its four stages – **parametric design**: A parametric model-based design conception, **multi-data simulation:** robot-oriented multi integral data virtual simulation, **robotics application:** Construction-aimed robot end effector development, and **robotic construction:** Robotic tectonics represented through automated construction. Within the confines of these individual stages, students can easily break down this overly complex and technically difficult workflow into successive phased steps which each contribute to the learning objectives of this new pedagogy. (Fig. 19)

This framework explores the entirety of the typical design and construction cycle,

providing the necessary technical skills required to make automated construction into a reality. It expresses a global initiative for students to understand and apply contemporary technology to critical thinking in order to pursue design innovations towards a more sustainable future. Leaders in automated construction practices must be proficient not only in traditional computational and technical skills, but also in a new form of digital materialization which includes a critical understanding of constantly changing manufacturing processes.

Robotic Tectonics Teaching Practices: Toward a sustainable architectural education

To test DAMLab's experimental platform, we applied this pedagogical approach to several experimental teaching practices, including four international workshops and dozens of classes and lectures. The four workshops have been outlined below, each representing a successful application of the new pedagogy. Not only are each of the workshops a complete experiment exploring the entire robotic tectonic workflow, but each one also imposes a more targeted emphasis on one of the four stages in order to explore that stage's role in architectural education in detail. In addition, the workshops each take on a different material exploration to test diverse application of the didactic platform. The workshops are as follows: Robotic Clay Printing (exploring parametric design in-depth), Robotic Foam Cutting (exploring multi-data simulation in-depth), Robotic 3D Spatial Printing (exploring robotics application in-depth), and Robotic Wood Assembly (exploring robotic construction in-depth).

2.4. Summary

Architecture is often described as the intersection of art and science. However, these two distinct fields cannot be opposed to each other; they must be used together in the creation of the built environment. Architecture is a comprehensive art, which combines the design of production space with tangible reality such as gravity, material characteristics and assembly sequence. The study of architectural tectonics helps to clarify the cooperative relationship between these elements in the creation of building environment. Tectonics has many definitions, but they all tend to focus on the relationship between architectural elements that we tend to separate space and architecture, structure and decoration, atmosphere, and function. It seeks a relationship between space design and the reality of architecture, which is necessary for its existence.

This kind of structural framework is of great value to students majoring in architecture. Architectural tectonics is a study of duality. Therefore, it has the ability to help novice practitioners begin to understand and develop the links between design and construction, between assembled systems and massing systems, between architectural details and the buildings to which they belong, and between the visible surface of the structure and the underlying material that keeps the building stable.

In addition, this classification of ideas provides an excellent way to study the world around us. Careful analysis of precedents is an excellent way for beginners to understand the building environment. By using a structural perspective to study great architectural works, it is possible for students to obtain key courses on architectural practice from these case studies that will serve them for the rest of their education and follow them into the professional world.

Chapter 3. Parametric modeling based design conception

3.1. Introduction 3-1

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3.2.1. Experiment 1: Robotic clay printing 3-5

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3.4. Summary 3-19

3.1. Introduction

This Chapter focus on the process of Parametric Design and its efforts in the workflow of Robotic Tectonics, revealing the emerging design method of parametric modeling-based design conception, the initial steps of triggering Robotic Tectonics practice, and the relationship between other following steps.

Two experiments are introduced to demonstrate how parametric modeling tools are applied into the design process and what characteristics of parametric design enables tectonic thinking and ensures data passes to the next process and the entire workflow. Experiment 1 is based on a completed robotics application tectonic experiment, the robotic clay printing, explores the integration of algorithm and material behavior into early design conceptions. Experiment 2 is based on flat sheet digital fabrication process, explores the deform and unfold technique into the parametric modeling process and influence design decision.

After the description of parametric design process, the questionnaire focused on this process is analyzed, based on 135 participate students on the curriculum of *Robotic Construction Prime* and feedbacks from it, analysis is made and described. Empirical analysis proves the significant efforts of Parametric Design process for developing Robotic Tectonics workflow and creating tectonic thinking for design inspiration.

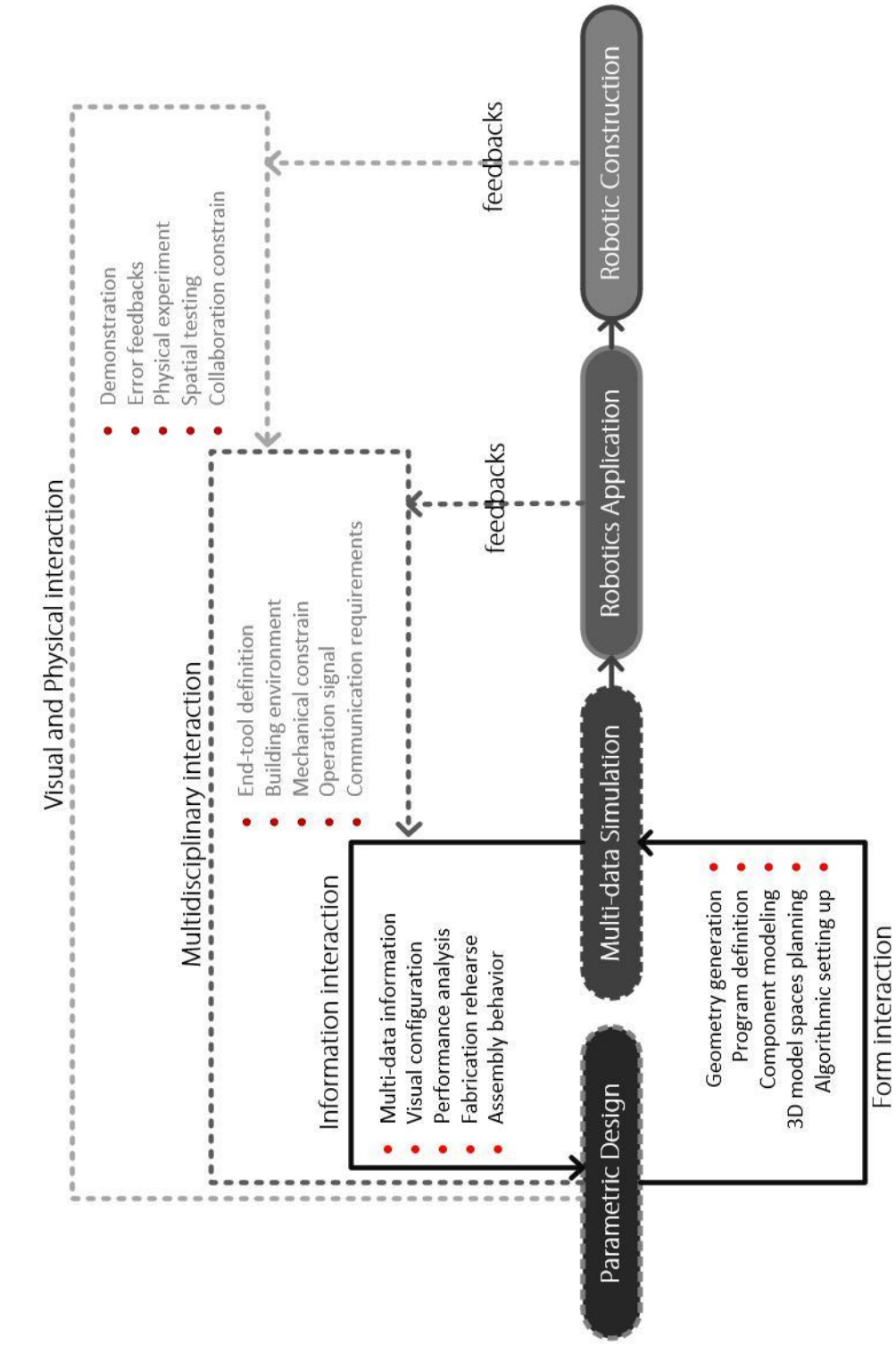


Fig. 20 Framework for process of parametric design

3.2. The concept and application of parametric design

Parametric modeling has played a significant role in architectural design in the last few decades (Hensel, Menges, & Weinstock, 2004). One of the most important features of parametric modeling is that its attributes can be relationally linked to one another in order to easily and actively change their features. This allows the designer to define entire classes of forms by simply changing relevant key parameters (as opposed to changing each individual instance). Before the advent of parametric

modelling, editing complex forms directly in the 3D modeling software was mundane work. As a simple example, modification of any geometry required the designer to change its length, breadth, and height independently. However, with parametric modeling, the designer needs only to alter one of such parameters as the others may be relationally bound to it. If one is changed, the other two parameters adjust automatically. Parametric models such as this focus less on the forms and more on the logical steps used to create the forms, thus benefiting the user in time-sensitive, dynamic design scenarios.

Grasshopper (a modeling plugin for the 3D modeling software Rhinoceros) has been the primary parametric software of choice for architects and students of architecture. Its unique visual programming interface allows designers to more easily understand parametric logic and ultimately save time in design generation and manipulation. The interface between the design “script” and the corresponding digital 3D models allows the designer to focus on the logic which can directly define building forms, as opposed to the forms exclusively.

Students subscribing to the robotic tectonic pedagogy are first introduced to parametric software such as this as a tool to explore the logic of geometrical systems so that they can begin to consider its use for generating design concepts. The impetus for exploring parametric logic in the first stage is to have students gain the ability to easily capture design intent and define families of building elements, thus anticipating the forthcoming industry-driven manufacturing processes in which production and fabrication methods have a massive impact on the built world.

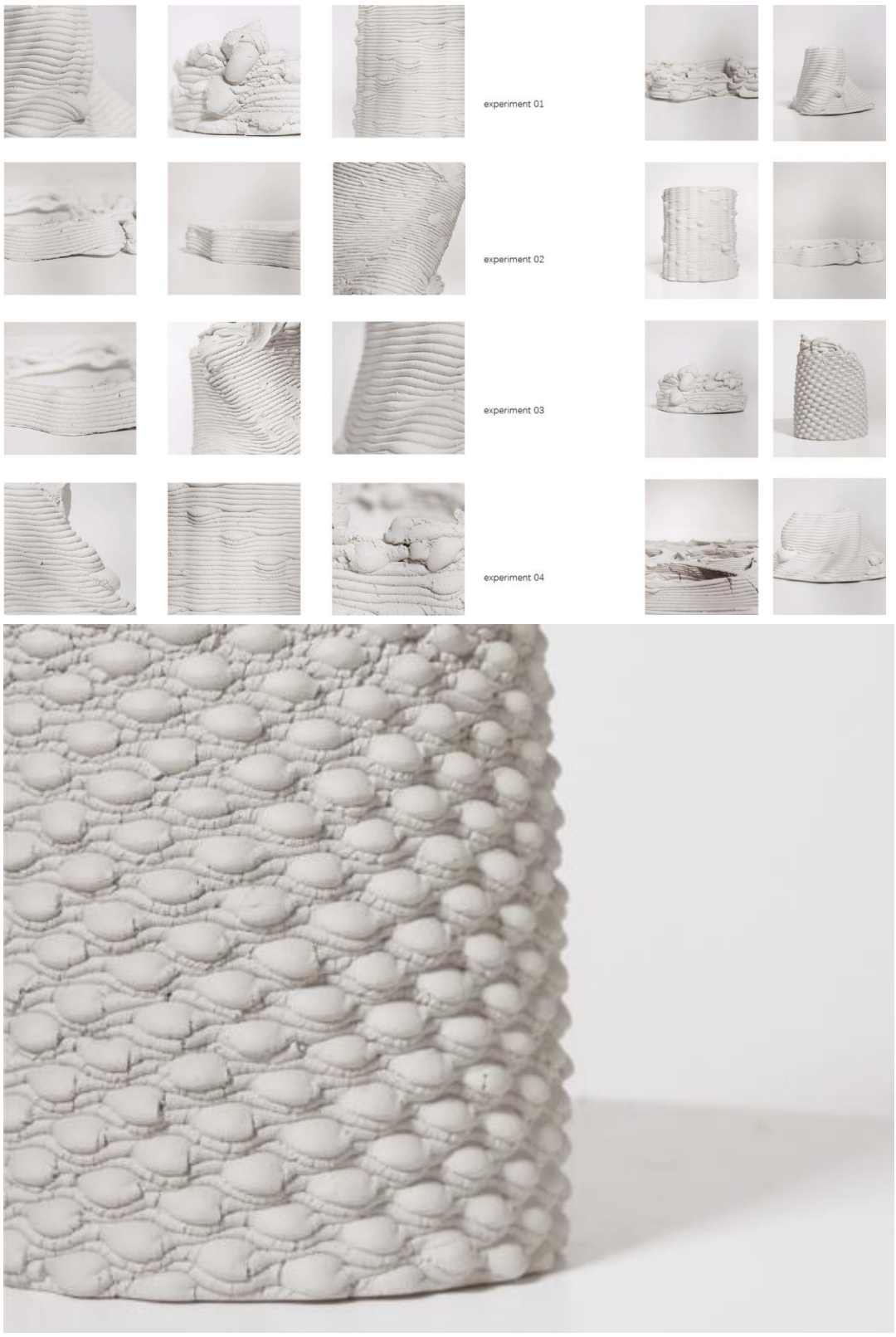


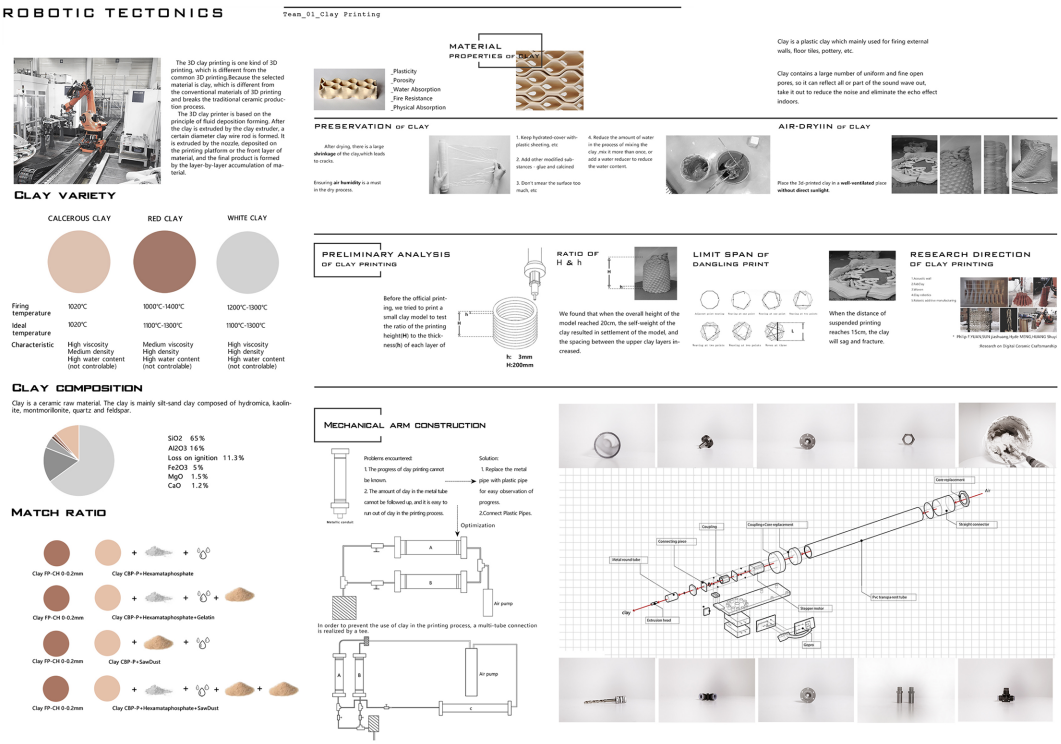
Plate 1 - Experiment 1: Robotic clay printing

3.2.1. Experiment 1: Robotic clay printing

As of late, clay has been utilized more frequently among architects and fabricators thanks to the success of 3D printing in industrial production. Clay has good sound absorption, water absorption, opacity, air permeability, and resistance to corrosion, all of which make it suitable for a variety of applications in the AEC industry. On top of this, its fluidity, plasticity, firmness, and cured strength allow it to meet the basic structural and physical requirements of 3D printed materials. The precise and programmable parameters of a standard clay extruder allow the material to be explored in a dynamic shore range, from soft (flowing) to hard (extruding). Control over these complex attributes inspires further exploration into surface texture and formal aesthetic of the final clay print (Keating & Oxman, 2013). In addition to the material's aesthetic qualities, the digital fabrication workflow allows us to obtain a quantitative analysis of the benefits of different textures and forms achievable.

Due to the potential of clay printing at an architectural scale, it was incorporated into the DAMlab workshop in April 2019, where it was explored under the constraints of parametrically generated façade panels. The workshop was used to study of clay's physical properties, its application potential, the optimization of its geometry, and the optimization of its printing process. At the outcome of the workshop, a parametric facade panel prototype was fabricated to highlight the advances in the new clay printing system.

The basic module used for the facade panel is a 600mm x 600mm square, which is then subdivided into multiple Voronoi polygons. Each Voronoi polygon forms the basic unit of a single facade panel and can be unique to its neighboring panels through transformational actions such as rotating, scaling, and translating. Interlinked relationships between the neighboring panels were established in Grasshopper, implementing precise control over the normal angle the Voronoi polygons, ultimately controlling the light transmittance of the entire facade panel. An environment analysis was then simulated with the Ladybug plugin in order to quickly iterate through design options based on the desired direct and indirect interior light values.



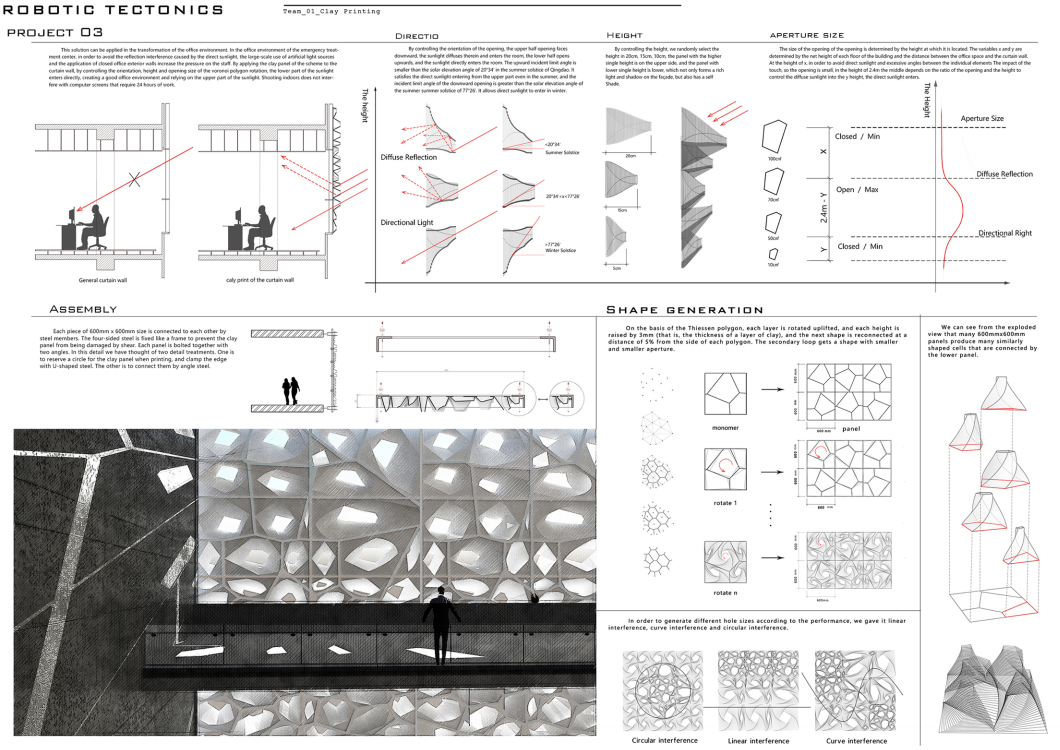
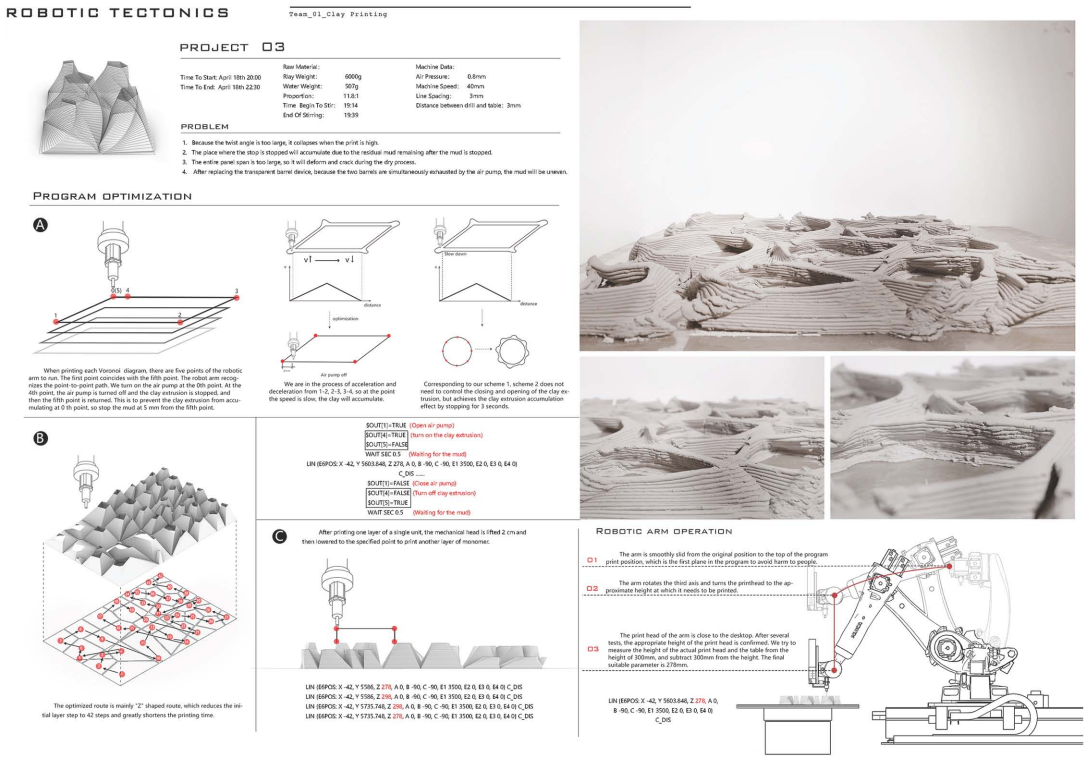


Plate 2 - Experiment 1: Robotic clay printing



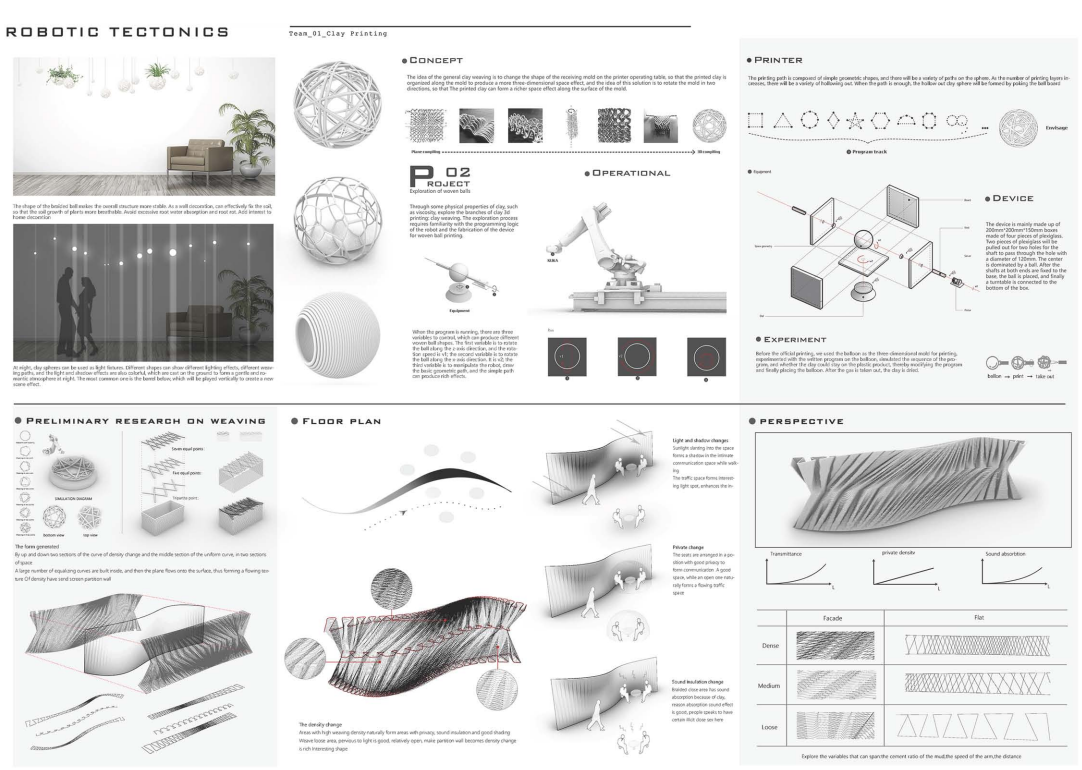


Plate 3 - Experiment 1: Robotic clay printing

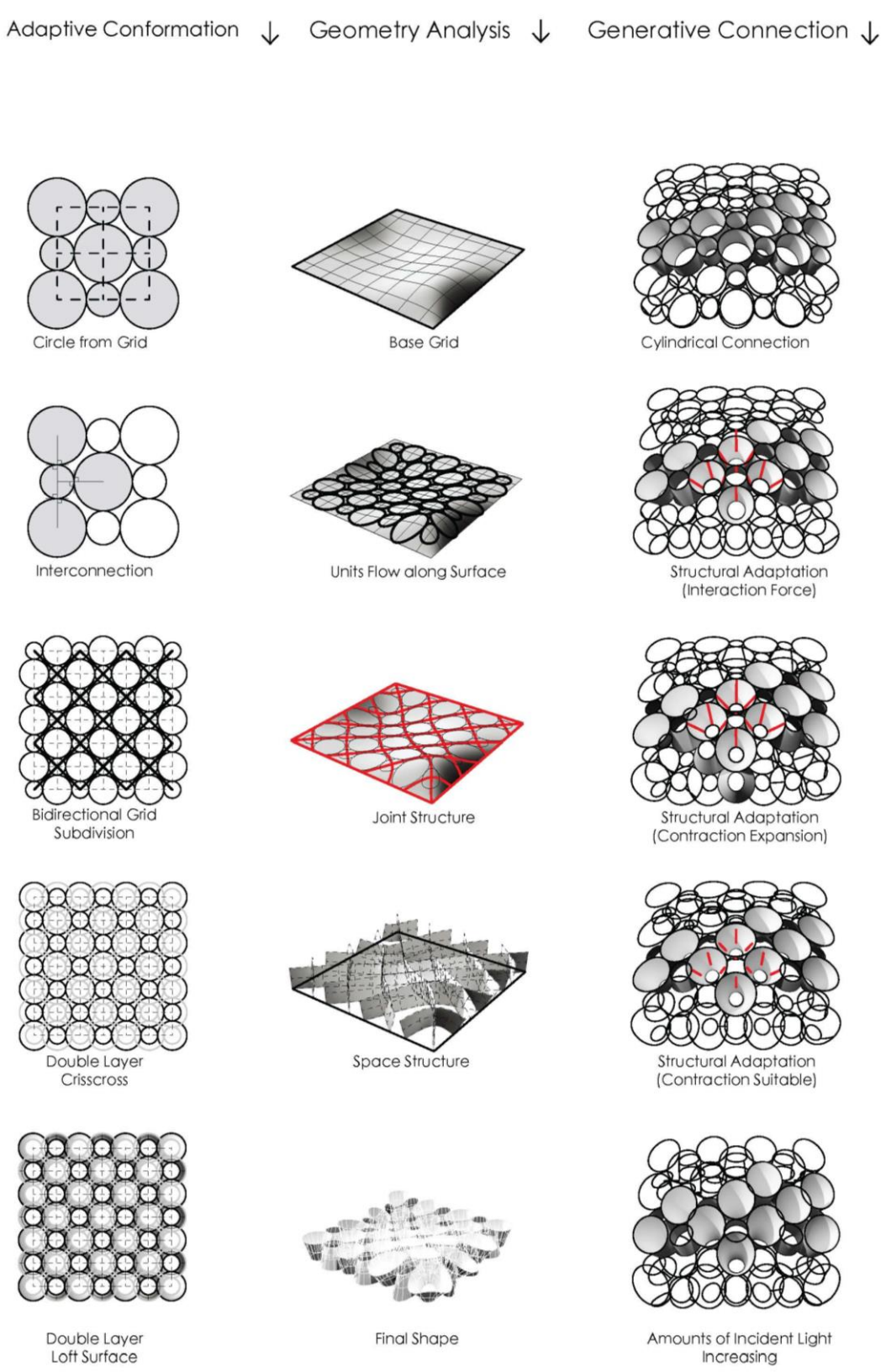


Plate 4 - Experiment 2: Site algorithm installation

Though parametric iteration is a critical part of this design process, fabrication must also be considered in the overall design development. Therefore, the other three stages of the didactic pedagogy must be considered. Since the panel is composed of multiple Voronoi polygonal monomers, it is necessary to print multiple pieces at the same time and to optimize the printing path between adjacent monomers in order to ensure the strength of their connection. This makes the fabrication process of the panel different from the continuous extrusion employed in standard clay printing. Likewise, the form of the panel has to be optimized by the physical constraints of its physical construction. Prior to the final printing, the maximum height of the clay print, the maximum dislocation distance between the upper and lower layers, and the optimal thickness of each layer had been tested and digitized so the that optimal form of each panel could be adjusted according to that data. Thus, as all aspects of design and fabrication fall back on parameterization for improving the efficiency of the overall system, it becomes critical as an introduction to the sustainable pedagogy.

3.2.2. Experiment 2: Site algorithm installation

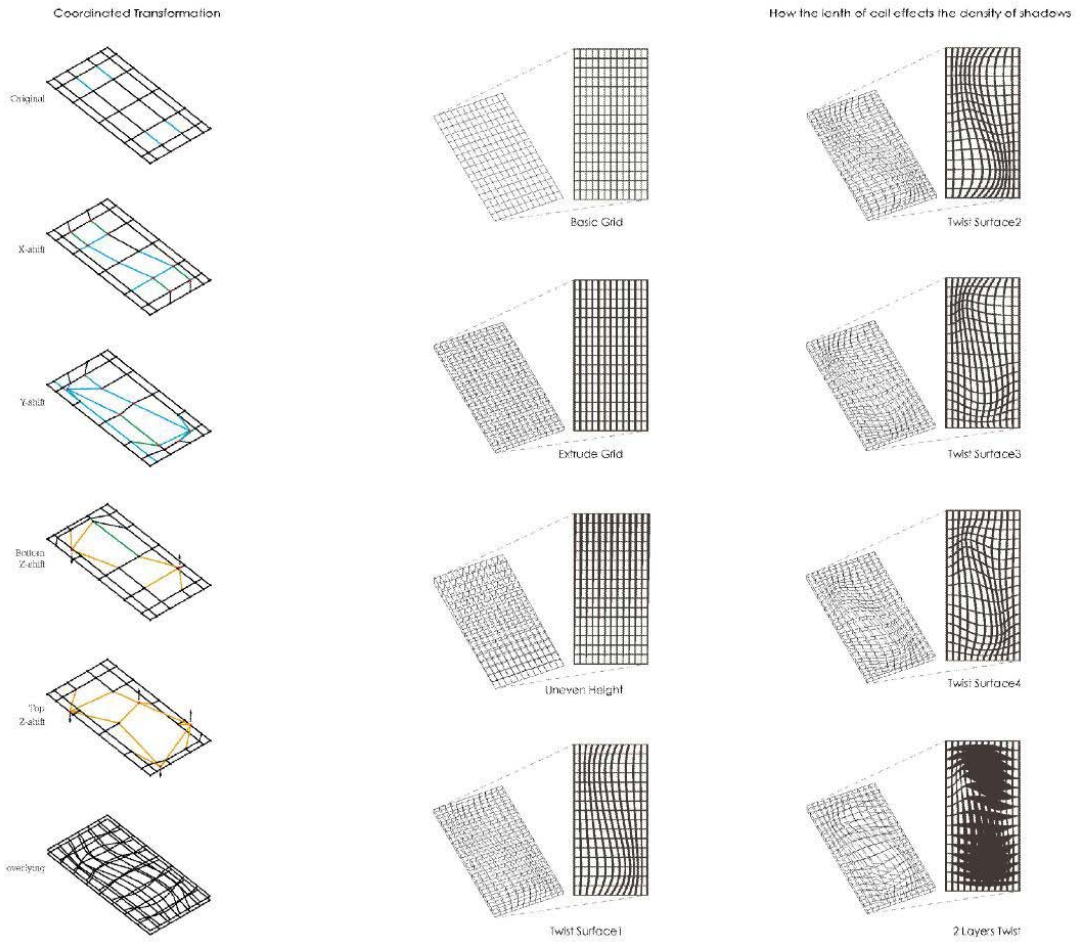
Installation site:

The base is in front of the second-floor entrance of the Building Hall of Qingdao University of Technology. The area of the base is about 140 inches, which is a building gray space 5 stories high. The space is open to the west and is always like a viewfinder, where people can overlook the scenery and beautiful port of Qingdao. As a multi-purpose space, temporary exhibitions, opening ceremonies and other activities are often held here.

Design concept:

The key word of this DAM LAB workshop is "site algorithm". Through the observation and analysis of the base and its surrounding environment, three problems are found:

1. Light, due to the general layout of the building. The base space needs to be opened to the west, but the main problem caused by the large area opening to the



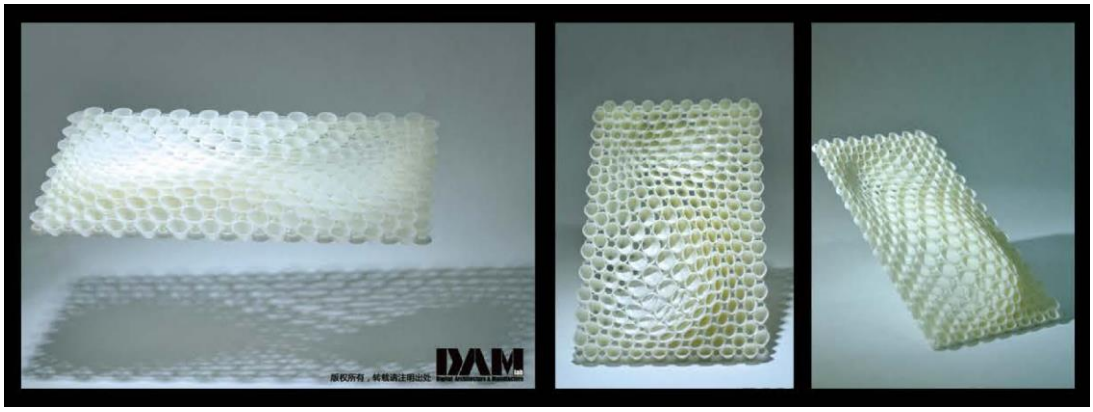


Plate 5 - Experiment 2: Site algorithm installation

west is the western sun. Most activities such as opening or ceremonies are held in the afternoon, and whenever in the afternoon or near dusk, strong sunlight is directed into the base space, reducing the comfort of the use of the space.

2. Vertical space, the area of the base is only 140 inches, but the height is 5 stories (about 20 meters), and the base space and the entrance space are separated by a vertical aisle. Standing on the base facing the entrance will create a feeling of exposure to the towering and sealed barreled space, reducing the comfort of space use.

3. Atmosphere, the base is in the old campus of Qingdao University of Technology. Entering the campus, walking from the library to the building, through the huge rectangular mass, you can feel the rigorous and dreary atmosphere of most science and engineering colleges and universities. For the School of Architecture, which contains art, humanities, and social disciplines, it lacks a trace of poetry. Therefore, in the design, we hope to make use of the limited conditions to provide atmosphere embellishment.

Parametric design tools:

With the wide application of time and parameterization, parametric tools have gradually developed from software in other fields to software specially developed in the field of architecture. This DAM LAB workshop mainly uses Grasshopper with Rhinoceros as the platform for parametric design. Grasshopper is very suitable for the rapid experiment in the scheme conception stage, and it has a convenient visualization function. At the same time, the later manufacturing and production can be realized on the platform of Rhinoceros.

Design method:

After determining the design concept, we draw a large number of sketches, starting from the overall shape and system, define the operational characteristics of several systems and the relationship between system elements, and finally determine a system. Then the design of the "interrelated" way between the various elements of the system, that is, to formulate the rules for the operation of the system. It includes the shape and system of the transparent unit, the overall grid structure layout system,

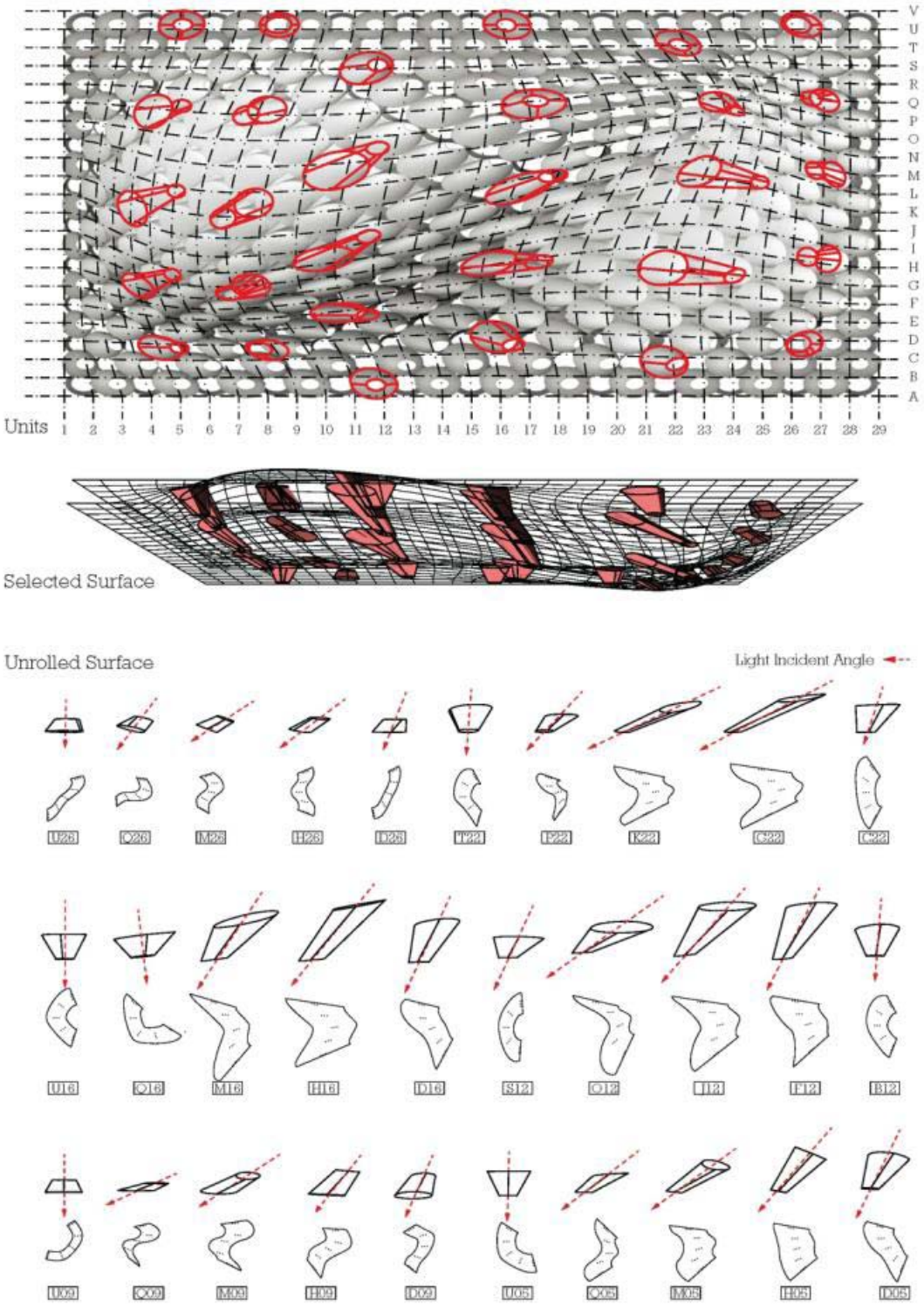


Plate 6 - Experiment 2: Site algorithm installation

site behavior, light shadow distribution system. By organizing these parameters, the cylinder-like element, logic and model of the light cloud device are obtained. Finally, the use of 3D printer to generate grass models and basic elements for deepening.

Construction method:

1. Data extraction, extract the data needed for manufacturing and production on the computer, and number all the basic units in the existing Grasshopper file. Next, we need to find out the intersection lines and intersection points between each quasi-cylindrical unit, in order to facilitate the later assembly. Because the value of π in Grasshopper's circle algorithm is approximate, all cylinder-like elements do not intersect mathematically, which brings trouble for us to extract intersecting lines and intersecting points. Finally, Tudor makes the intersection line by using the grid of the cylinder-like element system, and takes out the intersection point at the same height to solve this problem, after projecting the intersection point onto the cylinder-like body. Finally, all the cylinder-like elements are expanded and numbered and exported to two-dimensional graphics.

2. Cutting, input all the two-dimensional graphic data into the engraving machine, and finally the engraving machine cuts out the plane graphics we want through the data.

3. Material test, in the computer simulation, we tested three kinds of materials, mirror material, transparent material, and white diffuse material. Three kinds of materials have different strength and bendability, we give the largest group of units to the mirror material, so that the light can be reflected into the device to the maximum extent; the medium unit is white diffuse reflection material, which can soften the light emitted by the self-luminous body entering the device or the device; the smallest group of units placed as the main link and the self-luminous body is set as a transparent material. Through the test of abs board, soft glass, plexiglass, fiberboard, and other materials. Finally, abs plate and mirror paste are used to construct.

4. The cylinder-like units are linked to each other, and then the units are assembled according to the computer model through the numbering of the units, and finally all the units are linked with nails.

5. The device suspension structure, the non-uniform mesh steel cable system, in which the steel cable is arranged by leaving a gap between the elements during the assembly, and the device is arranged with more dense steel cables from the center to the outside due to the increase of force strength.

3.3. Investigation on the efforts of parametric modeling for design conception

As shown in Fig. 21, all the results are normally distributed with a relevant higher average value in each question. From the values of mean, median and mode, the frequency distribution of the workflow feedback in Stage 1 showed a negative skewed unimodal distribution. The performance score of the highest frequency values in all three dimensions is 7. It can be seen in Fig.21 and Table 3 that: (1) The participation of most students in Stage 1 of parametric design courses is generally high (mean=6.67, Std.D=2.12), and the participation of 117 students (86.67% of total) exceeds 50%. (2) The course in Stage 1 is relatively difficult for students to learn (mean=6.42, Std.D=1.88) due to the lack of modeling ability using parametric software for architectural design. (3) Most students believe that Stage 1 is very important for the entire workflow (mean=6.98, Std.D=1.66). It mainly for the reason that the parametric modeling technology as a useful tool for generating diverse and complex forms that could bring advantages in solving more aesthetic and functional issues.

Besides, from the frequency distribution of the content understanding in Stage 1, the results of Q4-1 and Q5-1 present a negative skewed unimodal distribution while Q6-1 presents a slightly positive skewed unimodal distribution. The distribution of data with respect to mean and standard deviation for Q4-1 was 6.33/7.72, 7.72/1.45 for Q5-1, and 7.08/1.53 for Q6-1, which is indicated that: (1) the course content of Stage 1 is helpful is for students to understand the concept of "Tectonic".（2）This stage is very effective for understanding “Tectonics means clear and logic structure”, so it is better to focus on the logical training of students in Stage 1. The main features of this stage can be seen intuitively from the radar chart (Fig. 22) based on the mean values of the above questions.

In addition, through the correlation and regression analysis of the results of Q3-1 and three questions for content understanding (Fig.23 and Table 4), the author found that there are significant positive liner correlative relationships between the degree of participation (Q3-1) and content understanding of the concept "tectonic", especially for understanding the content of “Tectonics means clear and logic structure”.

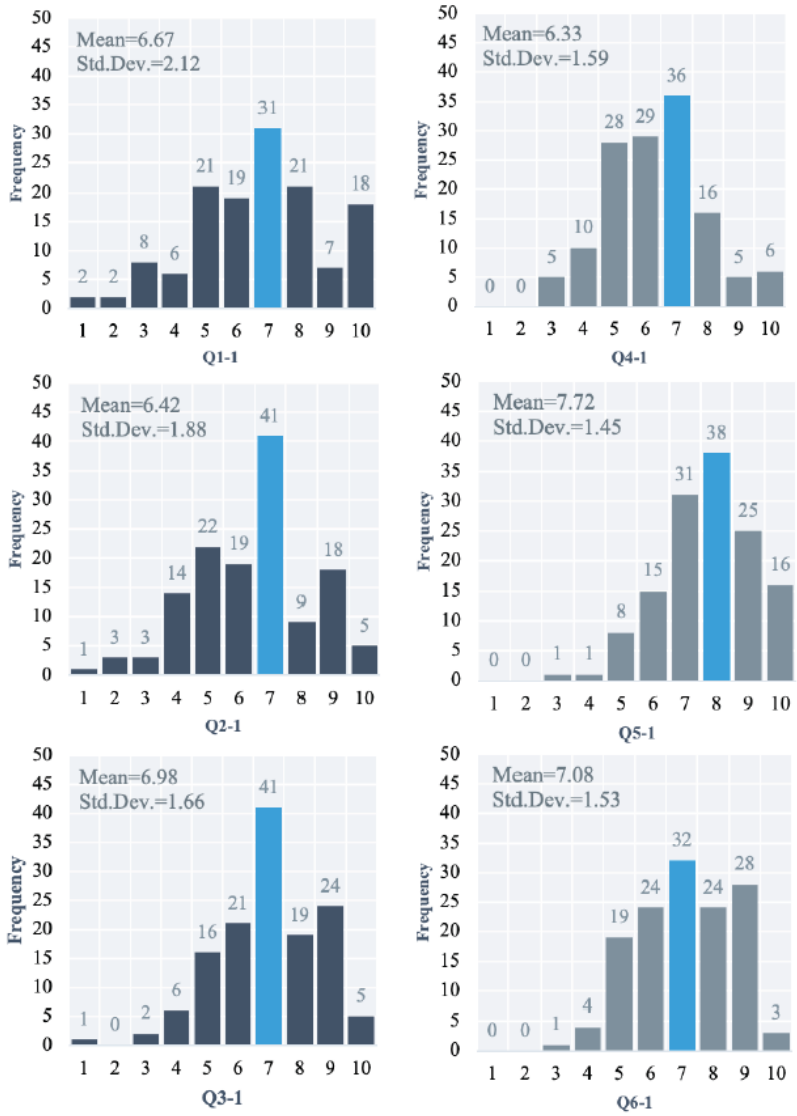
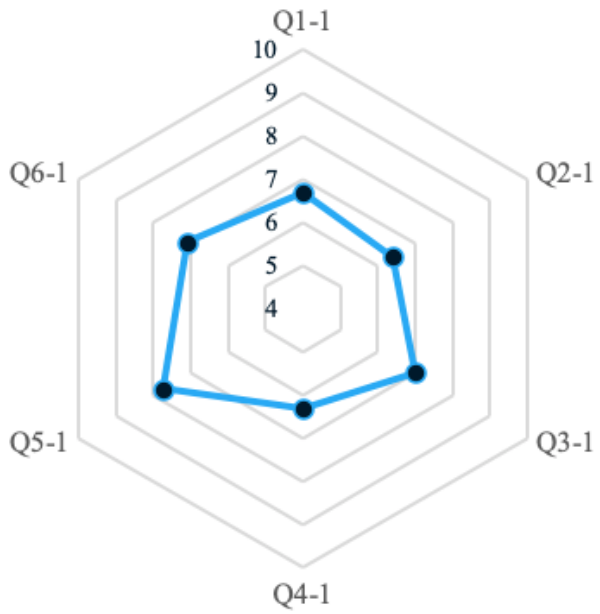


Fig. 21 Frequency distribution analysis of the content understanding in Stage 1

	Q1-1	Q2-1	Q3-1	Q4-1	Q5-1	Q6-1
Mean	6.67	6.42	6.98	6.33	7.73	7.08
Std. Error	0.18	0.16	0.14	0.14	0.13	0.13
Median	7	7	7	6	8	7
Mode	7	7	7	7	8	7
Std.Dev.	2.12	1.88	1.65	1.59	1.49	1.53
Variance	4.50	3.53	2.74	2.53	2.22	2.34
Range	9	9	9	7	7	7
Minimum	1	1	1	3	3	3
Maximum	10	10	10	10	10	10
Sum	901	867	942	854	1043	956
N	135	135	135	135	135	135

Table 3 Empirical results' list by frequency distribution analysis of Stage 1



Q1-1. The degree of participation in each stage
Q2-1. The difficulty degree of each stage to the overall workflow
Q3-1. The importance of each stage to the overall workflow
Q4-1. The degree of understanding "Tectonics lays in the interaction between material and construction"
Q5-1. The degree of understanding "Tectonics means clear and logic structure"
Q6-1. The degree of understanding "Tectonics represents performative architecture"

Fig. 22 Characteristic analysis of Stage 1 by using the mean data of the frequency distribution

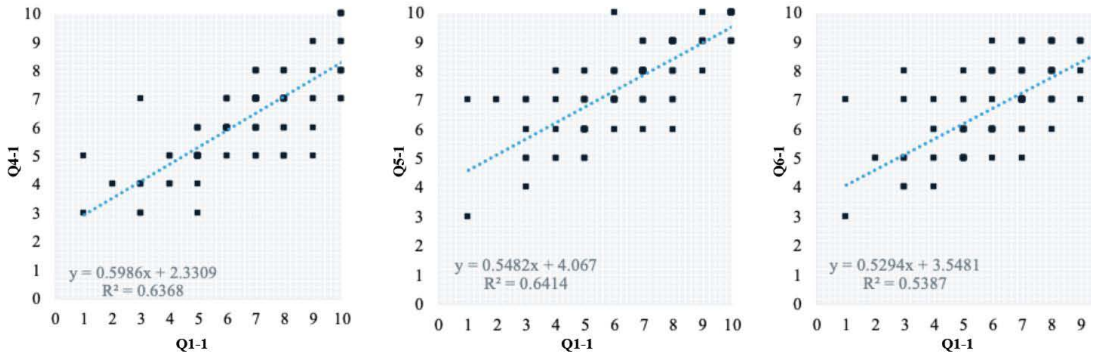


Fig. 23 Linear regression analysis of the participation degree and content understanding degree of Stage 1

Variables	Pearson correlation	Linear regression					ANOVA		N
		R^2	Slope	Y-intercept	t	Sig.	F	Sig.	
Q4-1	0.798	0.637	0.599	2.331	15.270	0.000	233.183	0.000	135
Q5-1	0.801	0.641	0.548	4.067	15.424	0.000	237.901	0.000	135
Q6-1	0.734	0.539	0.529	3.548	12.461	0.000	155.286	0.000	135

Table 4 Empirical results' list of linear regression and for Stage 1

All R-squared values were relatively higher over 0.5, and 1% growth of student participation would promote 0.798%, 0.801% and 0.734% understanding of the three main theoretical points (Q4-1、 Q5-1 and Q6-1) by conducting and passing all statistically significant test. Therefore, it is necessary to increase student participation in the process of Stage 1.

3.4. Summary

In this chapter, the parametric modeling based design conception as the first stage of Robotic Tectonics workflow is fully described with two experiments demonstration and correspondingly questionnaire survey for the feedbacks from curriculum participants. Conclusions are summarized as follow.

1) Parametric modeling allows its attributes can be relationally linked to one another in order to easily and actively change their features, so that designer could define entire classes of forms by simply changing relevant key parameters. Parametric models such as this focus less on the forms and more on the logical steps used to create the forms, thus benefiting the user in time-sensitive, dynamic design scenarios.

2) Grasshopper as the greatest parametric modeling tools for architectural design, it built a platform for other fields' parameters applied into the design environment, such as physical parameter, mechanical parameter, robot's control parameter, so that it allows multi-data engage and interact with each other, giving designer the opportunity of integrated design workflow from design to construction.

3) From the experiment 1, we could find the parametric design process offers the possibility of combine the material attributes with the design conception and the simulation of its robotic fabrication process, by doing so, it actually performs the tectonic concept of interaction between material and construction, offers a new way of tectonics practice under current emerging technology conditions.

4) From the experiment 2, we could find the digital fabrication abilities and constrains can also represented as building sequences attributes for parametric design. By pulling the fabrication parameters up to the early design stage, it allows designers create based on reality conditions, practice as an integrated design to build workflow, which presents the tectonics' concept of integrated form-finding process with emerging technology background.

5) From analysis of the feedbacks from participants of the curriculum teaching questionnaires, we could found students are strongly recognized and agreed with the importance efforts of the parametric design stage for the entire workflow of

Robotic Tectonics, it reflects the students' sense of identity with this pedagogical concept, and gains deeply understandings of tectonic thinks by deep participation.

Chapter 4. Virtual simulation of multiple data for Robotic Tectonics approach

4.1. Introduction 4-1

4.2. Virtual simulation application for design conception 4-3

4.2.1. Experiment 3: Robotic foam cutting 4-3

4.2.2. Experiment 4: Robotic stick weaving assembly 4-9

4.3. Investigation on the efforts of virtual simulation for design conception 4-13

4.4. Summary 4-17

4.1. Introduction

This Chapter focus on the process of Multi-data Simulation and its efforts in the workflow of Robotic Tectonics, introduced the newest situation of virtual technologies applied into architectural design and its digitally manufacturing process, especially in the workflow of robotic oriented design to construction process.

Two experiments are introduced to demonstrate how importance of virtual simulation of multiple data for Robotic Tectonics practice, how it easily connected with parametric design process and by doing so how it could bring multiple data to the design stage and deeply influence the design decision. With newest developed simulation tools as KAKAprc, architects and students could easily simulate KUKA robots in the design software virtual environment, which allows the tectonic building process pre-simulated. Experiment 3 explores a cutting technique based on the careful design and simulation of cutting tool-path and sequence, the complex surfaces are designed according to cutting simulation. Experiment 4 is more focused on building sequences simulation and its feed back influence on design making, hundreds of standard wood sticks are picked up and placed into the accurate positions in 3D space, form a continues deforming space and structure.

The questionnaire survey for this stage is analyzed, also based on 135 participate students on the curriculum of *Robotic Construction Prime* and feedbacks from it. Empirical analysis proves the significant efforts of virtual simulation of multiple data process for developing Robotic Tectonics workflow and enables tectonic concepts for design inspiration.

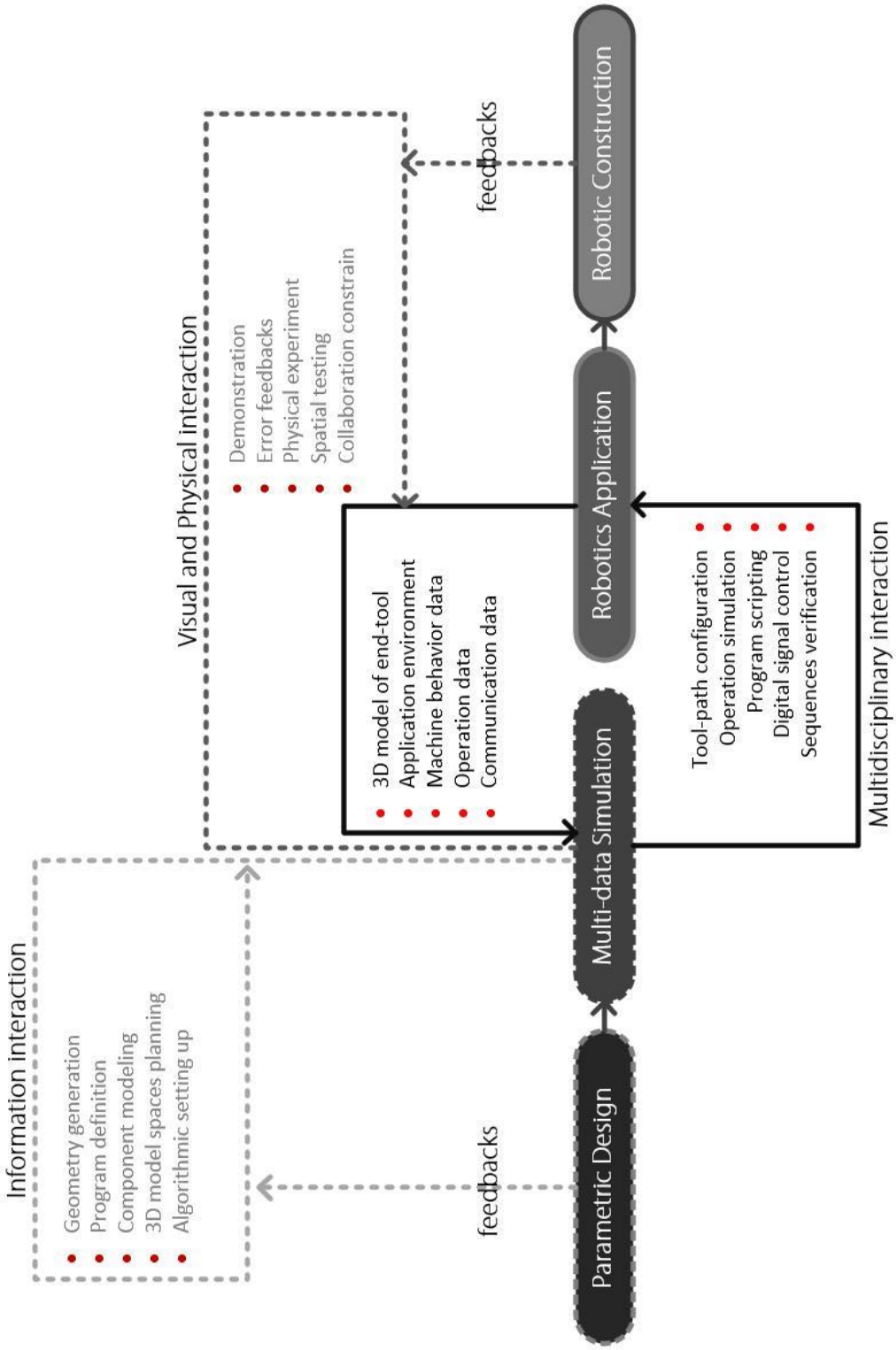


Fig. 24 Framework for the process of virtual simulation

4.2. Virtual simulation application for design conception

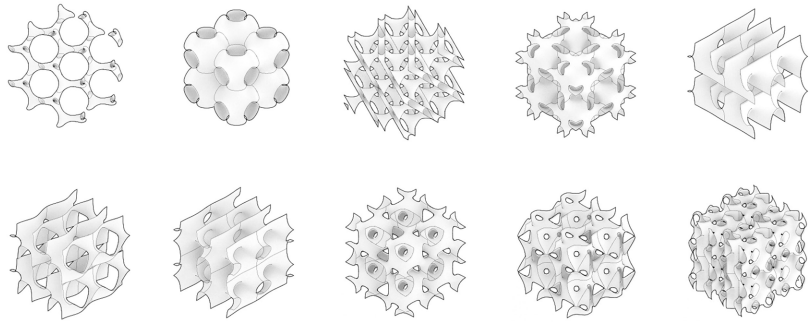
Once these relationships are programmed to conceptualize new building and construction logic, the same virtual model can then be used to create simulations for fabrication or assembly. This single virtual model represents a combination of various logic-based databases such as geometry, spatial location, form generation, construction sequence, simulation data, operation constraints, etc. The parametric model establishes links between all of this data, resulting in a comprehensive simulation mechanism in which the revealed robotic operations will most definitely have an impact on the overall design.

Thanks to the advanced robotic simulation and control software KUKA|prc (which is embedded in Grasshopper), the simulation of the robotic construction process has become more accessible to designers. It provides a virtual, visual simulation in a safe environment for architects or students to analyze every detailed step of the construction process previous to its implementation. Simulation is set as the second stage of the overall pedagogy in order to help students gain robotic operational skills and to trigger critical thinking about the impact of these operations so that they can later optimize the parametric design concepts generated in the previous stage.

4.2.1. Experiment 3: Robotic foam cutting

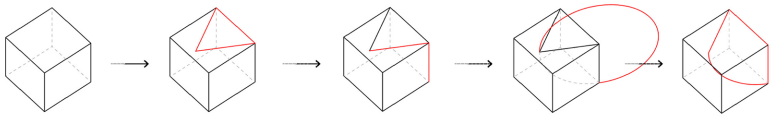
The hot-wire foam cutting project aims to build a single continuously curved periodic surface which can then be assembled into a greater complex form with blurred boundaries - a space which could be inhabited and used for meditation and relaxation. By converting the digitally generated form into the robot tool path for the hot-wire cutting tool, the physical robot can precisely cut the EPS foam into a continuous three-dimensional surface, which can act as a building block for a single aggregated surface that can be infinitely extended. As a fundamental part of this project, the link between the form generating script and the tool-path generating script was prioritized, which allowed the resulting virtual simulation to aid in the optimization the fabrication process. (Plate 7-9) Thus, this project was selected to

PROTOTYPE RESEARCH



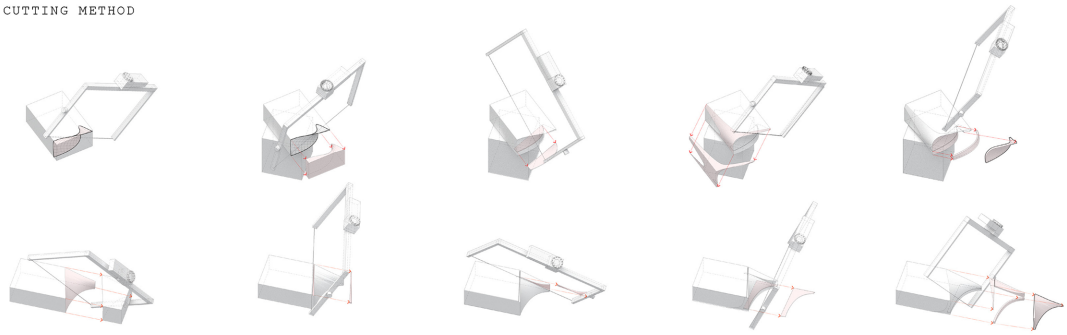
The purpose of this hot-line cutting is to construct a structure of continuous striated surface [PERIODIC SURFACE], to create a complex, blurred, and growable space for people to enter and meditate and relax. After the camp, the multi-program design, comparison and discussion,we finally clarified a set of construction plans. The structure is constructed on the basis of human scales to create a core area for staying. The boundary between the inner and outer spaces is blurred by a continuous curved surface around the core area, and the experience is extended infinitely by the natural growth of the continuous curved surface.

GENERATING LOGIC

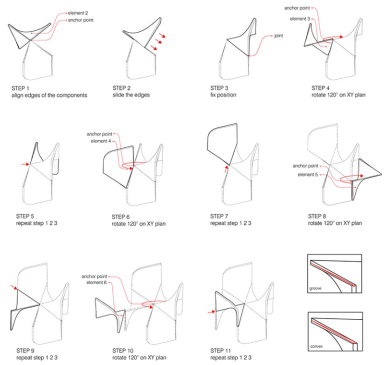


In the following continuous surface generation process, the basic unit is evolved by various methods such as moving, copying, mirroring, and rotating to obtain various units. Due to the limitation of the cutting size, the unit is further fine-tuned after the unit combination mode is determined, so that the original quarter circle is reduced, and at the same time, the line is filled with two straight lines, and the addition of more straight elements makes the large unit It is easier to splicing each other.

CUTTING METHOD



STUCTURAL UNIT COMBINATION METHOD



COMBINATION LOGIC BETWEEN UNITS

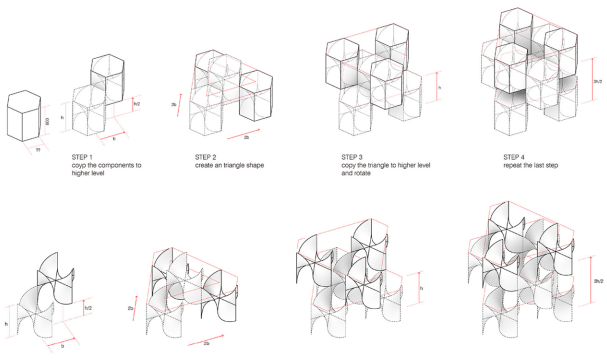
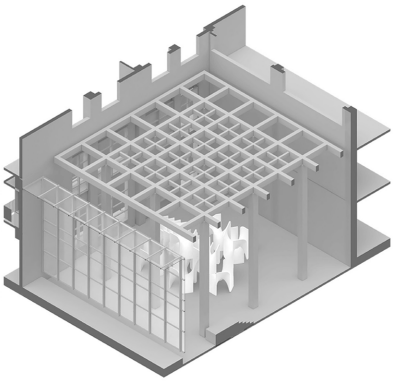
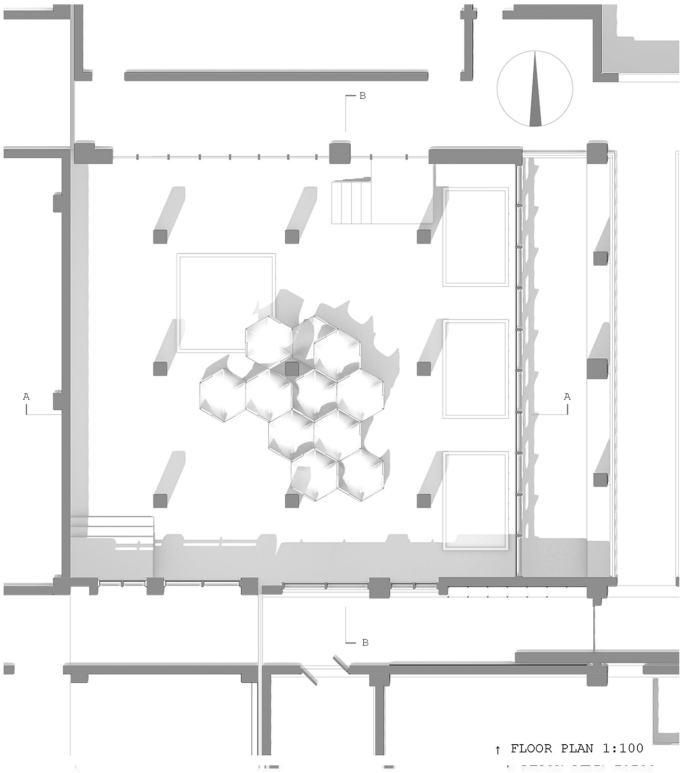


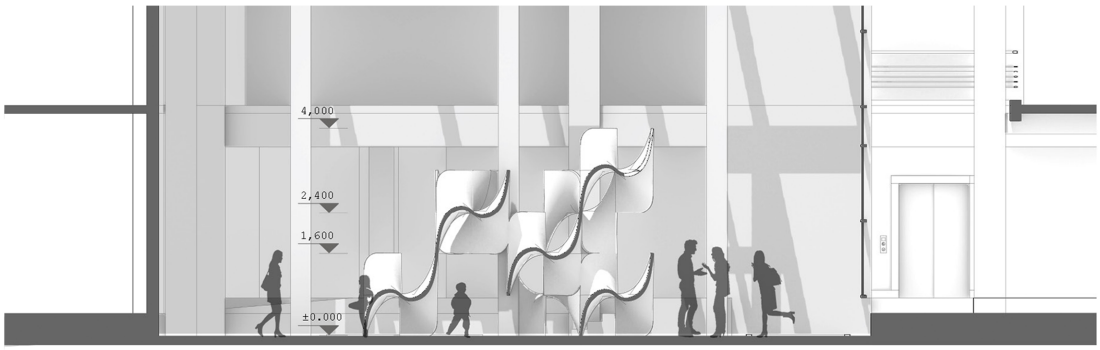
Plate 7 - Experiment 3: Robotic foam cutting



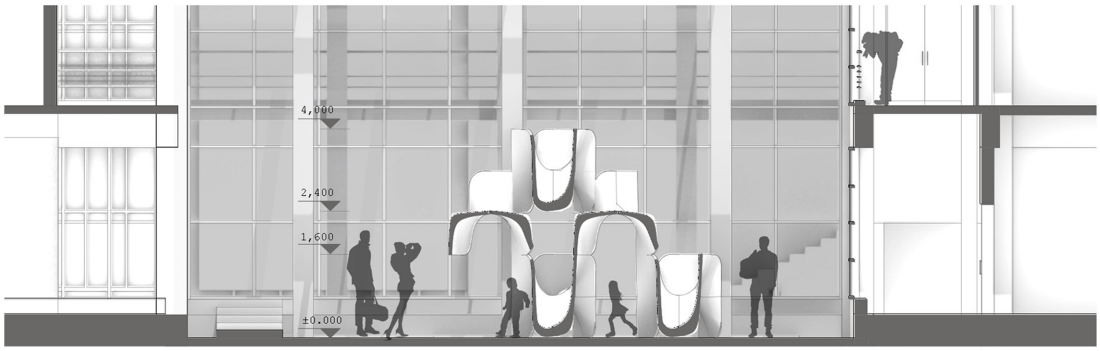
While the shape of the unit body can be determined, it is necessary to fully consider the cutting ability of the unit body and simulate the processing path of the robot hot wire cutting to ensure that the hot wire held by the robot smoothly cuts out the shape of the desired unit body, and does not Injury to other materials and materials. Write and simulate the robot machining path through the Grasshopper built-in plug-in KUKaprc, and finally output the robot processing file. After repeatedly debugging the machining program, adjusting the machining parameters, and testing the sample, the KUKA robot was adjusted from the T1 debugging mode to the Auto automatic mode, and began to enter the automatic machining process of a large number of machining unit bodies. In the end, we will use 15 foam cells to connect to each other to form a structural device with an infinitely curved surface, placed in the atrium of the school, and through the dialogue with the sun to produce rich light and shadow effects.



↑ FLOOR PLAN 1:100

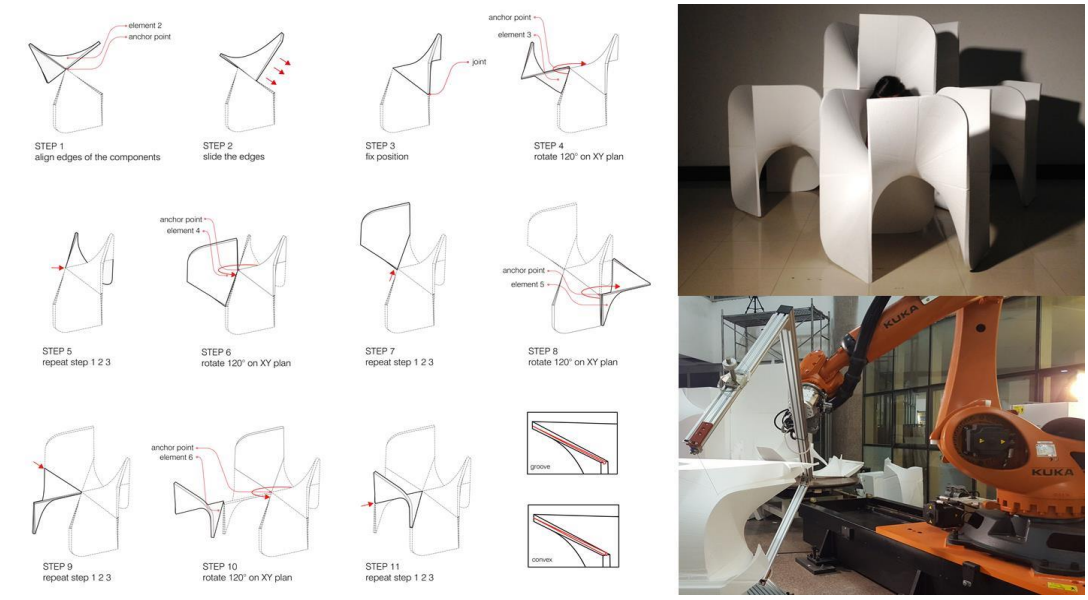


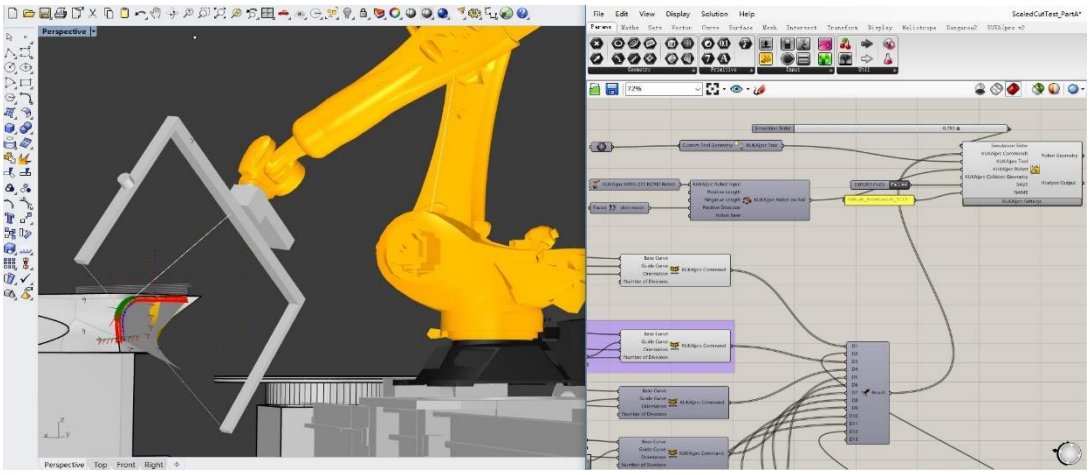
↑ A-A SECTION 1:75



↑ B-B SECTION 1:75

Plate 8 - Experiment 3: Robotic foam cutting





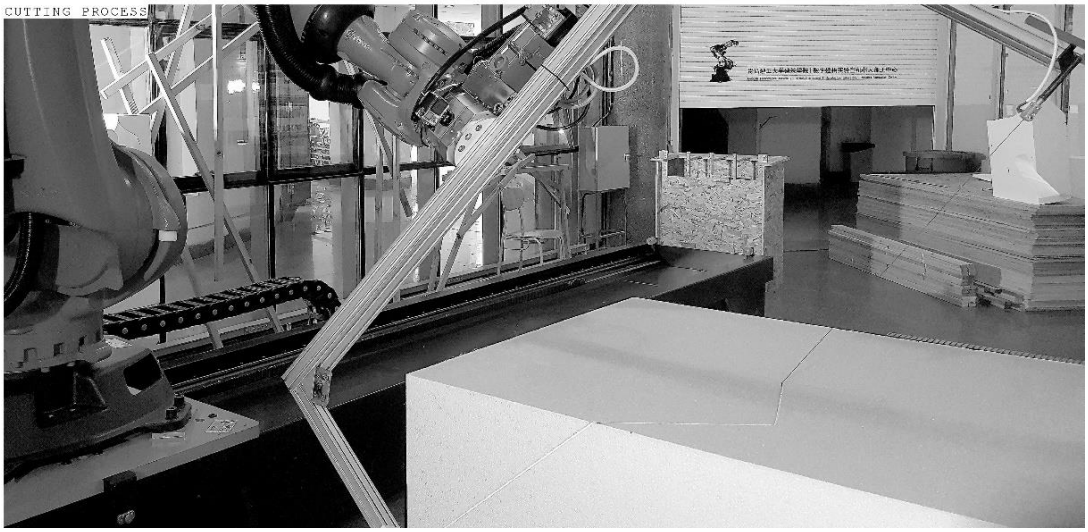


Plate 9 - Experiment 3: Robotic foam cutting

primarily represent the second stage of cross-simulation data and how it is necessary to the overall pedagogy.

The purpose of this hot-line cutting is to construct a structure of continuous striated surface [PERIODIC SURFACE], to create a complex, blurred, and growable space for people to enter and meditate and relax. After the camp, the multi-program design, comparison and discussion,we finally clarified a set of construction plans. The structure is constructed on the basis of human scales to create a core area for staying. The boundary between the inner and outer spaces is blurred by a continuous curved surface around the core area, and the experience is extended infinitely by the natural growth of the continuous curved surface.

In the following continuous surface generation process, the basic unit is evolved by various methods such as moving, copying, mirroring, and rotating to obtain various units. Due to the limitation of the cutting size, the unit is further fine-tuned after the unit combination mode is determined, so that the original quarter circle is reduced, and at the same time, the line is filled with two straight lines, and the addition of more straight elements makes the large unit It is easier to splicing each other.

To systematically link the form generation to robotic motion, the periodic surface component to be cut was abstracted into a single, continuous curve. This allowed the surface to be the driver for the motion path for the hot wire end-tool. With each new part as a discreet element in the whole aggregation, the tool-path of each piece had to be continuously adjusted to reflect any changes made to the final form. This link allowed the team to visualize the fabrication process and optimize the rotational movement of each axis prior to the final cutting, reducing both production time and potential for fabrication error. Needless to say, the other stages of robotic tectonics also have an effect on the simulation data. The shape and angle of the hot-wire tool, as well as the physical constraints of the foam material, heavily influence the constraints of fabrication with regards to the robot's motion paths. Due to the complexities of this foam-cutting process, one can see that simulation is integral to the overall platform as both a constraint and a design opportunity.

While the shape of the unit body can be determined, it is necessary to fully consider the cutting ability of the unit body and simulate the processing path of the

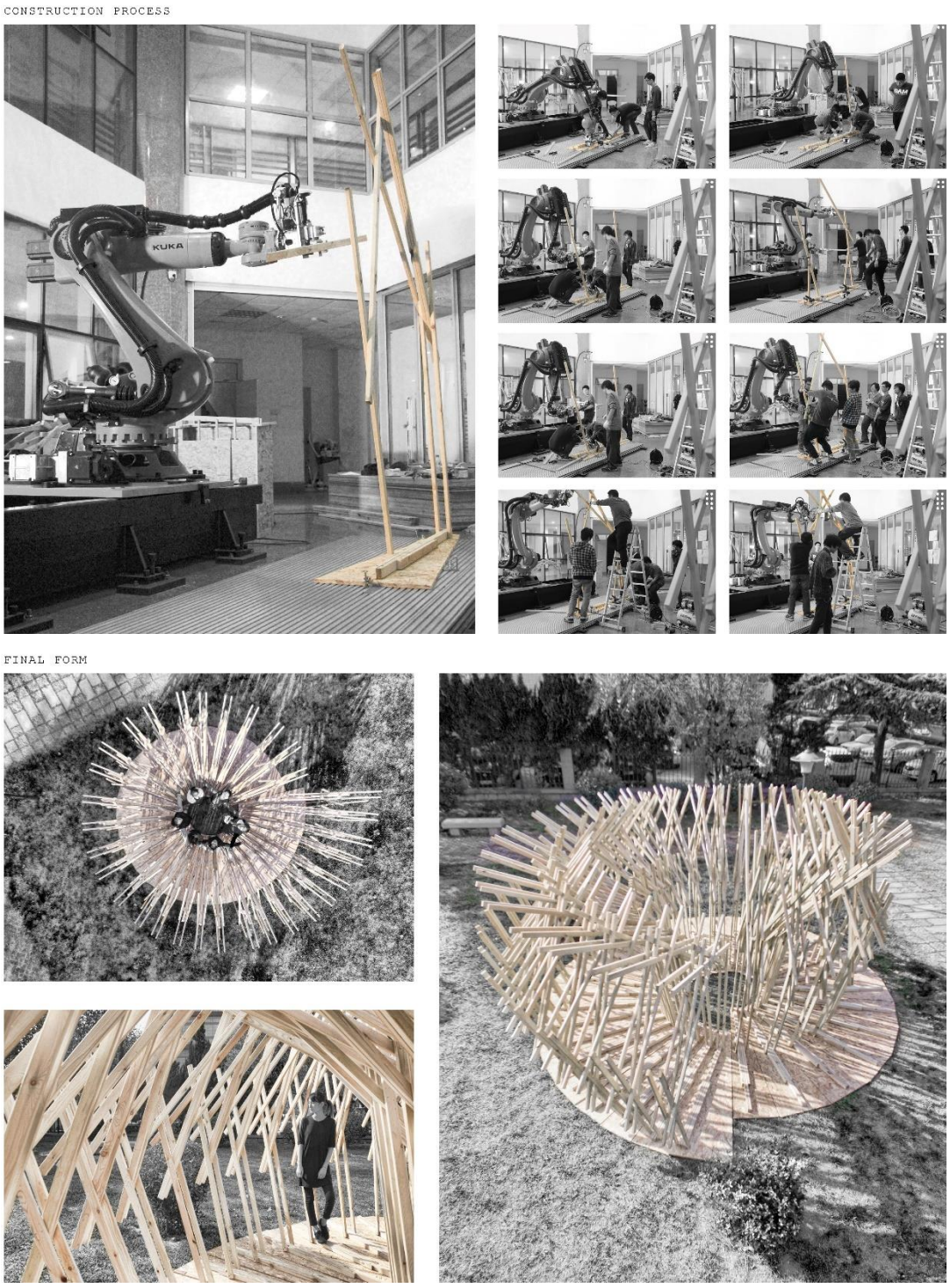


Plate 10 - Experiment 4: Robotic stick weaving assembly

robot hot wire cutting to ensure that the hot wire held by the robot smoothly cuts out the shape of the desired unit body, and does not Injury to other materials and materials. Write and simulate the robot machining path through the Grasshopper built-in plug-in KUKAprc, and finally output the robot processing file. After repeatedly debugging the machining program, adjusting the machining parameters, and testing the sample, the KUKA robot was adjusted from the T1 debugging mode to the Auto automatic mode, and began to enter the automatic machining process of a large number of machining unit bodies. In the end, we will use 15 foam cells to connect to each other to form a structural device with an infinitely curved surface, placed in the atrium of the school, and through the dialogue with the sun to produce rich light and shadow effects.

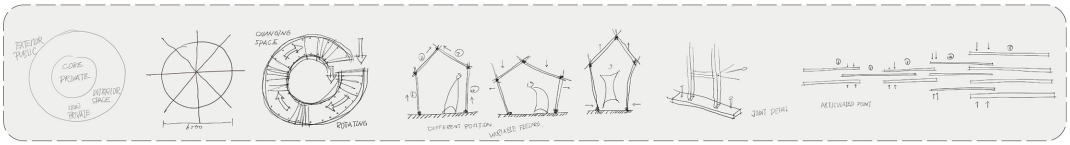
4.2.2. Experiment 4: Robotic stick weaving assembly

The theme of the construction experimental design is tea room. The purpose of the utilizing mechanical arm is to construct a structure with continuous changing sections to meet the scale requirements of the "living-sitting-relief" for the tea room space, at the same time, forming spaces which people will have different experiences of private, semi-private and public respectively.

The construction is based on standardized wooden strips of uniform size, but the position, direction and angle of each wooden rod are different in space. Therefore, the construction process is based on robot-assisted grabbing and positioning. In this process, the gripper orientation, motion, signal and other information determined by the orientation of the rod are compiled into robot-recognizable statement commands, and the robot sequentially places the different rods into a specific spatial position according to the command, and then fixes them with a gas nail gun. Complete all the components in turn and flatten them together to achieve the final build.

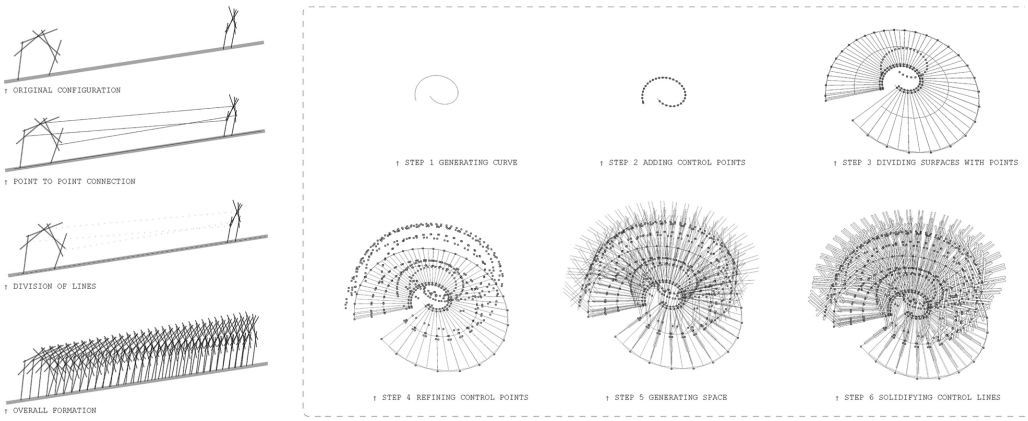
In the design process of concept and form, we first determined the plane shape of the tea room, that is, the corridor surrounded by two concentric circles of different sizes. To connect private, semi-private and public spaces in a softer way, we cut the complete circle and move one of the breakpoints inwards. At the same time, we envisage the space of the corridor, which should be continuously changing in the

CONCEPT DESIGN

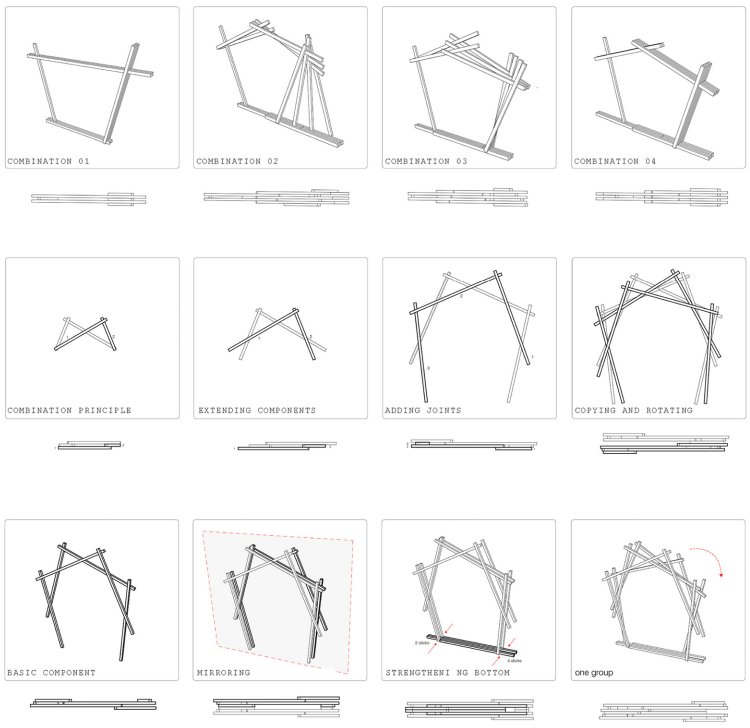


In the design process of concept and form, we first determined the plane shape of the tea room, that is, the corridor surrounded by two concentric circles of different sizes. To connect private, semi-private and public spaces in a softer way, we cut the complete circle and move one of the breakpoints inwards. At the same time, we envisage the space of the corridor, which should be continuously changing in the shape of the section to meet the needs of different interaction activities. In the connection method, we envisage the method of artificial fixation of nails to improve work efficiency and realize the original intention of human-machine cooperation.

GENERATING LOGIC



CONSTRUCTION UNIT DESIGN



EXPLORING POSSIBILITIES

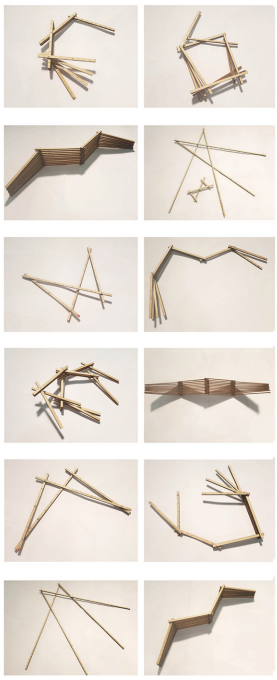


Plate 11 - Experiment 4: Robotic stick weaving assembly

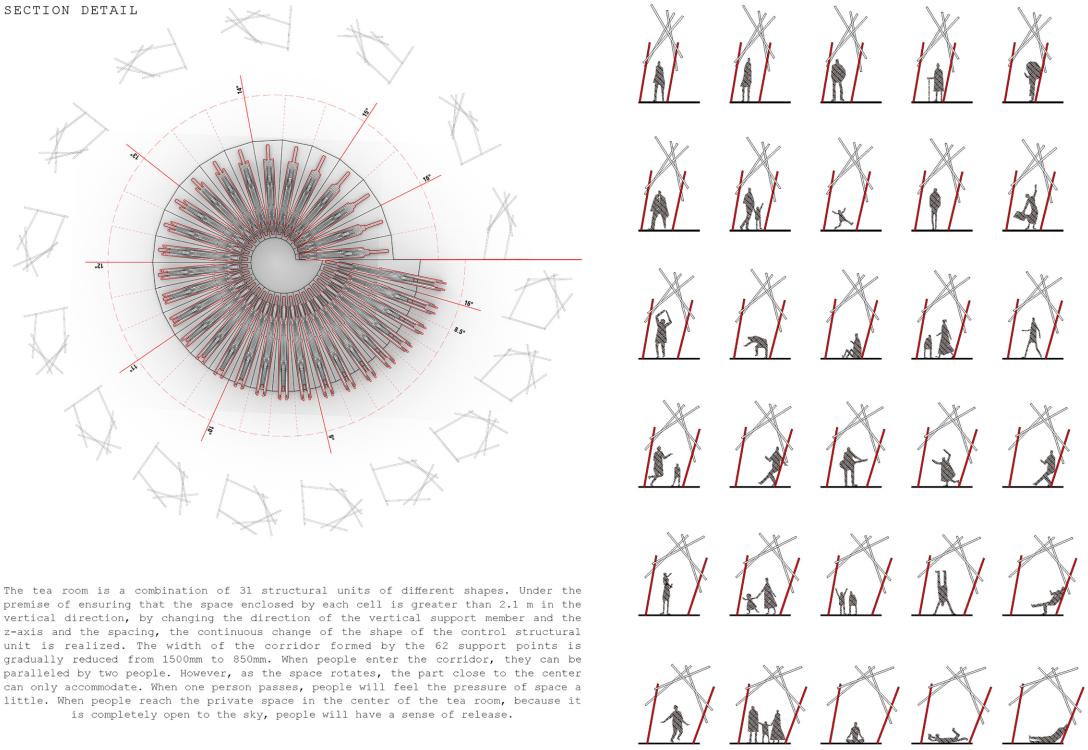


Plate 12 - Experiment 4: Robotic stick weaving assembly

shape of the section to meet the needs of different interaction activities. In the connection method, we envisage the method of artificial fixation of nails to improve work efficiency and realize the original intention of human-machine cooperation.

The tea room is a combination of 31 structural units of different shapes. Under the premise of ensuring that the space enclosed by each cell is greater than 2.1 m in the vertical direction, by changing the direction of the vertical support member and the z-axis and the spacing, the continuous change of the shape of the control structural unit is realized. The width of the corridor formed by the 62 support points is gradually reduced from 1500mm to 850mm. When people enter the corridor, they can be paralleled by two people. However, as the space rotates, the part close to the center can only accommodate. When one person passes, people will feel the pressure of space a little. When people reach the private space in the center of the tea room, because it is completely open to the sky, people will have a sense of release.

4.3. Investigation on the efforts of virtual simulation for design conception

From the questionnaire results of Stage 2 (Fig and Table), it could find that there are normally distributed with a relevant higher average value in each question. The frequency distribution of the workflow feedback in this stage shows a negative skewed unimodal distribution for Q1-2 and Q2-2 while a positive skewed unimodal distribution presented for Q3-2. The performance scores given by the greatest number of students are all 7 points. As the Figure and Table shows: (1) Although the participation of students has remained at a relatively high level (mean=6.36, Std.D=2.34), it has declined compared with Stage 1, mainly because the courses in this stage involve knowledge of programming and simulation, which is not in the conventional architectural design curriculum. (2) Stage 2 is more difficult for students (mean=6.82, Std.D=1.84), which is also one of the reasons that affect the enthusiasm of students to participate in the course. Despite this, (3) most students still believe that this stage is of significant importance in the entire workflow (mean=7.18, Std.D=1.63), with 75.2% of students scoring more than 7. At this stage, they previewed the actual construction process of their design model in a visual and virtual way and found that this process helps to discover a sequence of key issues that will be faced later.

Moreover, the frequency distribution of the content understanding in Stage 2 presents a negative skewed unimodal distribution for Q4-2 and Q5-2 while a positive skewed unimodal distribution presented for Q6-2, and the most students gave scores of 7, 8, and 8, respectively. The results show that: (1) The course content of Stage 2 could promote students' understanding of the concept of "Tectonic" with the mean values of 6.65 for Q4-2, 7.60 for Q5-2, and 7.16 for Q6-2. (2) This stage helps to deepen the understanding of "Tectonics means clear and logic structure", which is the same as Stage 1. From the radar chart (The Fig.25), due to the increased difficulty of the second stage, the participation decreased compared with Stage 1. This stage involves performance simulation, so it is helpful for understanding materials and construction to some extent.

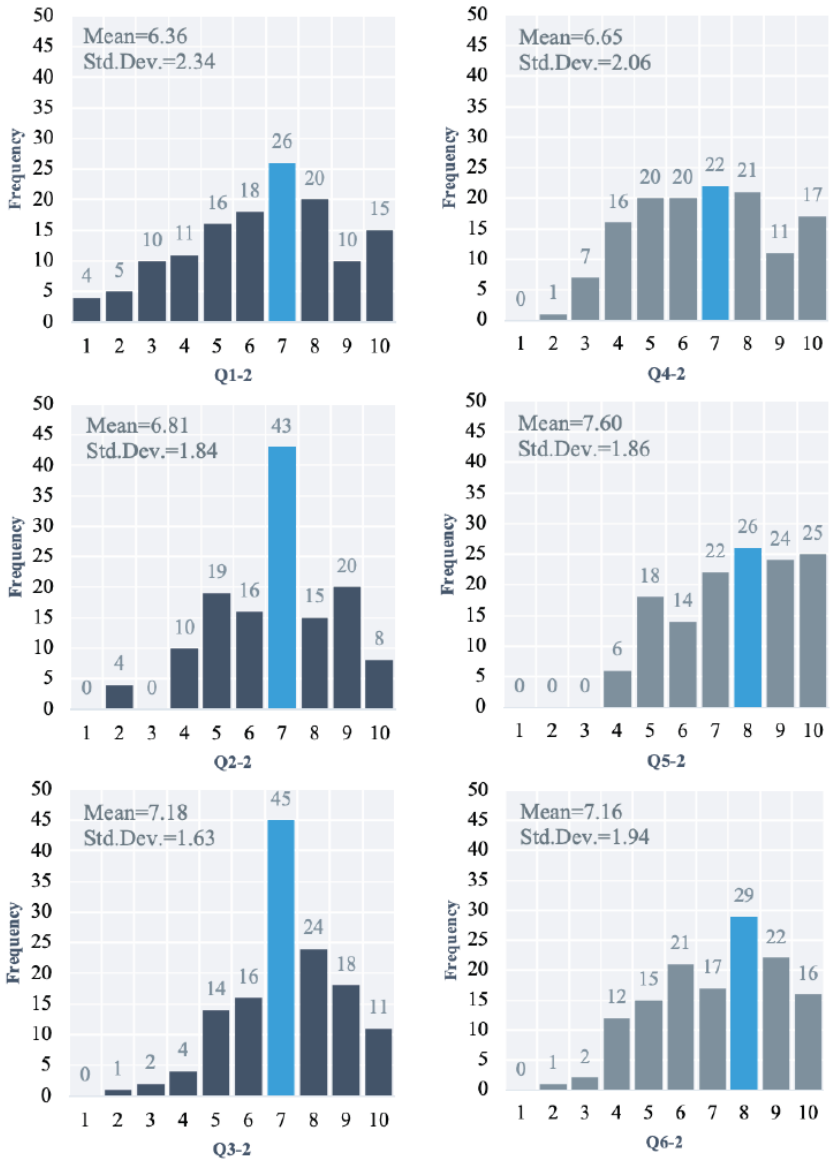
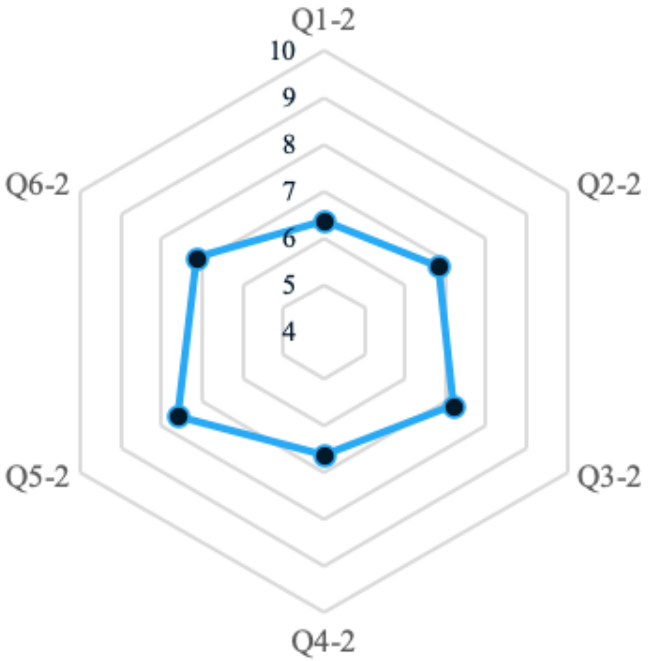


Fig. 25 Frequency distribution analysis of the content understanding in Stage 2

	Q1-2	Q2-2	Q3-2	Q4-2	Q5-2	Q6-2
Mean	6.36	6.81	7.18	6.65	7.60	7.16
Std. Error	0.20	0.16	0.14	0.18	0.16	0.17
Median	7	7	7	7	8	7
Mode	7	7	7	5	10	8
Std.Dev.	2.36	1.84	1.63	2.06	1.85	1.94
Variance	5.59	3.37	2.65	4.24	3.44	3.76
Range	9	9	8	7	7	8
Minimum	1	2	2	3	4	2
Maximum	10	10	10	10	10	10
Sum	858	921	969	898	1032	966
N	135	135	135	135	135	135

Table 5 Empirical results' list by frequency distribution analysis of Stage 2



Q1-2. The degree of participation in each stage
Q2-2. The difficulty degree of each stage to the overall workflow
Q3-2. The importance of each stage to the overall workflow
Q4-2. The degree of understanding "Tectonics lays in the interaction between material and construction"
Q5-2. The degree of understanding "Tectonics means clear and logic structure"
Q6-2. The degree of understanding "Tectonics represents performative architecture"

Fig. 26 Characteristic analysis of Stage 2 by using the mean data of the frequency distribution

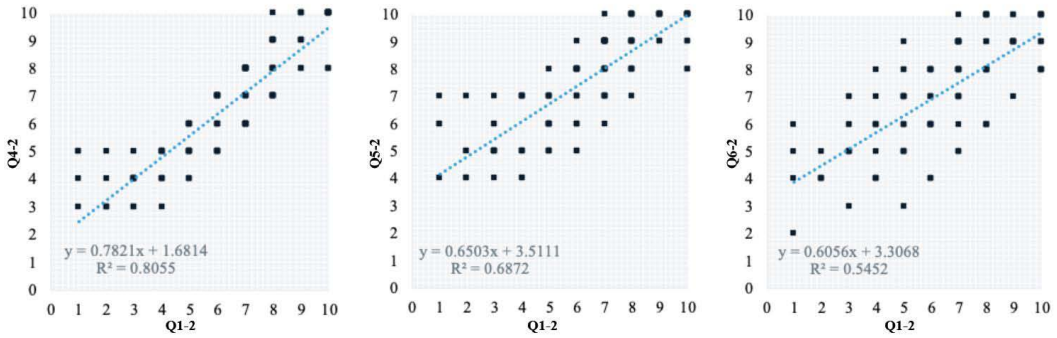


Fig. 27 Linear regression analysis of the participation degree and content understanding degree of Stage 2

Variables	Pearson correlation	Linear regression				ANOVA			N
		R^2	Slope	Y-intercept	t	Sig.	F	Sig.	
Q4-2	0.898	0.806	0.782	1.681	23.472	0.000	550.955	0.000	135
Q5-2	0.677	0.485	0.473	5.019	10.609	0.000	112.541	0.000	135
Q6-2	0.738	0.545	0.606	3.307	12.627	0.000	159.451	0.000	135

Table 6 The empirical results' list of linear regression for Stage 2

Similarly, there are significant positive liner correlative relationships between the degree of participation (Q3-2) and content understanding of the concept "tectonic" with the R-squared values between Q3-2 and Q4-3 were 0.806, followed by 0.545 of Q6-2 and 0.485 of Q5-2 (Fig and Table). Therefore, improving participation is a particularly effective approach for understanding the content of “Tectonics lays in the interaction between material and construction”.

4.4. Summary

In this chapter, the virtual simulation of multiple data for design to fabricate as the second stage of Robotic Tectonics workflow is fully described with two experiments demonstration and correspondingly questionnaire survey for the feedbacks from curriculum participants. Conclusions are summarized as follow.

1) Multi-data simulation, this virtual model provides a platform to brings various logic-based databases such as geometry, spatial location, form generation, construction sequence, simulation data, operation constraints, etc. together. Based on the parametric model establishes links between all of this data, resulting in a comprehensive simulation mechanism in which the revealed robotic operations will most definitely have an impact on the overall design.

2) Grasshopper embedded robotic simulation and control software KUKA|prc provides a virtual, visual simulation in a safe environment for architects or students to analyze every detailed step of the construction process previous to its implementation. Simulation is set as the second stage of the overall pedagogy in order to help students gain robotic operational skills and to trigger critical thinking about the impact of these operations so that they can later optimize the parametric design concepts generated in the previous stage.

3) From the experiment 3, we could find the simulation process provides a virtual 4D environment, with the three-dimensional space and the timeline based cutting sequence, which could easily test the design results of the complex continues surface, providing the intuitive feedback for designer, to understanding creation of tectonic thinking through virtual simulation practice.

4) From the experiment 4, we could find the virtual simulation is used for the assembly process, to put a wooden stick into a precise position spatially, it not only requires a building sequence to achieve, but also have to follow the structural balance principle to keep it stiff while assembling process. This multi-data imbedded simulation allows designer think broadly and keep controlling the entire tectonic practice.

5) From analysis of the feedbacks from participants of the curriculum teaching questionnaires, we could found students are strongly recognized and agreed with the importance efforts of the multi-data simulation stage for the entire workflow of Robotic Tectonics, it reflects the students' sense of identity with this pedagogical concept, and gains deeply understandings of tectonic thinks by deep participation.

Chapter 5. Construction aimed digital tool development and application

5.1. Introduction 5-1

5.2. Digital tool application in advanced architectural design 5-3

5.2.1. Experiment 5: Robotic 3D spatial printing 5-3

5.2.2. Experiment 6: Robotic Brick Construction 5-9

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5.4. Summary 5-17

5.1. Introduction

This chapter focused on the process of End-tool Application and its efforts in the workflow of Robotic Tectonics, revealing the utilization of different end tool effectors applied to digital fabrication process, how these construction-aimed digital tool developed and influenced the design process.

Two experiments are introduced to demonstrate the necessity of developing the end tool effectors that combined the design concepts, materialization, and fabrication processes into the integrated digital design to fabrication process. In this end toll development and application stage, interdisciplinary knowledge is collected and applied to the renovation of building construction, which brings mechanical engineering, signal control engineering, automation engineering, computational engineering together into the construction aimed research and development process. Experiment 5 demonstrated a self-build 3D printing tool applied into the robotic arm for spatial 3D printing project, which printing light weighted components that could potentially use as façade components. Experiment 6 is demonstrating a self-build picking, gluing, and placing end tool effector that could used for a automation brick construction process, with its fast and precise ability, a creative brick tectonic practice is presented.

For the construction-aimed digital tool development and application, a questionnaire focused on this process is analyzed, based on 135 participate students on the curriculum of *Robotic Construction Prime* and feedbacks from it, analysis is made and described. Empirical analysis proves the significant efforts of End-tool Application process for developing Robotic Tectonics workflow and creating tectonic thinking for design inspiration.

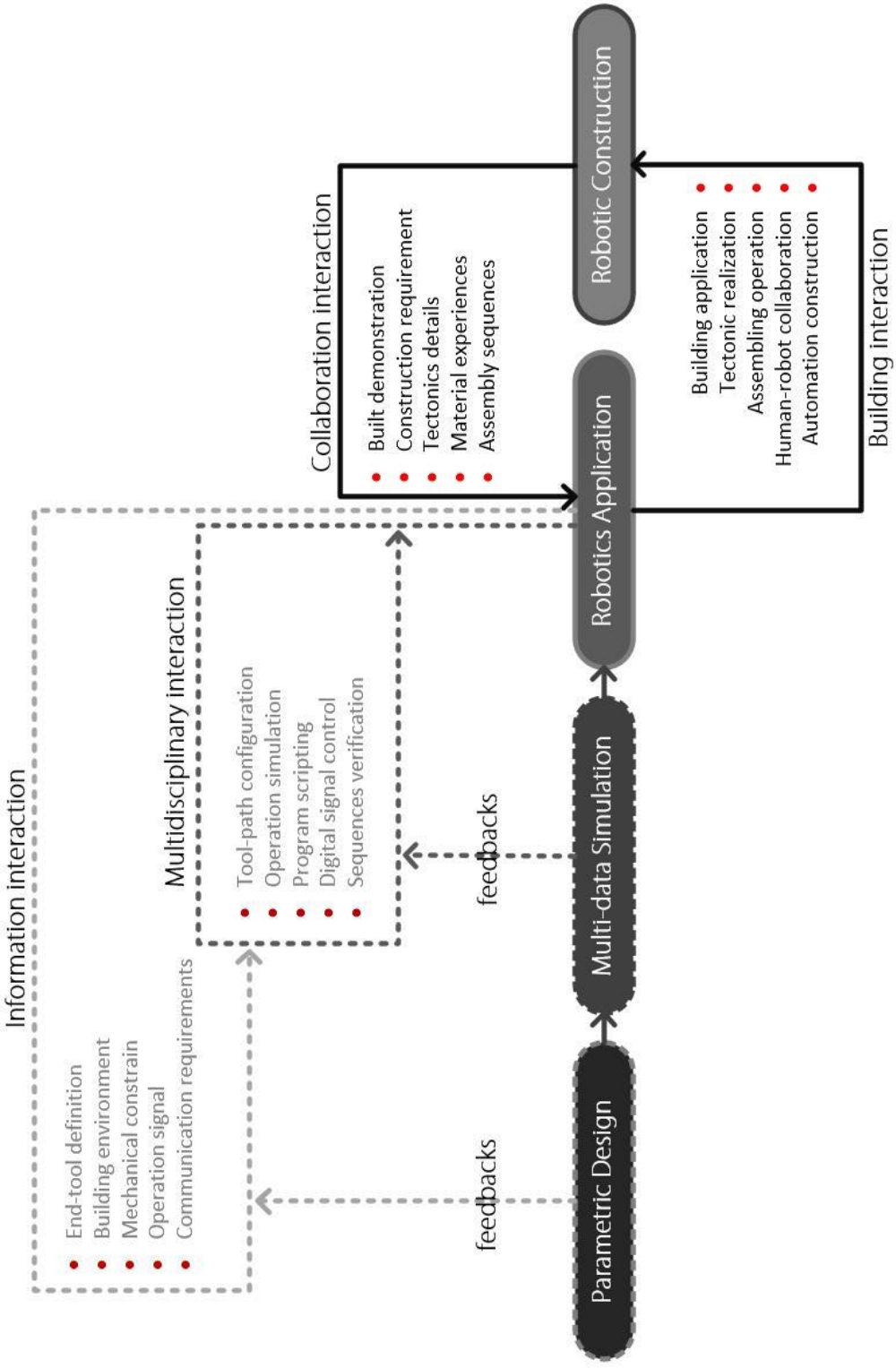


Fig. 28 Framework for the process of robotics application

5.2. Digital tool application in advanced architectural design

Programming the robots' movement in virtual simulation software is already quite a complicated process, but it is merely a representation of the construction workflow that will need to be utilized in order to bring these designs into reality. Generally speaking, industrial robots can only respond to positional commands, and they have no awareness of what is going on in their environment. This could lead to unforeseen motion that can damage the environment, the work, or even the people in proximity to the robot. Therefore, any form of automation in the realm of construction needs a carefully programmed, simulated, and detailed model of its operating environment, especially when it comes to the design and integration of construction-oriented end effectors into the system.

The end effector (sometimes called the end tool) is arguably the most important component of the industrial robotic arm. It helps to realize the construction or fabrication sequence and it is the only part of the robot specifically designed to interact with its physical environment. Its weight, shape, function, and precision are all critical to the construction process. Therefore, the objective of this stage is to guide students to understand the importance of interdisciplinary cooperation between engineering and design and to introduce them to construction-oriented robotic end tools. These tools, as instrumental aspects of robotic fabrication, need to be customized and integrated by those under the robotic tectonic pedagogy so they (the students) can provide maximum flexibility for robots as automation tools, thus continuing to enhance the efficiency of the overall system.

5.2.1. Experiment 5: Robotic 3D spatial printing

With the advance of technology and changes in aesthetic demand, advanced digital technologies have been increasingly used in the construction industry and the form of architecture has become more flexible. Many non-linear architectural works have been emerging and diverse components are introduced to meet the change in architectural needs, which makes it difficult for traditional manufacturing processes

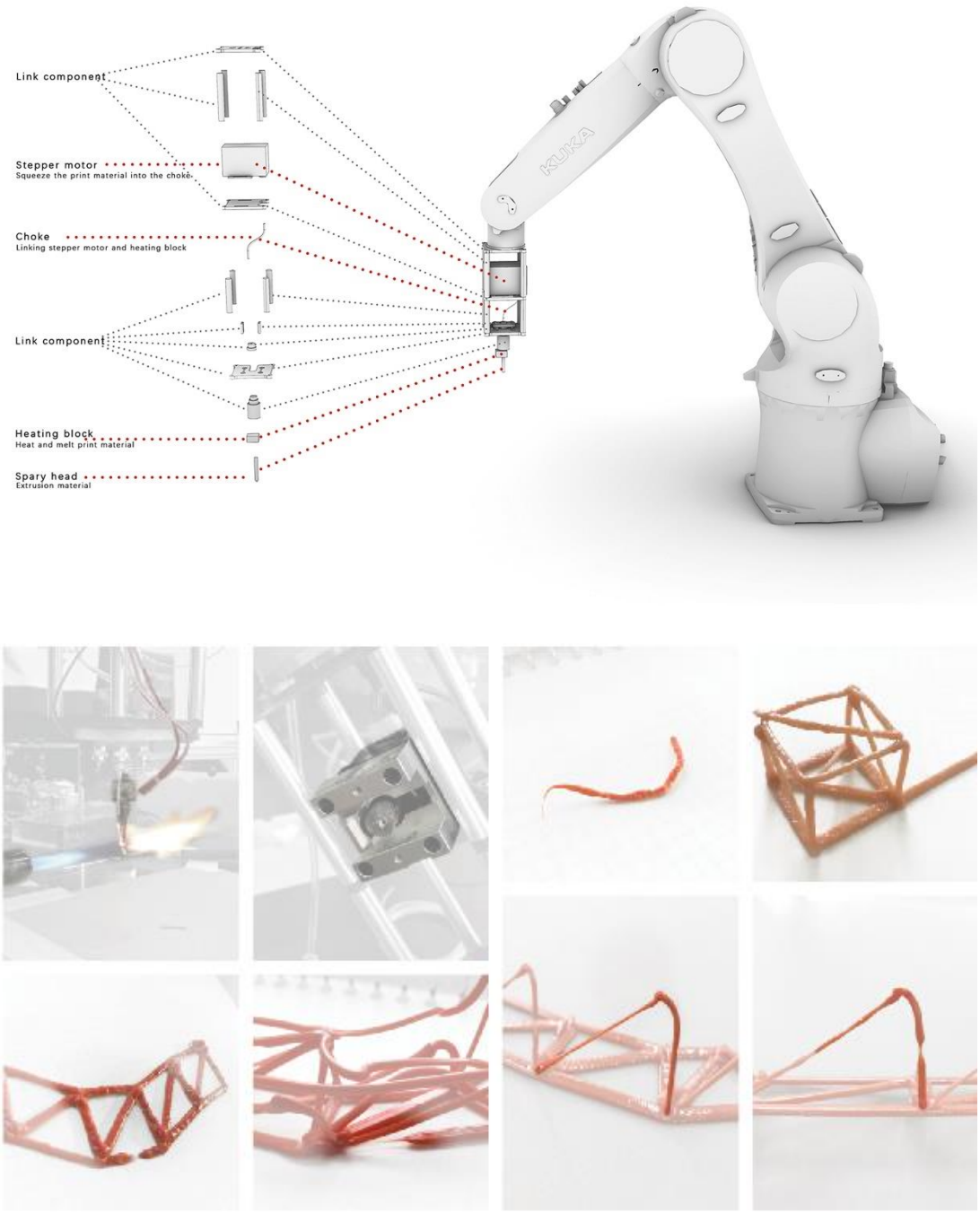
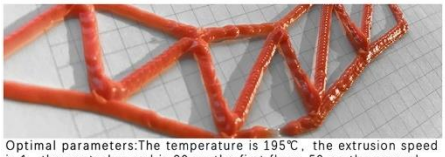
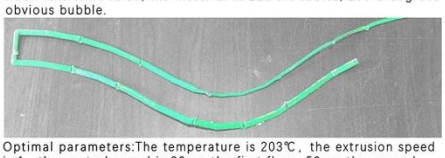


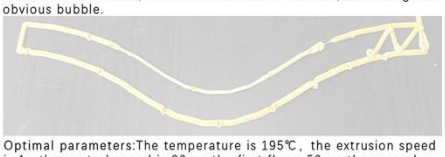
Plate 13 - Experiment 5: Robotic 3D spatial printing



Optimal parameters:The temperature is 195℃, the extrusion speed is 1, the control speed is 30 on the first floor, 50 on the second floor. And limit value, the material at 220℃ bubbles, 230℃ degrees obvious bubble.



Optimal parameters:The temperature is 203℃, the extrusion speed is 1, the control speed is 30 on the first floor, 50 on the second floor. And limit value, the material at 220℃ bubbles, 230℃ degrees obvious bubble.



Optimal parameters:The temperature is 195℃, the extrusion speed is 1, the control speed is 30 on the first floor, 50 on the second floor. And limit value, the material at 220℃ bubbles, 230℃ degrees obvious bubble.

Optimal parameters:The temperature is 190℃, the extrusion speed is 1, the control speed is 30 on the first floor, 50 on the second floor. And limit value, the material at 225℃ bubbles, 230℃ degrees obvious bubble.

Optimal parameters:The temperature is 210℃, the extrusion speed is 1, the control speed is 30 on the first floor, 50 on the second floor. And limit value, the material at 225℃ bubbles, 235℃ degrees obvious bubble.

Optimal parameters:The temperature is 225℃, the extrusion speed is 1, the control speed is 30 on the first floor, 50 on the second floor. And limit value, the material at 235℃ bubbles, 240℃ degrees obvious bubble.

PLA(orange)	1	2	4	5	6	7	8
Time	0.547917	0.554167	0.560417	0.570139	0.574306	0.75486	0.760417
Actual temperature	200	220	218	230	230	230	240
Setting temperature	202	198	198	200	270	195	210
Forecast temperature	200	200	200	200	270	195	195
Extrusion speed	10	9	10	9	9	1	0
Printing speed	30	50	30	50	50	30	50
Room temperature	19	19	19	19	15	19	17

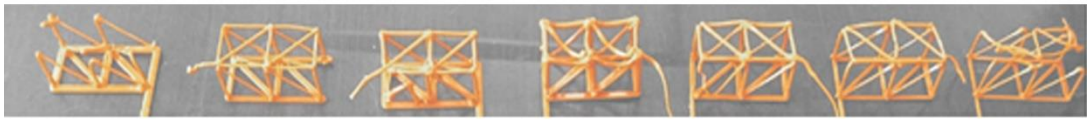
PLA(green)	1	2	3	4	5	6	7
Time	0.685417	0.69375	0.709722	0.745139	0.44653	0.454167	0.709722
Actual temperature	240	244	246	233	230	230	230
Setting temperature	209	210	209	209	203	270	205
Forecast temperature	205	210	210	210	203	270	205
Extrusion speed	0	0	0	0	1	1	1
Printing speed	50	50	50	50	30	50	50
Room temperature	19	19	19	19	19	19	19

PLA(gradient)	1	2	3	4	5	6	7
Time	0.831944	0.873611	0.554167	0.560417	0.83194	0.873611	0.554167
Actual temperature	230	223	220	218	220	223	220
Setting temperature	210	211	198	198	195	211	198
Forecast temperature	210	210	200	200	195	210	200
Extrusion speed	0	0	9	10	1	0	9
Printing speed	75	75	50	30	30	75	50
Room temperature	18	20	19	19	18	20	19

PLA(black)	1	2	3	4	5	6	7
Time	0.4375	0.440972	0.444444	0.44792	0.4375	0.440972	0.444444
Actual temperature	250	230	220	205	250	230	220
Setting temperature	230	211	197	190	230	211	197
Forecast temperature	230	210	197	190	230	210	197
Extrusion speed	0	0	0	1	0	0	0
Printing speed	0	text	text	30	0	text	text
Room temperature	19	19	19	19	19	19	19
Material viscosity	bad	bad	general	excellent	bad	bad	general
Bubbles	many	many	a few	not have	many	many	a few

PLA(gray)	1	2	3	4	5	6	7
Time	0.4375	0.440972	0.444444	0.447917	0.4375	0.44097	0.444444
Actual temperature	250	230	220	205	250	230	220
Setting temperature	230	211	197	190	230	211	197
Forecast temperature	230	210	197	190	230	210	197
Extrusion speed	0	0	0	0	0	0	0
Printing speed	75	50	100	30	50	30	30
Room temperature	19	19	19	19	19	19	19
Material viscosity	bad	bad	general	excellent	bad	bad	general
Bubbles	many	many	a few	not have	many	many	a few

PETG(clarity)	1	2	3	4	5	6	7
Time	0.9375	0.938194	0.938889	0.9375	0.938194	0.938889	0.938194
Actual temperature	240	230	240	240	230	240	230
Setting temperature	225	218	223	225	218	223	218
Forecast temperature	225	220	222	225	220	222	220
Extrusion speed	0	0	0	0	0	0	0
Printing speed	text	text	text	text	text	text	text
Room temperature	19	19	18	19	19	18	19
Material viscosity	general	bad	general	general	bad	general	bad



Temperature: 185	Temperature: 195	Temperature: 205	Temperature: 215	Temperature: 195	Temperature: 195	Temperature: 195
Speed: 30	Speed: 30	Speed: 30	Speed: 30	Speed: 50	Speed: 75	Speed: 100

Plate 14 - Experiment 5: Robotic 3D spatial printing

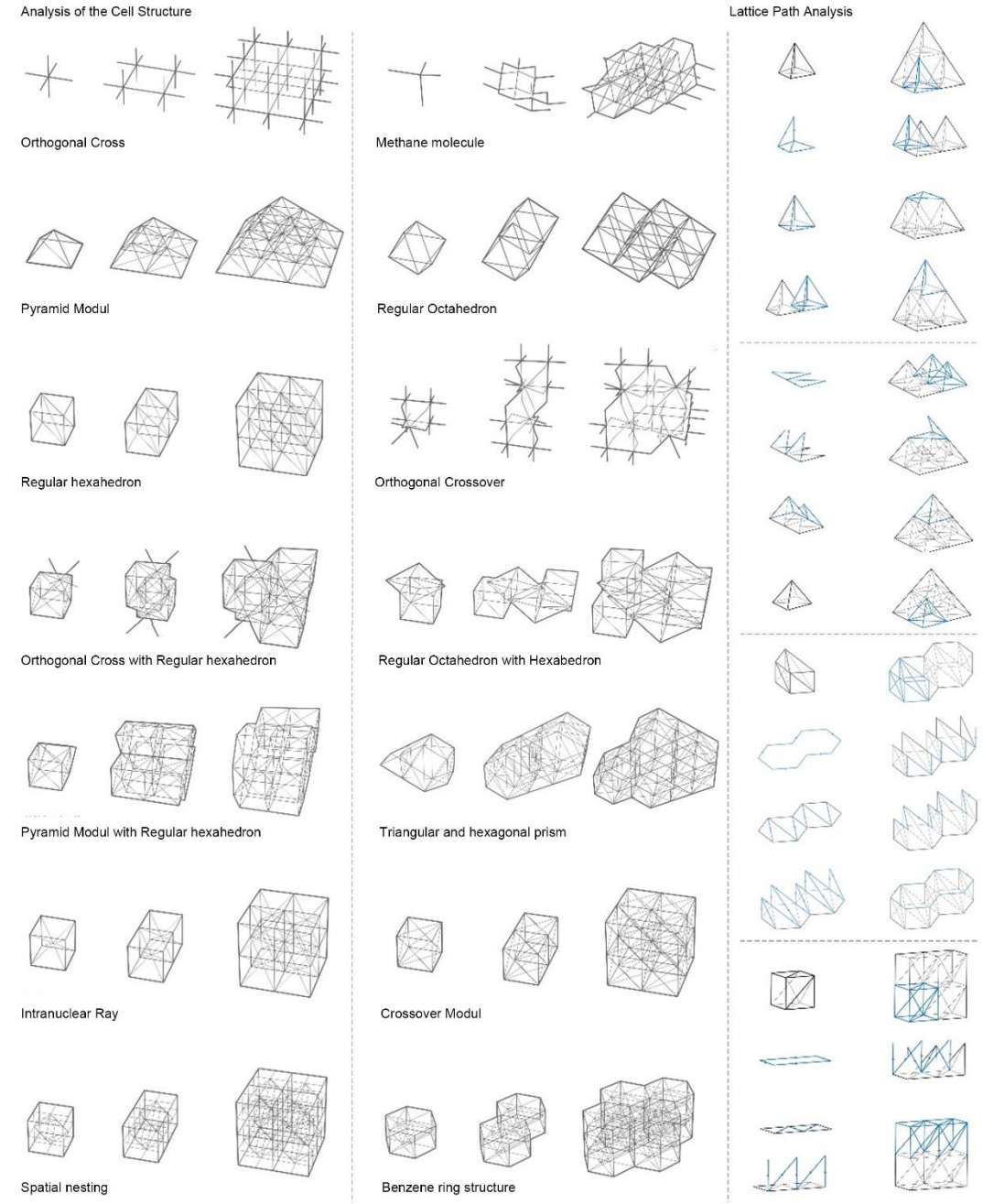


Plate 15 - Experiment 5: Robotic 3D spatial printing

to meet the demand of production, and the cost of free formed structures is difficult to control. Therefore, it's urgent to develop automatic mass production technology for free formed components.

In this context, this experiment try to come up with a solution with spatial printing (SP) technology. It explores the workflow and the application of SP technology construction logic first with plastic and followed by other possibilities of materials and printing methods. Also, here we tried to combine this technic with other disciplines such as computer algorithms, robotic digital construction and bionics, to explore approaches and possibilities for efficient mass production of free formed building components.

Polylactide (PLA) must be heated to a very specific temperature before it converts to a more viscous form (Melnikova, Ehrmann, & Finsterbusch, 2014). For proper spatial printing, when the molten material meets the cold air at the extrusion nozzle, the material temperature must then decrease rapidly. If done properly, the molten plastic quickly solidifies in mid-air. This unique feature achieves the formal qualities of 3D printing without relying on the traditional layering technique. The robot arm, unlike other deposition tools, can accurately navigate to the position of each node in the structure and quickly construct a self-supporting unit, eventually resulting in the designed form. (Plate 13-15)

Compared with the traditional fused deposition 3D printing (FDM), spatial 3D printing has several advantages (Gaub, 2016; P. F. Yuan, Meng, Yu, & Zhang, 2016). Firstly, while ensuring the strength of the structure, spatial 3D printing can build components of similar volume in less time and with less material. With the robot arm, the position of each printed node is more accurate, which greatly improves the aesthetics and structural stability of the components. Secondly, the spatial printing process is less limited by the need for support material, so the standard restrictions on the final form are greatly reduced. Lastly, it results in large open spaces inside the individual prints, so that when they are used as building components, these spaces could allow for the integration of other building components or systems. Therefore, robotic 3D spatial printing has been greatly anticipated in the field of architecture. This workshop specifically focused on exploring the feasibility of generating a complex morphological structure through a self-built PLA extruder. This required

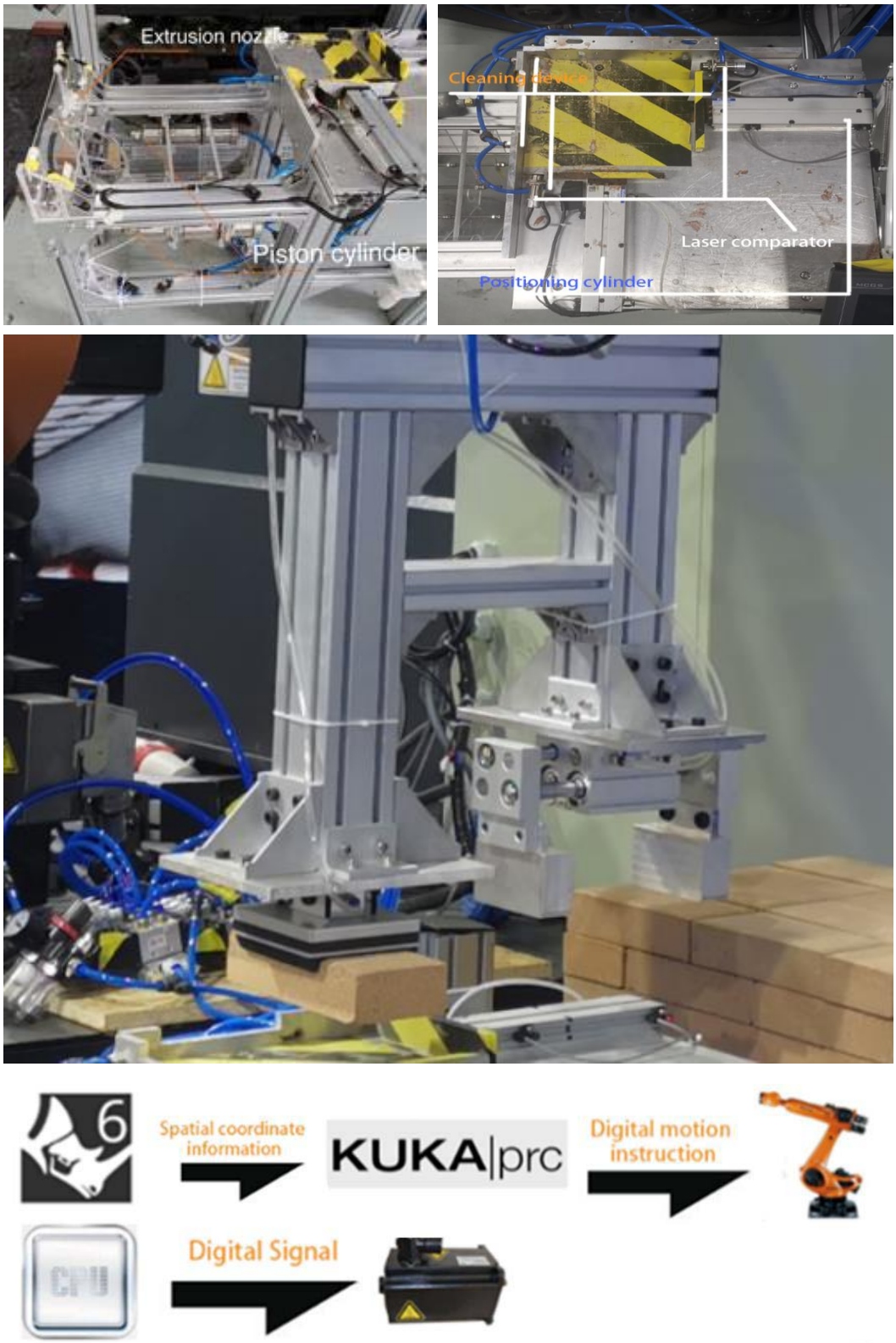


Plate 16 - Experiment 6: Robotic Brick Construction

repetitiously optimizing the extruding system to reliably accommodate the various demands of spatial printing. The end-tool became the priority, as very precise temperature changes had profound impacts on the overall design of the structure.

If the temperature at the nozzle gets too high, the material will be overheated, producing bubbles which affect the appearance and structural strength of the work. If the temperature is too low, it will reduce the viscosity of the material and lead to insufficient joint strength. In addition, the wind speed of the cooling airflow and the extrusion rate of the material will have a direct impact on the printing results. These issues became the focus of the optimization as they had the most profound impact on the overall design, simulation, and material properties of the final product. As such, this workshop demonstrates that the third stage of the workflow (development of the end tool) is equally a critical part of the platform and greatly effects the efficiency of the entire system.

5.2.2. Experiment 6: Robotic Brick Construction

With the rapid development of the industry, digital methods have been widely used in architecture design in recent years. Various technologies have greatly improved the production efficiency and construction accuracy. This article is trying to explore a complete workflow from digital design to digital construction including

robotic tools design, architectural design, and building construction. This article took the traditional brick as the pointcut and applied parametric modeling software to simulate and optimize the scheme. Finally, realized the automatic construction of the dynamic brick wall based on the universal KUKA platform and tools required.

During the construction of this entire experiment, we directly realized the design through the “Design-Procedure-Fabrication” (DPF) workflow construction, instead of the traditional “Design-Drawing-Construction” (DDC) workflow. By applying DPF workflow, the design expression was realized consistently rather than series mistakes due to the data loss in the DDC workflow, while lots of repeated human labor were reduced.

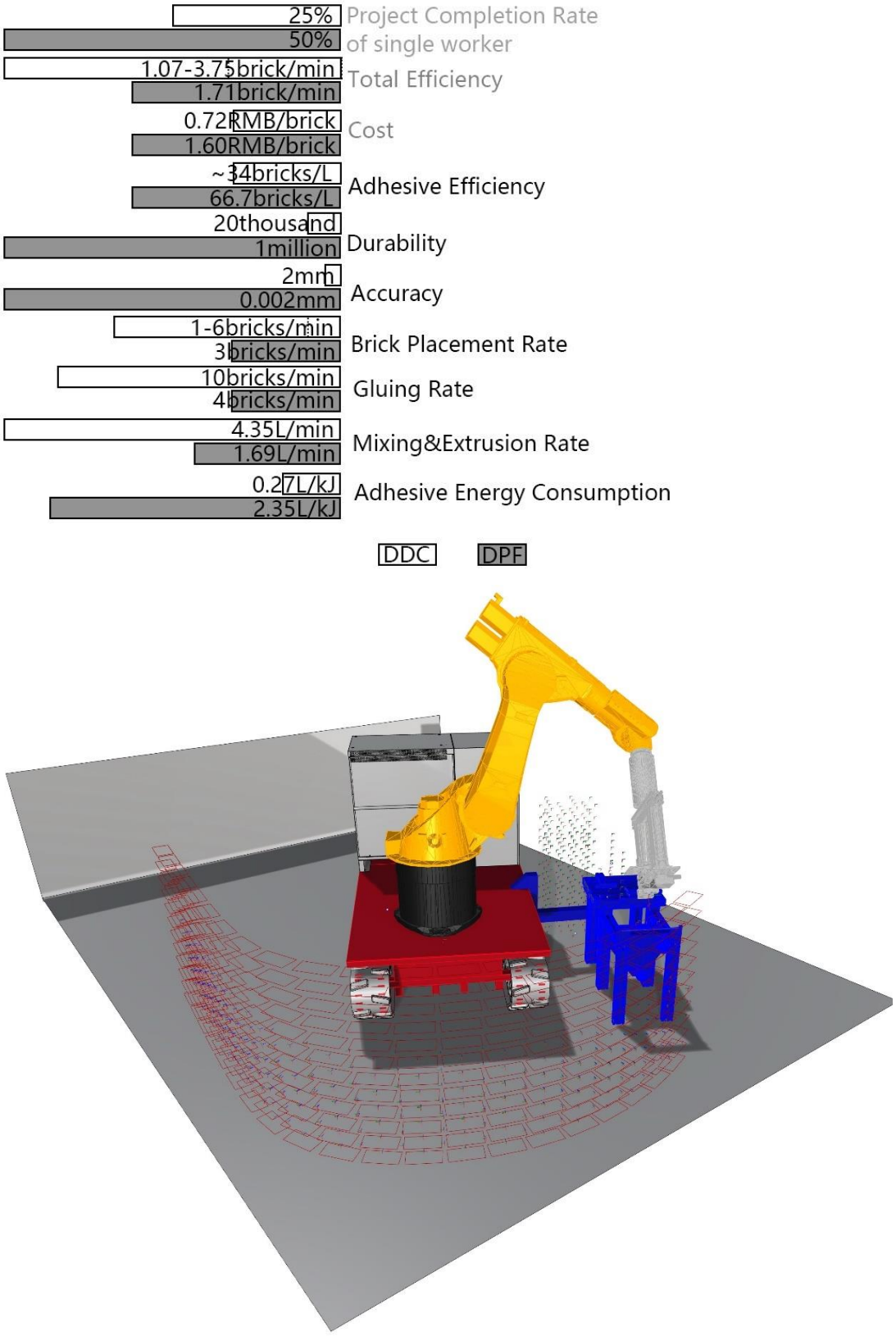


Plate 17 - Experiment 6: Robotic Brick Construction

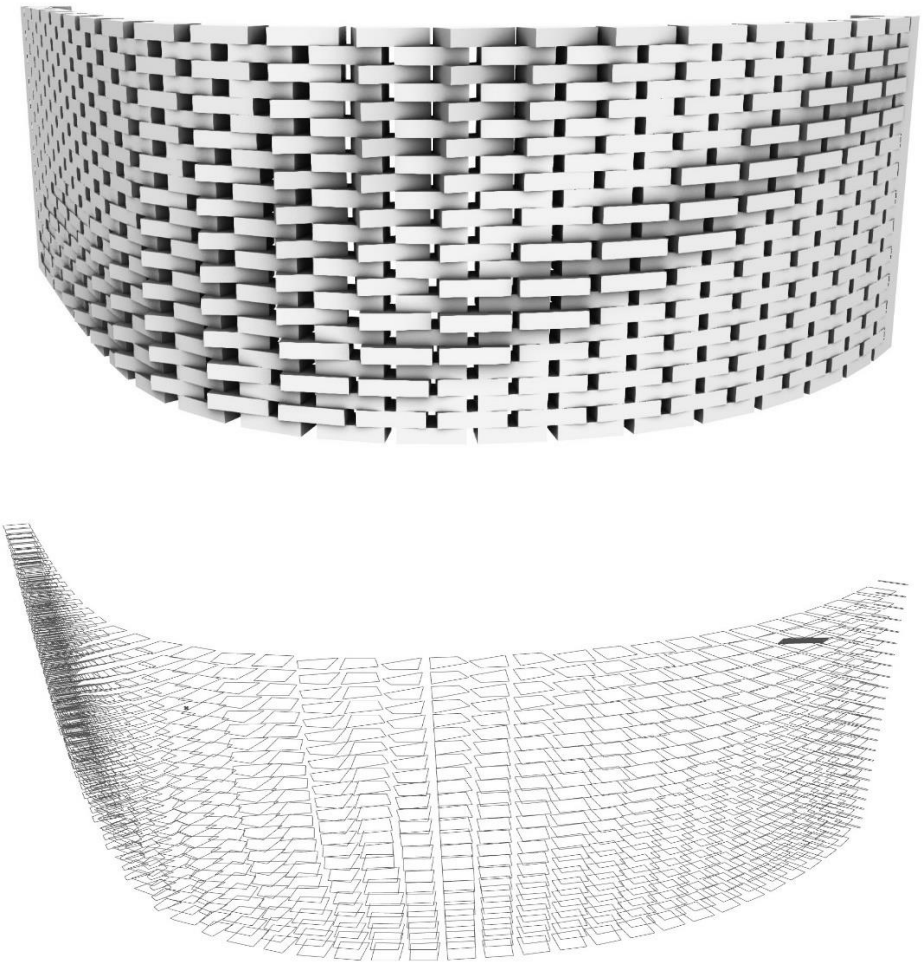


Plate 18 - Experiment 6: Robotic Brick Construction

Non-linear and digital designs are being sought after by more. However, traditional DDC workflow will generate enormous data loss, but require a lot of costs to achieve them. It can be predicted that, with DPF workflow maturing, more possibilities of architecture will be implemented completely and high-efficiently.

The addition of digital construction has improved the accuracy of construction products and avoided the waste of materials in the process of the brick building. Realize the architect's vision more accurately and faster. The integration of the workflow of robot construction and the construction process opens the vertical transmission channel of building information to building construction. At the same time, the KUKA | PRC plug-in provided by the platform enables the architects to transfer the designed building information quickly and effectively to the processing end. It does not need to transform the data as in DDC workflow, avoiding the loss of data. But the tools of digital construction still need further optimization. The case involved in this article uses offline programming of the KUKA Robot and cannot monitor the surrounding environment in real-time. A dangerous situation is caused by the judgment and termination of the operator. In the subsequent design, more intelligent detection methods will be added to enable the robotic arm to deal with risks on its own. At the same time, the errors generated during the construction process also need to find a solution. We can believe that in the unwilling future, digital construction will be matured, and it will help people to produce buildings faster, more economically, and more efficiently.

5.3. Investigation on the efforts of Robotics application in architectural design

The frequency distribution analysis of the questionnaire results of the workflow feedback in Stage 3 (Fig.29 and Table 7) shows that a negative skewed unimodal distribution for Q1-3 and Q3-3 while a positive skewed unimodal distribution presented for Q2-3. The performance scores given by the greatest number of students are all 7 points like Stage 1. Among them: (1) from the mean and standard deviation, student participation has improved from the previous two stages (mean=6.70, Std.D=2.17). Compared with the previous computer design process, the hands-on practice in this stage can stimulate students' interest in learning. Also, (2) the difficulty of this stage has been reduced (mean=6.29, Std.D=2.07), mainly considering the limited ability of students in the introductory stage. Therefore, in the teaching workflow, the part of R&D and production of end-tools was escaped, and directly uses existing tools for application learning and slight improvement. That may indirectly lead to (3) a decrease in the students' awareness of the importance of this stage (mean=6.93, Std.D=1.77) compared with the previous feedback of Stage 1-Parametric Design and 2-Multi-data Simulation.

From the perspective of the curriculum course content, the questionnaire results show a positive skewed unimodal distribution for Q4-3 and Q5-3 while a negative skewed unimodal distribution presented for Q6-3. Most students gave a score of 7 points, of which the number of students holding the same opinion on Q6-3 reached a maximum of 43 persons. Then, from the mean value Stage 3 helps to deepen the understanding of "Tectonics lays in the interaction between material and construction" (mean=7.21, Std.D=1.91), which is consistent with the teaching content focused at this stage, especially enhancing the students' knowledge of typical properties of materials. Combined with the radar chart analysis (Fig. 30), the promotion of understanding Q5-3 at this stage (mean=7.15, Std.D=1.74) is obviously not as good as the previous two stages.

As with the conclusions of Stage 1 and Stage 2, the degree of participation and content understanding still show a positive linear relationship (Fig.31 and Table 8). It

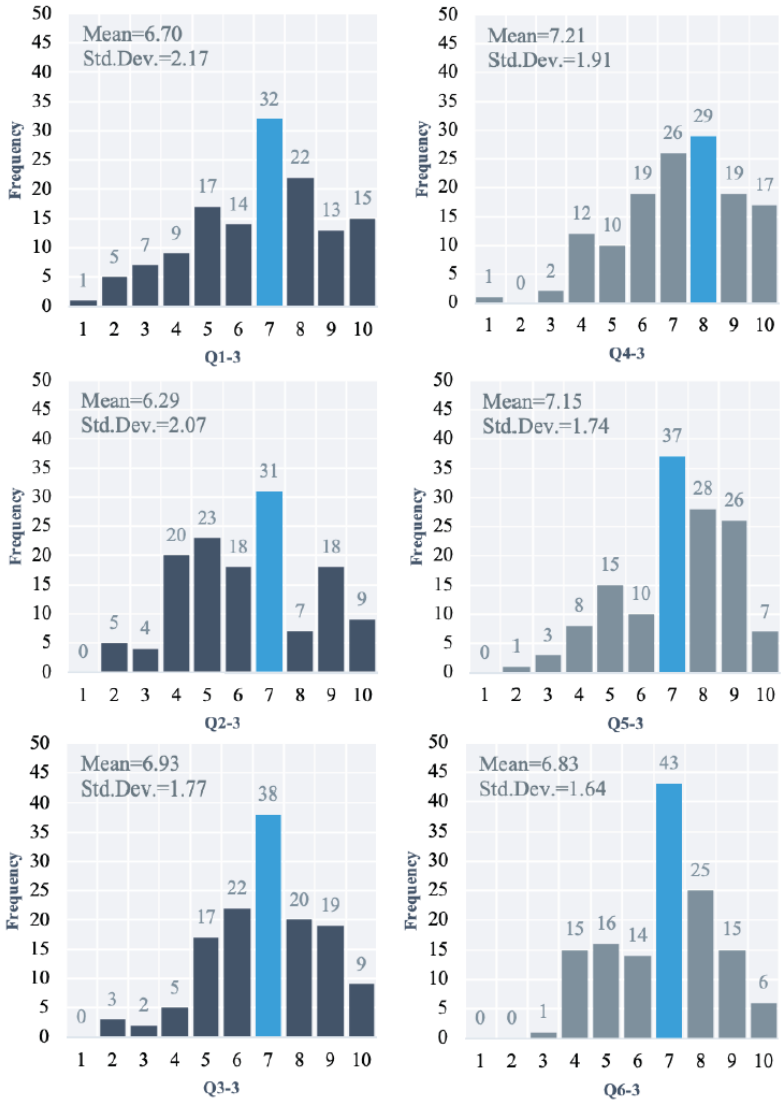
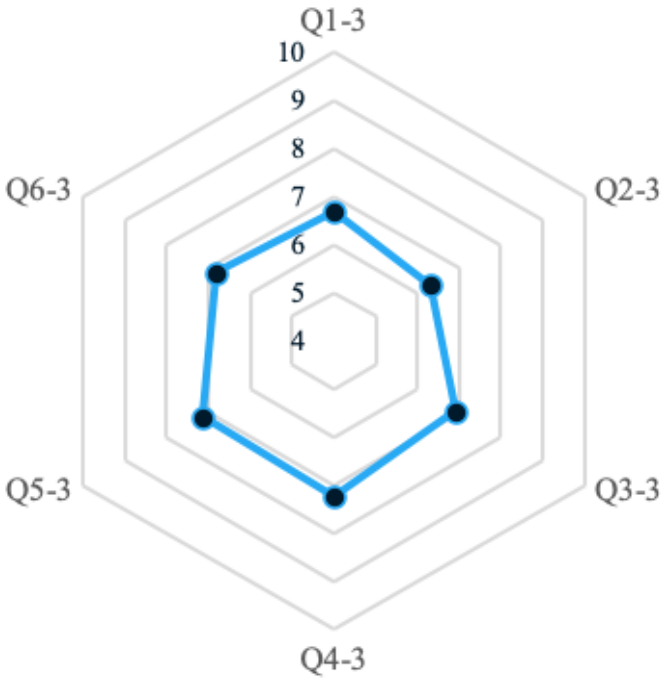


Fig. 29 Frequency distribution analysis of the content understanding in Stage 3

	Q1-3	Q2-3	Q3-3	Q4-3	Q5-3	Q6-3
Mean	6.70	6.30	6.93	7.21	7.15	6.83
Std. Error	0.19	0.18	0.15	0.16	0.15	0.14
Median	7	6	7	7	7	7
Mode	7	7	7	8	7	7
Std.Dev.	2.17	2.07	1.77	1.91	1.74	1.64
Variance	4.72	4.27	3.12	3.63	3.04	2.68
Range	9	8	8	9	8	7
Minimum	1	2	2	1	2	3
Maximum	10	10	10	10	10	10
Sum	904	850	936	974	965	921.5
N	135	135	135	135	135	135

Table 7 The empirical results' list by frequency distribution analysis of Stage 3



Q1-3. The degree of participation in each stage
Q2-3. The difficulty degree of each stage to the overall workflow
Q3-3. The importance of each stage to the overall workflow
Q4-3. The degree of understanding "Tectonics lays in the interaction between material and construction"
Q5-3. The degree of understanding "Tectonics means clear and logic structure"
Q6-3. The degree of understanding "Tectonics represents performative architecture"

Fig. 30 Characteristic analysis of Stage 3 by using the mean data of the frequency distribution

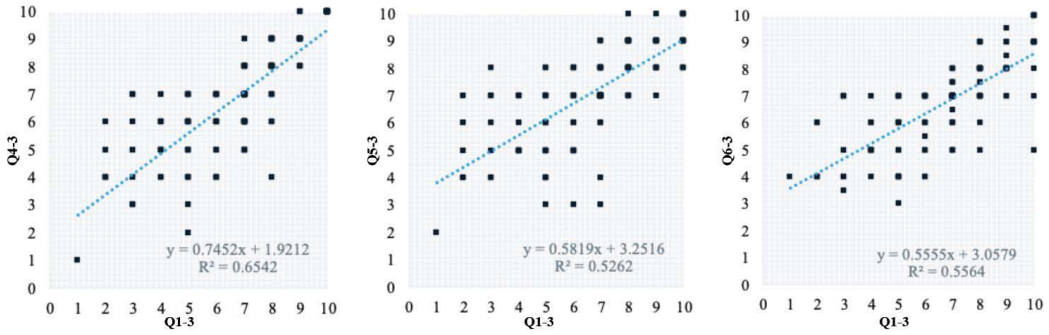


Fig. 31 Linear regression analysis of the participation degree and content understanding degree of Stage 3

Variables	Pearson correlation	Linear regression					ANOVA		N
		R^2	Slope	Y-intercept	t	Sig.	F	Sig.	
Q4-3	0.863	0.745	0.757	2.146	19.690	0.000	387.685	0.000	135
Q5-3	0.725	0.526	0.582	3.252	12.153	0.000	147.703	0.000	135
Q6-3	0.746	0.557	0.562	3.064	12.922	0.000	166.977	0.000	135

Table 8 Empirical results' list of linear regression for Stage 3

is consistent with the teaching knowledge of Q4 emphasized at this stage analyzed above, and the R-square value reaches 0.745.

5.4. Summary

In this chapter, the construction-aimed digital tool development and application as the third stage of Robotic Tectonics workflow is fully described with two experiments demonstration and correspondingly questionnaire survey for the feedbacks from curriculum participants. Conclusions are summarized as follow.

1) End-tool application helps to realize the construction or fabrication sequence and it is the only part of the robot specifically designed to interact with its physical environment. any form of automation in the realm of construction needs a carefully programmed, simulated, and detailed model of its operating environment, especially when it comes to the design and integration of construction-oriented end effectors into the system.

2) Design and development of the end-tool for robot is an interdisciplinary cooperation which highly concerned its mechanical property with the construction aim, since industrial robot itself can only respond to positional commands, and they have no awareness of what is going on in their environment, the end-tool's weight, shape, function, and precision are all critical to the construction process. These tools, as instrumental aspects of robotic fabrication, need to be customized and integrated by those under the robotic tectonic pedagogy with the tectonic thinking to practice the construction-aimed workflow.

3) From the experiment 5, we could find the process of design and develop this self-build printing head as the end-tool effecter of robotic arm, is a integrated process of combing material attribute, printing nozzle prototype, printing path algorithm, and design geometry definition, by carefully control the heating temperature, nozzle scale, printing speed and pathway, a well-designed complex component could be fabricated. It could clearly demonstrate how importance of end-tool application influence the understanding of tectonic thinking for material and construction.

4) From the experiment 6, we could find the automation system for brick tectonics provides series actions of picking up brick, relocation brick's position, gluing on each brick, and positioning to precise location, this automation devices as end-tool

for robot offers an end-effecter building environment, formed an automated construction system for robotic tectonics workflow.

5) From analysis of the feedbacks from participants of the curriculum teaching questionnaires, we could found students are strongly recognized and agreed with the importance efforts of the end-tool application stage for the entire workflow of Robotic Tectonics, it reflects the students' sense of identity with this pedagogical concept, and gains deeply understandings of tectonic thinks by deep participation.

Chapter 6. Robotic Tectonics demonstrated Advanced Architectural Design

6.1. Introduction 6-1

6.2. Robotic Tectonics as full-scale experiments and demonstrations . 6-3

6.2.1. Experiment 7: Robotic wood assembly 6-3

6.1. Investigation on pedagogical approach of Robotic Tectonics as didactic demonstration 6-11

6.2. Summary 6-13

6.1. Introduction

This chapter is focused on the final stage of the Robotic Tectonics workflow, the Robotic Tectonics represented automation construction practice, is the highly integrated process of combining all kinds of robotic techniques aiming its application on fully built practices.

Two experiments are introduced to demonstrate the full-scaled built practice, how it enables architects and students focus on the complete aims of utilize all kinds of emerging techniques for the robotic construction. Experiment 7 is presenting a wooden pavilion consisted by standard wood blocks, form a shell-shaped structure, which creates a stiff, diversity variations space. Experiment 8

The questionnaire survey for this stage is analyzed, also based on 135 participate students on the curriculum of *Robotic Construction Prime* and feedbacks from it. Empirical analysis proves the significant efforts of robotic tectonics demonstrated full-scale built practice for developing Robotic Tectonics workflow and enables tectonic concepts for design inspiration.

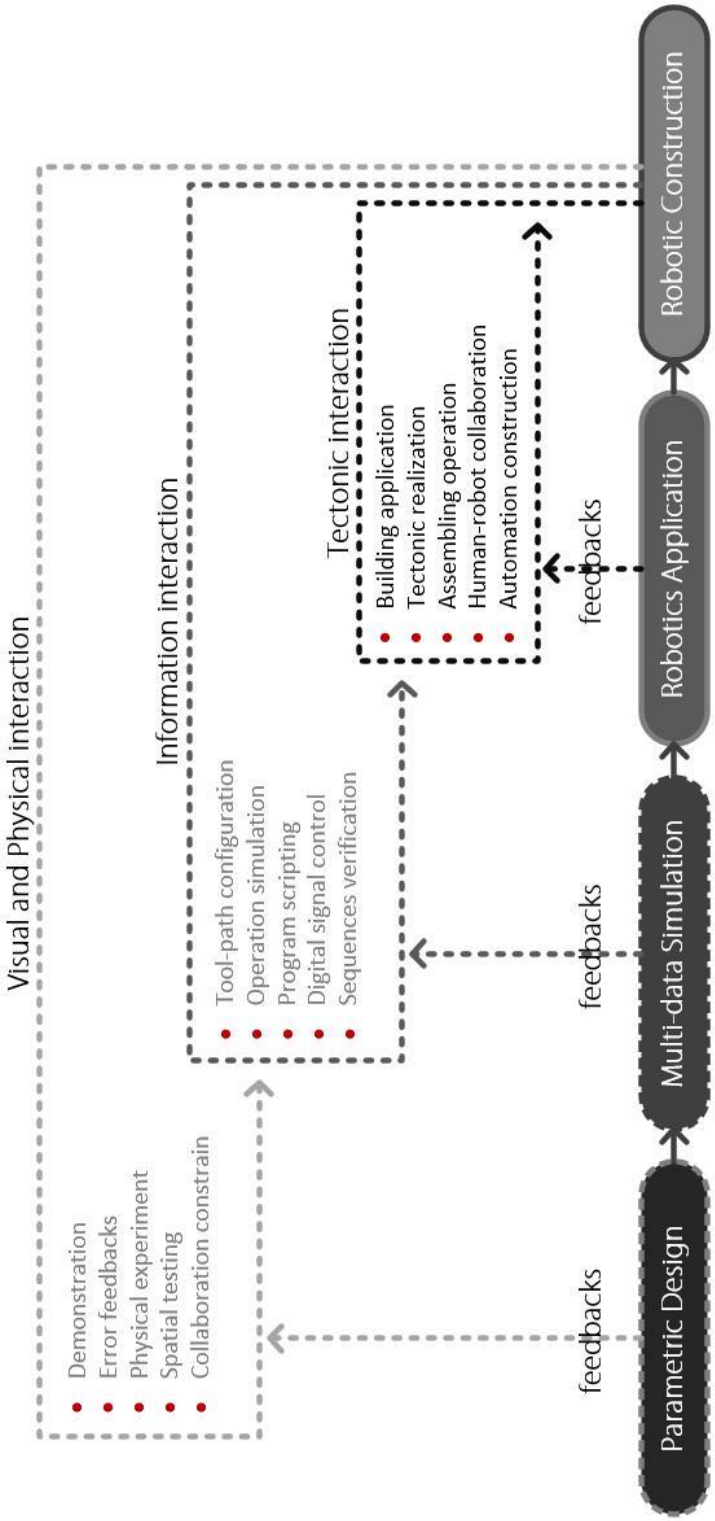


Fig. 32 Framework for the process of robotic construction

6.2. Robotic Tectonics as full-scale experiments and demonstrations

The final stage of this workflow is robotic construction, where both successes and design defects from the construction process can turn into priceless experience that then feed back to the early stage of design conception and simulation (Stumm, Braumann, von Hilchen, & Brell-Cokcan, 2017). This holistic look at design reveals that the entire robotic tectonics process is one of dynamic adjustment and adaptation, making it extremely beneficial to explore at the educational level. This stage aims to provide a comprehensive testing environment for students to utilize all of the previously mentioned techniques and focus them on their final construction goals. The efficiency of the robot and the accuracy of the construction method depend on iteratively fine-tuning the relationship between the program, the robot, the tool, and the material. Robotic construction brings all of these components into a single realized outcome to get students to begin to think critically about improvements to sustainability in the architectural future.

Solving all of the physical considerations involved in the robot workflow is a priceless exercise that produces cascading effects throughout the education process. Once these components are fully designed, they must be modeled and programmed into a digital simulation. It is through this exercise that students gain an understanding of the process of dynamic adjustment and adaptation, which helps to see how computational information and robotics relate to each other and what they can achieve when used in tandem.

6.2.1. Experiment 7: Robotic wood assembly

Wood was once one of the most widely used of the traditional building materials. However, after the introduction and spread of reinforced concrete and steel in the AEC industry, the frequency of wood has been greatly decreased. The main exceptions are in some earthquake-prone regions such as Japan and California due to concrete's poor resistance to disasters, high maintenance costs, and so on. Wood is relatively renewable and provides effective sound insulation, heat insulation, moisture

Force Analysis

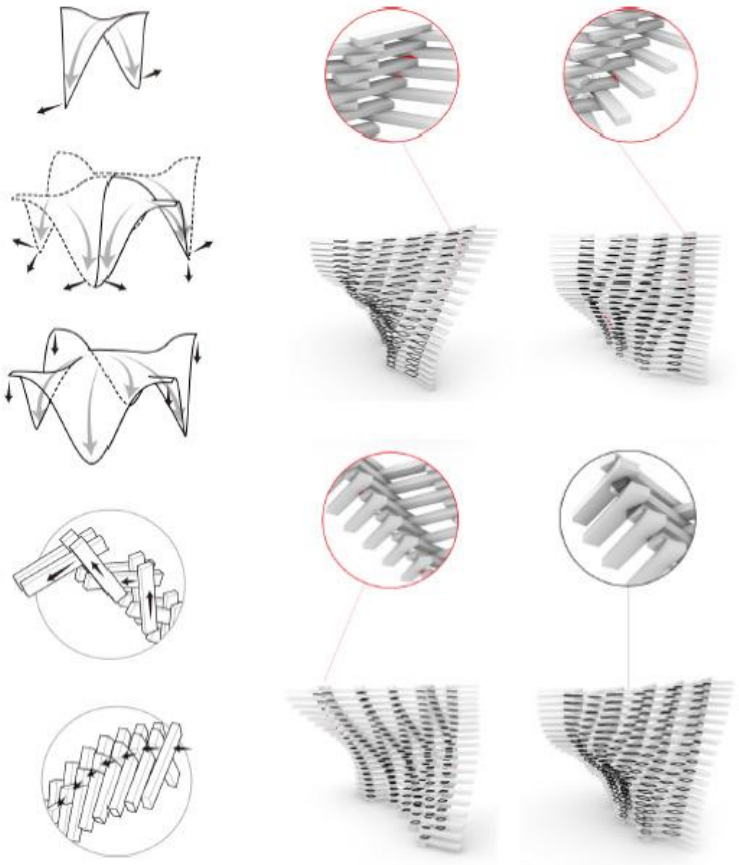
Each element is an arch which creates an outword need to be resisted.

When the 4 parts are combined with each other , some of the outword thrust can be offset.

The whole stable structure can be regarded as a cross arch with 4 overhangs.

The axial compression of each arch transmits through the joint of wood sticks.

The wood sticks sustain compression force predominantly and transmit the force to the ground through the joint.



Human Scale Analysis

Plane Dimension

On the plane, the flow of human activity flows in the X direction, which ensures the mobility of the activity, and at the same time increases the effect of the intersection point on the gathering of people.

Section Dimension

Designed in height to meet people's standing, leaning and sitting needs.

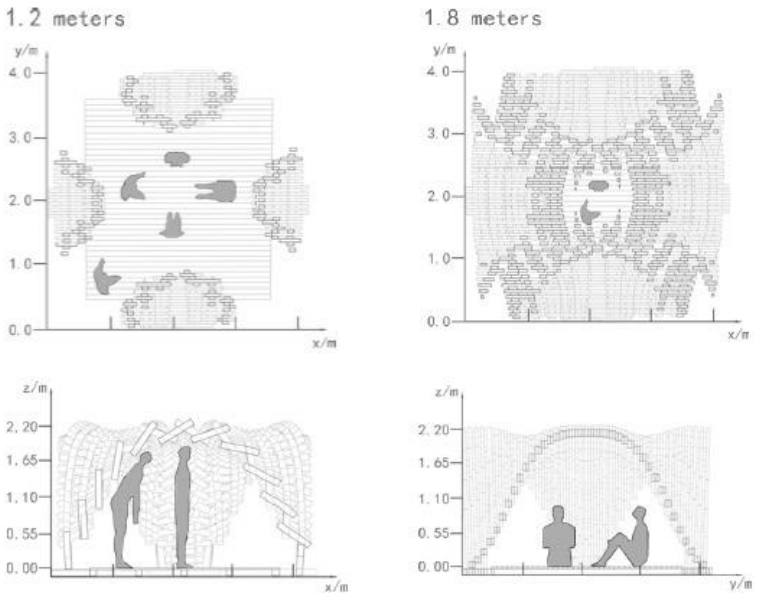
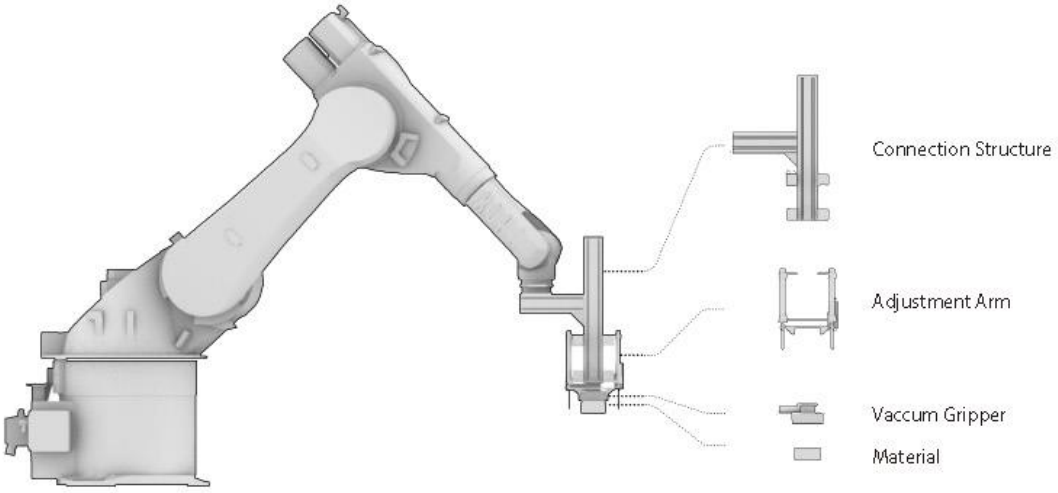


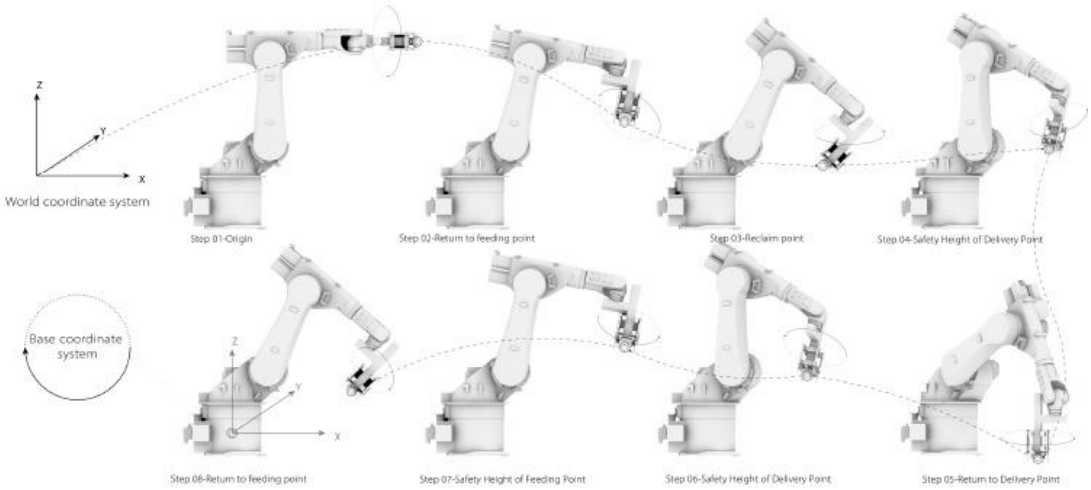
Plate 19 - Experiment 7: Robotic wood assembly

Tool Analysis

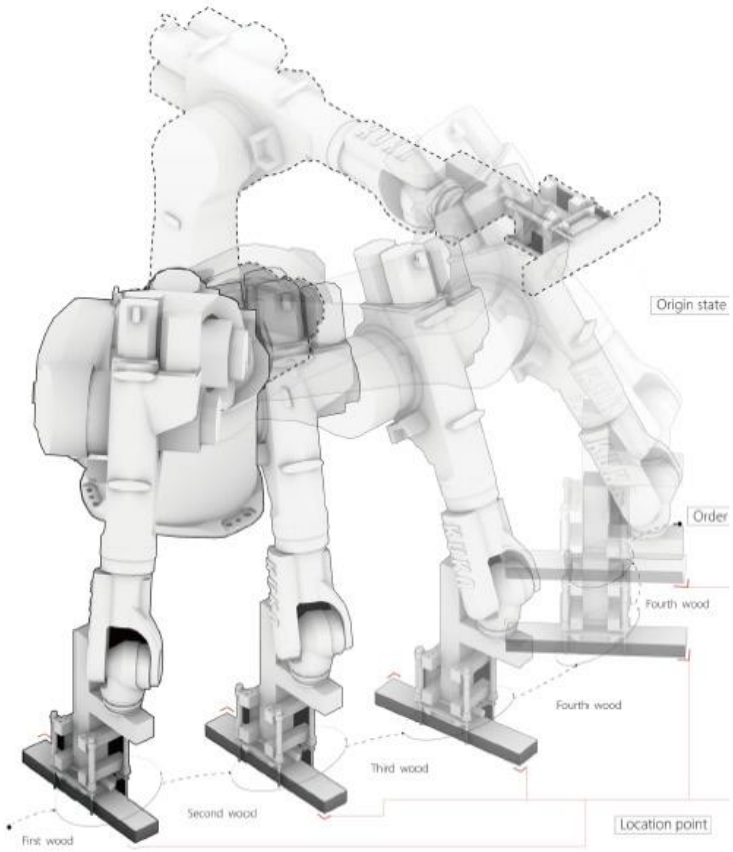


In order to make better use of the working efficiency of the KUKA robotic arm, it can meet the grasping and adjustment of strip wood, and facilitate the construction and positioning of wooden nodes in 3D dimensions with multiple directions and angles. The connector is fixed on the sixth axis of the robot arm, and an adjustment joint capable of flexibly adjusting the width is attached, and finally the vacuum gripper accurately and effectively grasps the strip of wood

Robot Movement Path



First Floor Construction Analysis

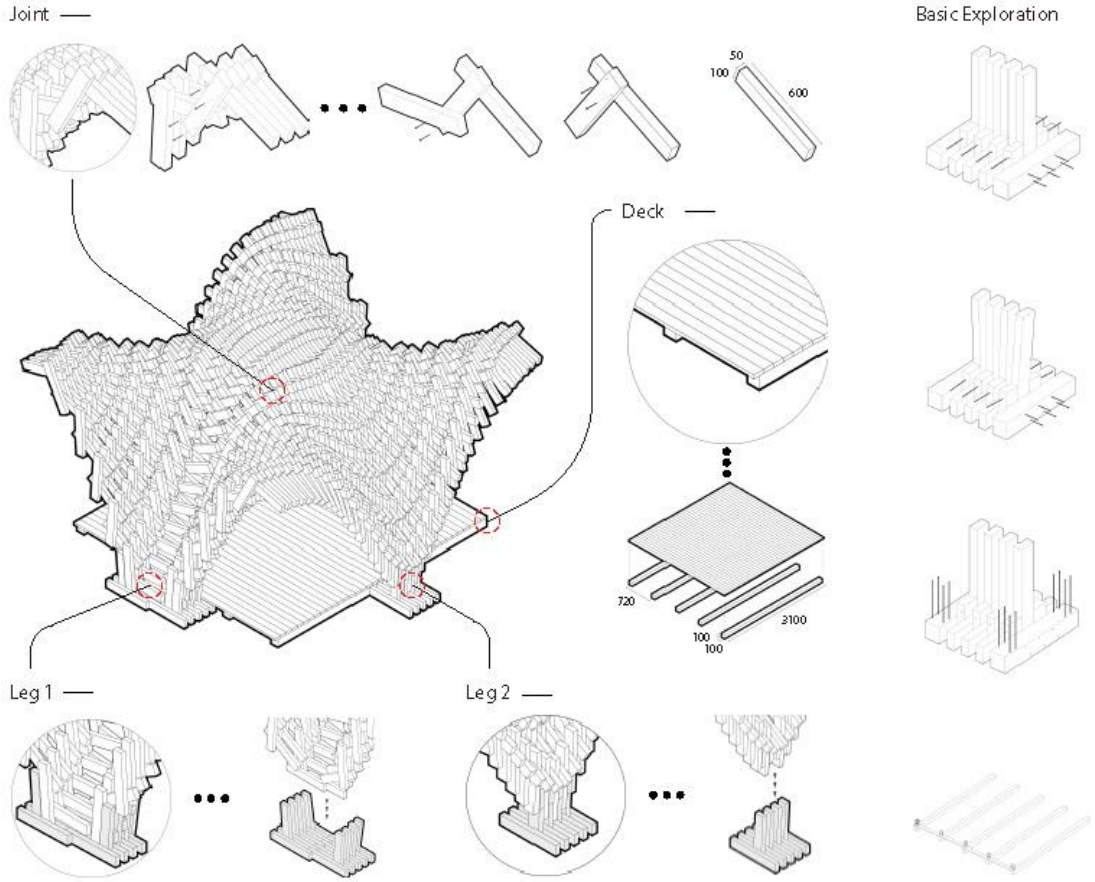


Construction Process

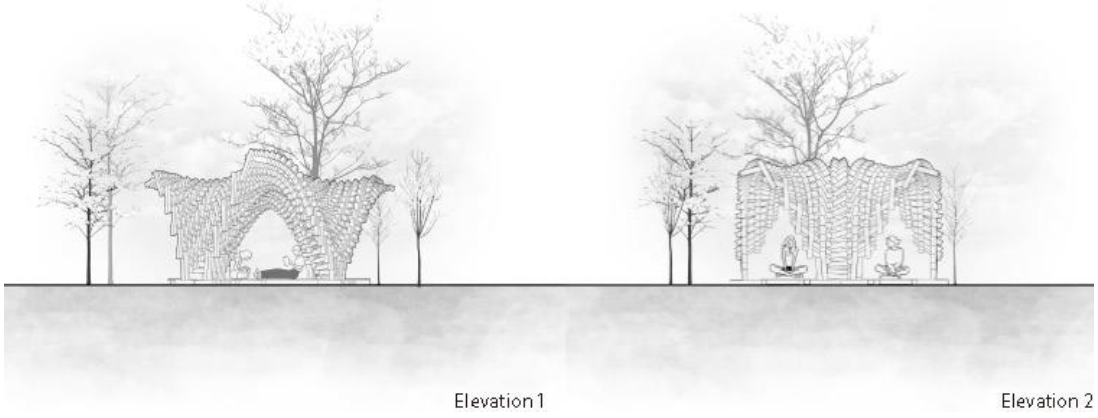
When we are positioning the robot, we pause the machine and apply glue to the opposite parts of the upper and lower layers. Then the wooden strip is dropped, and when the robot performs the fixing procedure, the nail is artificially nailed, and thus it is repeated until a single unit is built.

Plate 20 - Experiment 7: Robotic wood assembly

Axonometric Details



Axonometric Details



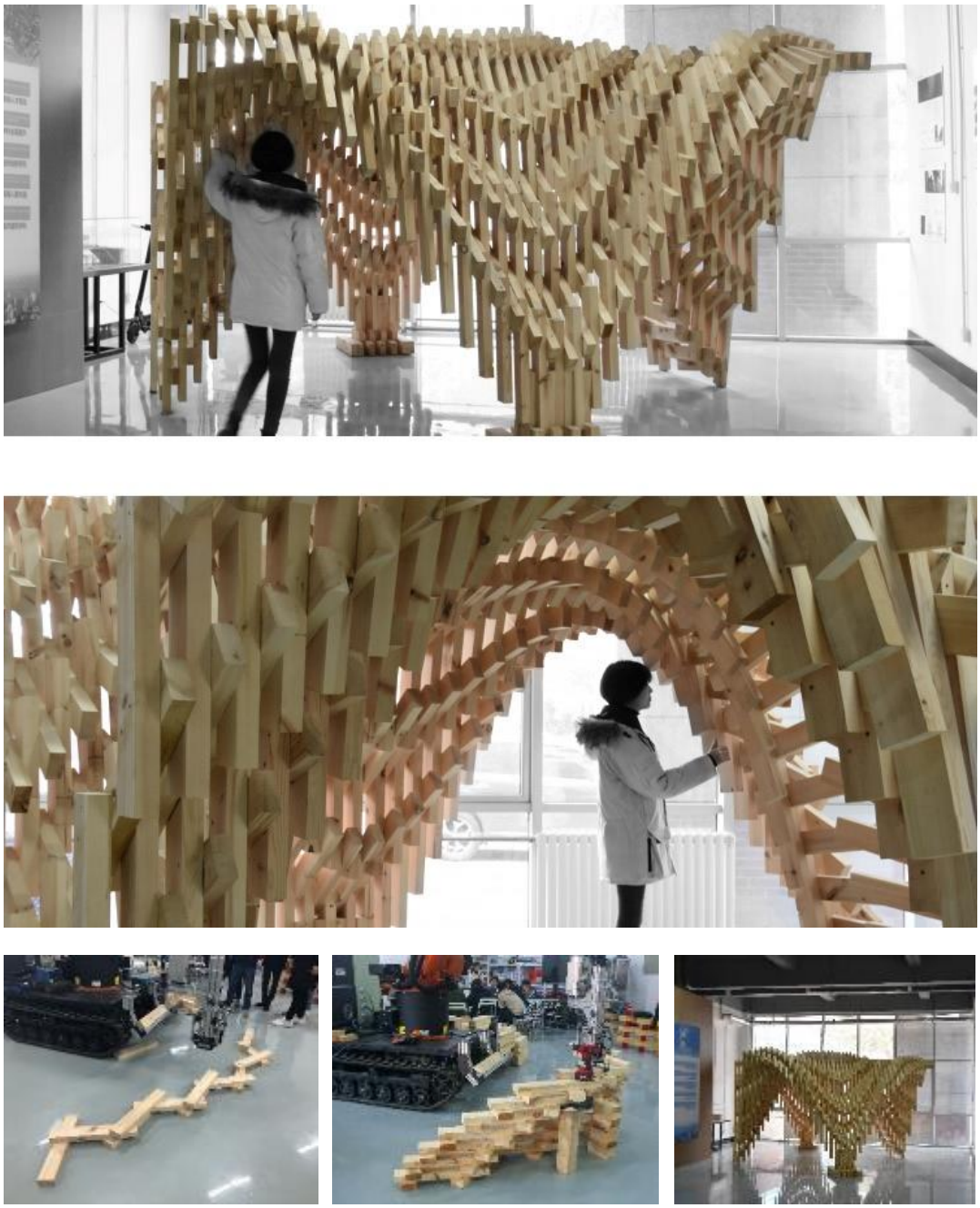


Plate 21 - Experiment 7: Robotic wood assembly

resistance, earthquake resistance, and corrosion resistance, while wood-structure buildings benefit from fast construction speed, low initial cost, and high comfort. These advantages have drawn attention back to wood in recent years and have inspired further research and development on wooden structures (Menges, Schwinn, & Krieg, 2016).

With the development of wood treatment and processing technology, the performance of wood has been continuously improved to meet the needs of contemporary architectural functions. Now, with digital construction and rapid modular construction, wood can be freed from the limitations of traditional timber construction techniques. Formal complexity and accuracy which are difficult to achieve by traditional techniques can be realized efficiently with the introduction of robotics into the workflow. Computer-aided parametric modeling and logical production make it possible to use wood to form complex structures through the optimization of its properties (Willmann et al., 2016). Through force analysis and formal optimization of the structure, an assembly can achieve excellent structural performance while maintaining uniformity, minimizing material waste, and achieving excellent aesthetic values such as formal complexity, quality lighting, and natural textures. The wood structure can now break through its traditional formality and parlay into the world of rapid construction of modular materials.

In this workshop, to maximize formal and aesthetic quality, parametric computation was used to analyze the forces on the final structure, which allowed the team to explore the feasibility of complex assembly methods for wood construction. Here, the construction of the assembly became the driving factor for the other stages of the robotic tectonic framework. The pick and place method of assembly was selected as the primary construction method, which was subsequently simulated to eliminate any problems that may be encountered during the robotic construction. The large, free standing structure required an extremely stable foundation, so the team also carried out a number of similar schemes for the foundation. In doing so, they had to perform many lab tests for damage resistance before building the final structure in order to explore its feasibility (see Plate 19-21). The construction and the installation of the entire structure was completed in 3 days with 780 pieces of wood, 1388 glue joints, and 2852 tapping nails.

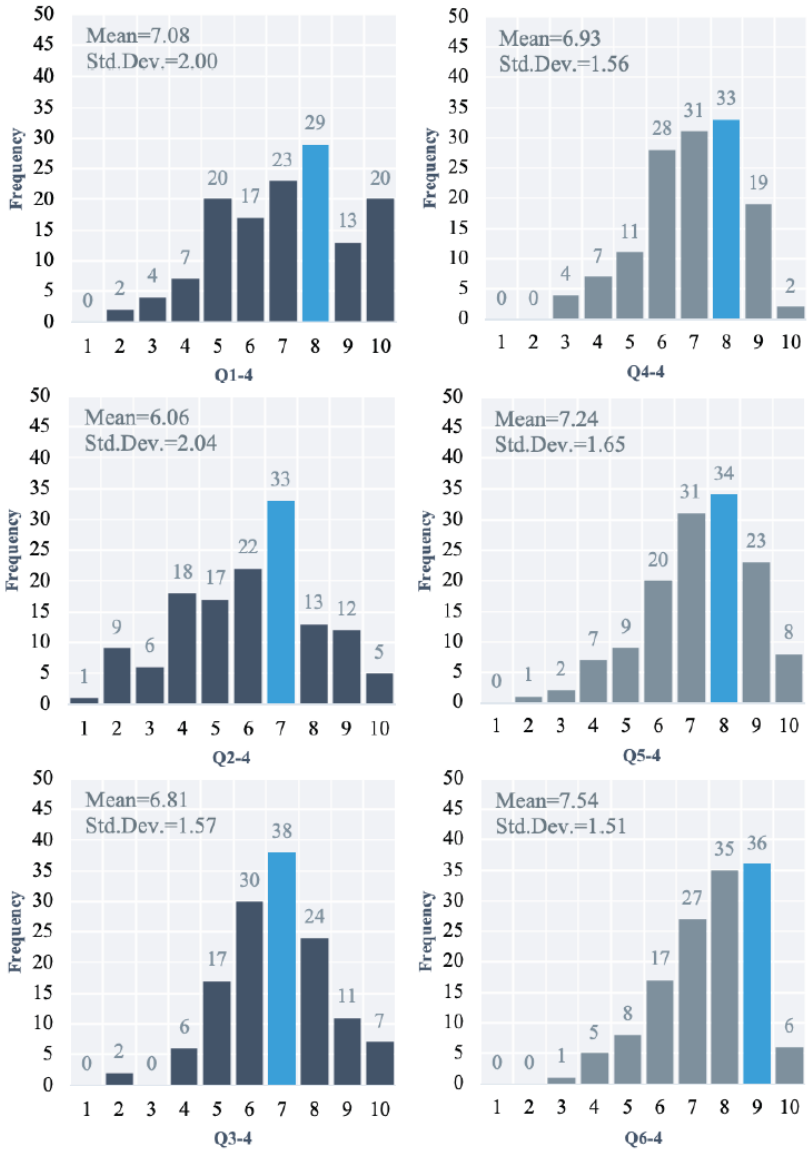


Fig. 33 Frequency distribution analysis of the content understanding in Stage 4

	Q1-4	Q2-4	Q3-4	Q4-4	Q5-4	Q6-4
Mean	7.08	6.06	6.81	6.93	7.24	7.54
Std. Error	0.17	0.18	0.13	0.13	0.14	0.13
Median	7	6	7	7	7	8
Mode	8	7	7	8	8	9
Std.Dev.	2.00	2.04	1.57	1.56	1.65	1.51
Variance	3.99	4.18	2.45	2.43	2.73	2.27
Range	8	8	8	7	8	7
Minimum	2	2	2	3	2	3
Maximum	10	10	10	10	10	10
Sum	956	818	920	935	977	1018
N	135	135	135	135	135	135

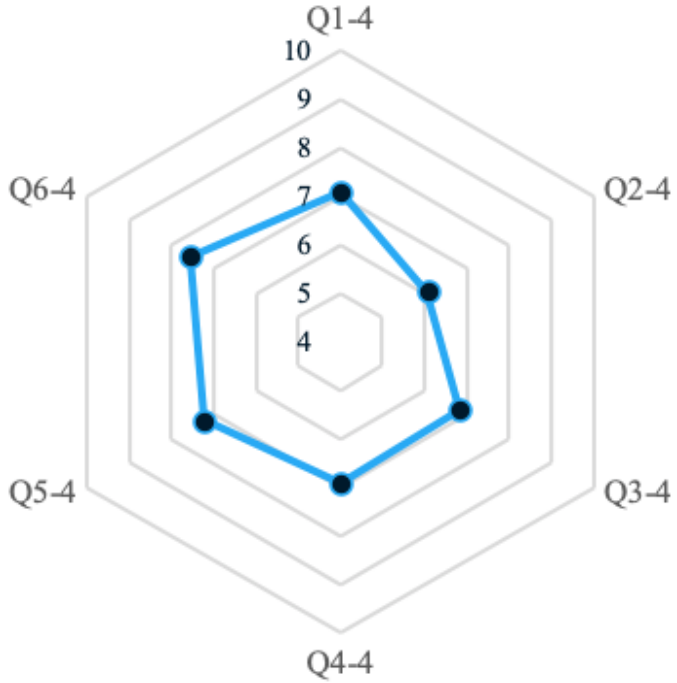
Table 9 Linear regression analysis of the participation degree and content understanding degree of Stage 4

6.1. Investigation on pedagogical approach of Robotic Tectonics as didactic demonstration

From the questionnaire results of Stage 4-Robotic Construction, it shows that the frequency distribution of the workflow feedback is a positive skewed unimodal distribution for Q1-4 while a negative skewed unimodal distribution presented for Q2-4 and Q3-4. It can be seen from Figure 33 and Table 9: (1) after three stages of participating and learning, the students showed a high level of enthusiasm in the stage of manipulating the robot to complete the construction work, and their participation has been significantly improved (mean=7.08, Std.D=2.00). (2) Most students believe that the difficulty level of this stage is lower than that of the previous stages (mean=6.06, Std.D=2.04), because they can exert their hands-on construction ability exercised in conventional architecture courses. Besides, (3) the importance of this stage in the whole workflow process is the lowest (mean=6.81, Std.D=1.57). This result is in line with expectations from the whole proposed framework because of previous three stages lay the important foundation for the last Stage 4.

Then, from the frequency distribution of the content understanding in Stage 4, it presents a negative skewed unimodal distribution for Q4-4 and Q6-4 while a positive skewed unimodal distribution presented for Q5-4. After the first three stages of learning and skill training, most students gave a high feedback score and the mode value is 8 for Q4-4 and Q5-4, even 9 for Q6-4. Moreover, from the values of mean and standard deviation, students' understanding of the concept of "Tectonics represents performative architecture" (mean=7.54, Std.D=1.51) through Stage 4 of study. In this part, the students expressed that this is the first time they have collaborated with a robot and tried to realize the seemingly impossible performance structure from design to real construction, which made them realize that a new design approach is emerging. And the radar chart at this stage also shows the above view intuitively (Fig.34).

In the same way, we conducted a correlation analysis of participation and content understanding and found a clear positive correlation between those two variables (Fig.35 and Table 10). The R-squared values between Q3-4 and Q6-4 were 0.660, followed by 0.589 of Q5-4 and 0.504 of Q4-4.



Q1-4. The degree of participation in each stage
Q2-4. The difficulty degree of each stage to the overall workflow
Q3-4. The importance of each stage to the overall workflow
Q4-4. The degree of understanding "Tectonics lays in the interaction between material and construction"
Q5-4. The degree of understanding "Tectonics means clear and logic structure"
Q6-4. The degree of understanding "Tectonics represents performative architecture"

Fig. 34 Characteristic analysis of Stage 4 by using the mean data of the frequency distribution

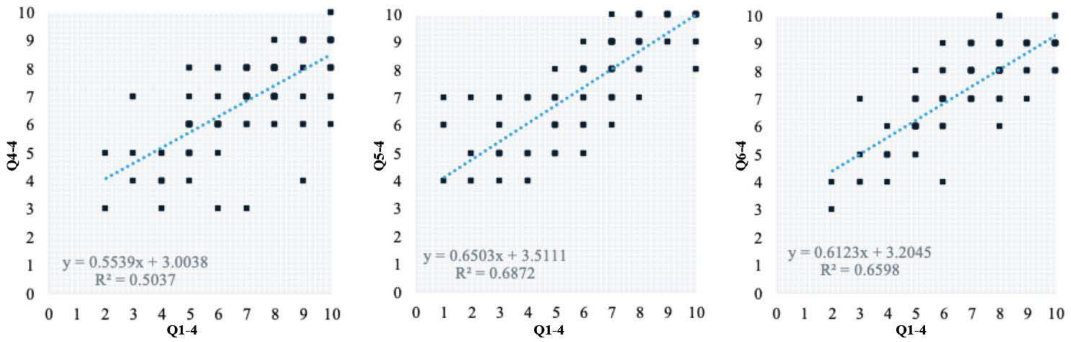


Fig. 35 Linear regression analysis of the participation degree and content understanding degree of Stage 4

Variables	Pearson correlation	Linear regression					ANOVA		N
		R^2	Slope	Y-intercept	t	Sig.	F	Sig.	
Q4-4	0.710	0.504	0.554	3.004	11.619	0.000	134.991	0.000	135
Q5-4	0.767	0.589	0.635	2.737	13.794	0.000	190.271	0.000	135
Q6-4	0.812	0.660	0.612	3.204	16.061	0.000	257.946	0.000	135

Table 10 Empirical results' list of linear regression for Stage 4

6.2. Summary

In this chapter, the final stage construction-aimed automation practice of Robotic Tectonics workflow is fully described with two experiments demonstration and correspondingly questionnaire survey for the feedbacks from curriculum participants. Conclusions are summarized as follow.

1) Robotic construction, utilize all of the available emerging techniques and focus them on their final construction goals. It's a testing platform to final confirm the parametric design model, the virtual simulated information, the design and applicated end-tool effectors could actually operate together for the physical construction process, same time, this construction practice experiences for testing react to the design conception decision, forming a looped, interactive workflow.

2) The efficiency of the robot and the accuracy of the construction method depend on iteratively fine-tuning the relationship between the program, the robot, the tool, and the material. Solving all of the physical considerations involved in the robot workflow is a priceless exercise that produces cascading effects throughout the education process. Leading students better understanding the concept of tectonic as practice.

3) From the experiment 7, we could find the robotic construction process provides a realized outcome to get students to begin to think critically about improvements to sustainability in the architectural future by deeply participate each stage of the workflow from initial parametric design to virtual simulation, end-tool development and construction practice. Through the wooden pavilion experiment, a better understanding of wooden material, its connecting method and tectonics, structure principle and building sequences are combined into the robotic tectonic thinking.

4) From the experiment, we could find the robotic tectonic thinking is transformed and applied into actual building practice, although robotic arms are not utilized in this project, but the workflow all along through parametric design, multi-data simulation, end-tool application, and realization construction are manipulated

and tested. It could clear demonstrate how this robotic tectonic thinking adapt into virous environment and service designers as design inspiration.

5) From analysis of the feedbacks from participants of the curriculum teaching questionnaires, we could found students are strongly recognized and agreed with the importance efforts of the robotic construction stage for the entire workflow of Robotic Tectonics, it reflects the students' sense of identity with this pedagogical concept, and gains deeply understandings of tectonic thinks by deep participation.

Chapter 7. Conclusions

7.1. The conclusion of deductive theory studies 7-1

7.2. The conclusion of inductive design experiments 7-2

7.3. The conclusion of quantitative analysis 7-6

7.4. Future studies 7-11

7.1. The conclusion of deductive theory studies

Automated construction methods require mastery of the relationship between programming, robots, software tools and material constraints. The resolution of these considerations when teaching robotic workflows to students shows that the teaching framework provides a structure to establish a tangible, non-computational relationship with parametric thinking. in order to understand and develop the digital processes needed to ensure the success of automated construction.

The term tectonics originally came from the Greek word *tekton*, means carpenter or builder. Later, it evolved to include the meaning of the creative process, referring to the creation of works of art. This includes skills, methods, materials, and even ideas. Carl Bötticher was the first to explain the role of tectonics in architecture. He believes that there are two main elements: the internal structure of the core-form and the external coating of the art-form (Boetticher, 1844). The outer cladding should reflect the true nature of the inner core. In addition to the concepts of nuclear and cladding, he also introduced the concepts of part and whole. Later, Gottfried Semper divided the building into four elements according to the architectural method: earthwork, hearth, framework and roof, and an enclosing membrane. In addition, he emphasized that "joints" are the most basic structural factors, and proposed construction methods of various materials: Wood and steel for the tectonics of frames, stone, soil and concrete for stereotomics of earthwork (Semper, 1851, 1989). In addition, Kenneth Frampton expanded his criticism of regionalism and Semper's theory, pointing out that the "joint" in the structure is the most basic and smallest basic unit. He further defined tectonics as constructive poetics (K. Frampton, 1982; K. Frampton et al., 1995).

Tectonics has been used in architectural theory for centuries. The term refers not only to the specific aspects of architectural art, but also to the abstract aspects of architectural art. It is pointed out that the main problems in term tectonics are the interaction between materials and structural types, as well as the logical communication between the selected structures. The definition of tectonics former involves the ontological aspect of architecture, while the latter involves the aspect of representation. With the emergence of digital tools, it is interesting to see how

architects use new technologies to change and improve architecture. There are great differences in the way computer technology is used in different offices. Judging from these processes, some people think that without the synthesis and construction process like the BMW pavilion, it is possible to achieve a structural result. In the process of looking for form, you can find the logical structure and structure of every desired and imaginable geometry, without even once considering it in the form-finding process.

Over the past few decades, synthetic materials have also become possible, and almost all conceivable properties can be combined. To some extent, this changes the logic of architecture, so it also changes the logic of construction. At the same time, computer technology has made it possible to build buildings that were previously impossible to manage, as seen at the Walt Disney Concert Hall and the National Swimming Center. In the two buildings, there is an inherent relationship between the architectural system and the space system, which produces a kind of constructive poetry through the interpretation of the art and space of science and the laws of nature.

Although the new tectonics is not only a challenge to the old architectural tradition and technology, but also a problem of comprehensive process. Therefore, robot tectonics is not only a supplement to traditional structural terminology of digital architecture. This is a new way to look at architecture as a clear and logical result of the mixing process.

7.2. The conclusion of inductive design experiments

The four workshops mentioned above each prioritized one of the four stages of the pedagogical framework, while all of them followed the continuous workflow of the new didactic method. They provide examples of how each stage of the pedagogy is critical to understanding the whole system and how a better understanding of the system can lead to improved efficiency in automated construction. As a result, this proposed pedagogy is set to meet the new demands of sustainable architectural education in this digitally dominated era. The introduction of this workflow at the academic level is critical, as iteration and continuous study improve its accuracy and

efficiency recursively. The more time students spend exploring each of the four stages, the more they will be able to design with the whole robotic tectonics process in mind, thus developing more optimized and sustainable designs. To recap:

Parametric Design has already had a remarkable effect on sustainable architectural design. Its logical workflow could easily bring interdisciplinary techniques of design and construction together for testing, generating, and analysis in a digital environment. As the first component of the pedagogy, parametric design asks students to focus on the digital modeling of design concepts through the lens of parametric logic. In this stage, the logic-based digital architectural model is established and becomes a platform for the upcoming simulation, application, experimentation, and modification of the design. By benefiting the user in time-sensitive, dynamic design scenarios, parametric design could help students explore more design possibilities. Take "Robotic Clay Printing" as an example. Through parametric design, we guided students to experiment with the Voronoi algorithm in order to achieve a creative solution for building more efficient ventilation panels. Once printed and analyzed, it was clear that this experiment brought novel sustainability and critical thinking concepts into their design processes.

Multi-data simulation requires students to understand different types of data (such as fabrication constraints and tool-path data) and merge them into one virtual simulated environment, which provides a safe method for students or architects to analyze every detailed step of the construction process before its implementation. There's no doubt doing so will significantly reduce the risk of production error, thereby saving material, labor, time, and cost. In the case of "Robotic Foam Cutting," the simulation revealed the process of cutting an infinite complex surface via its tool path. Through this robot-oriented simulation process, we are helping students to create new forms and spaces with minimum material use and almost zero waste in fabrication.

Robotics application acts as a critical component of the robotic construction process in that it is the main bridge between digital simulation and physical construction. Only with an end effector's exquisite design and efficient operation could the project achieve the precision necessary for more sustainable design. This stage helps students to realize how to deal with new materials, fabrication tools, operation constraints, mechanical and electronic design, and tool development. It is

an interdisciplinary stage where the physicality of the final product must finally be considered. In the case of "Robotic 3D Spatial Printing," we helped students develop the PLA extruder end effector, which dealt with sensitive control of the printing temperature and coordination between the extruding speed and tool path. This experiment was able to improve the sustainability of the project through the fabrication of complex components without a support system, in less time, and with minimal material.

Robotic Construction exemplifies how robotic tectonic practices might achieve our goal of architectural sustainability in the digital era. It represents the comprehensive stage for students to operate, test, build, collaborate, and ultimately achieve their initial design concept. Here, the students may also garner the most insight for new design concepts, as the constraints of the physical world are most obvious. For "Robotic Wood Assembly," precision, efficiency, material economy, and human-robot collaboration processes gave all the participants remarkable insight for the potential for sustainability through robotic tectonics and automated construction.

This novel pedagogical framework explores the complete architectural design and construction cycle. It represents a methodical approach to the 'design-to-fabrication process' and provides students with the necessary technical skills required to make automated construction a reality. Furthermore, it creates a global platform on which students can explore and critically apply contemporary technology in order

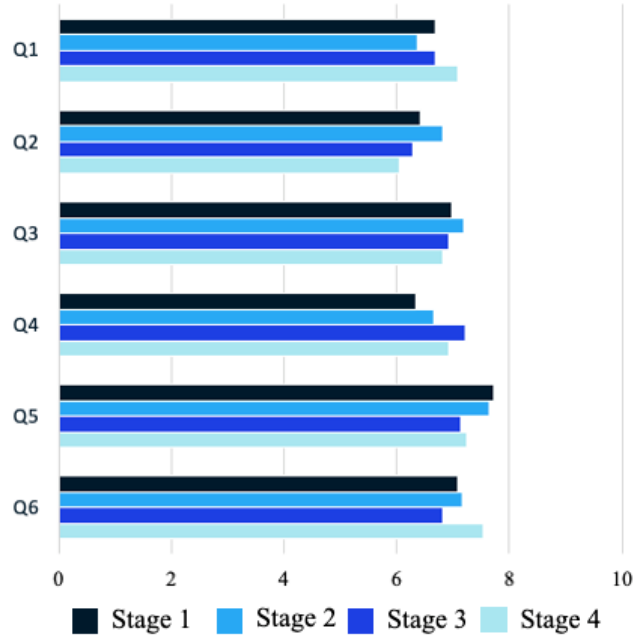


Fig. 36 Comparison and characteristic analysis of four stages by using the mean data of the frequency distribution

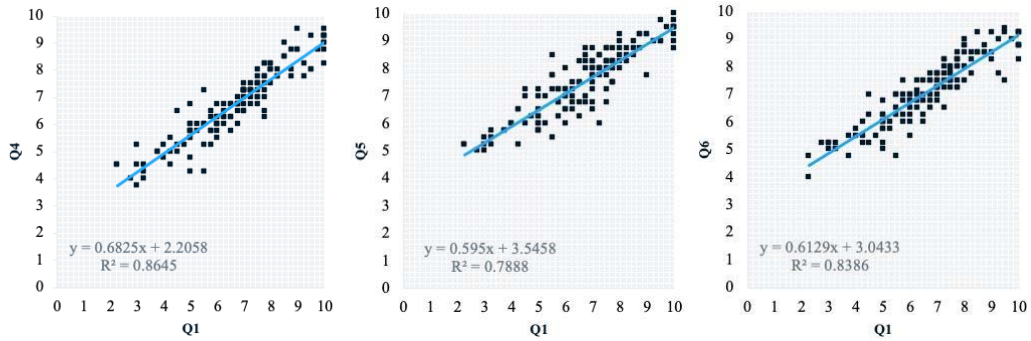


Fig. 37 Linear regression analysis of of the average participation degree and content understanding degree of the four stages

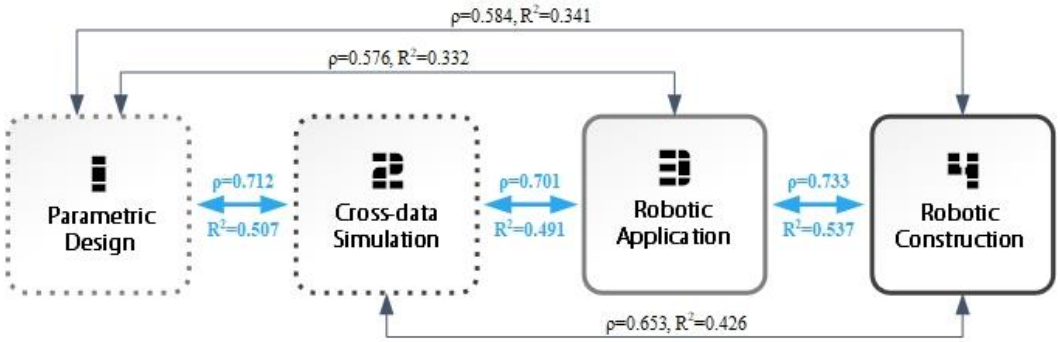


Fig. 38 Correlative relationship analysis of four stages by using the questionnaire results of participation degree

to push the limits of sustainability in both the profession and education. It aims to introduce the multi-faceted type of knowledge required to use robotics for automated construction, to demonstrate evidence of economic, social, and environmental improvements to the built world, and to provide insight into new and complex building processes that will redefine architecture in the near future.

7.3. The conclusion of quantitative analysis

Comparing the analysis of process feedback and content in the four stages (Figure 36), it can be seen that (1) Although the students think that Stage 2 is the most difficult, they also think that this stage is the most important. (2) From the perspective of participation, due to the increased difficulty, the participation has decreased significantly from Stage 1 to Stage 2. Fortunately, participation gradually increased afterward, reaching the highest level in the final stage 4. (3) Stage 1and Stage 2 of learning have a positive effect on students' understanding of Q5 questions, and Stage 3 and Stage 4 are helpful for understanding Q4 and Q6 questions, respectively.

Moreover, the regression analysis (Figure 37) of the average participation degree and content understanding degree of the four stages showed a clear positive correlation trend, indicating that the higher the participation degree, the higher the students' understanding of the course content. According to the correlative relationship analysis about four stages of robotic tectonics workflow by using the questionnaire results of participation degree (Figure 38), it could quantitatively indicate that the setting of workflow sequence is reasonable and effective for students. From the result values, although there is a relatively positive interaction relationship between every two stages, the coefficient and R-squared values ($\rho>0.7$, $R2>0.4$) of the proposed consecutive staged steps are larger than others, which means a more significant positive correlation relationship. By following the steps, it could help the students to explore the entire process more easily so as to ensure a higher participation degree of attending the course. Therefore, it is proved that the proposed framework can better cover and impart the three main theoretical concepts related to the tectonic of advanced architectural design. In order to obtain a better teaching effect, it is necessary to increase students' awareness of active participation and reduce the difficulty of teaching appropriately, especially in the introductory stage.

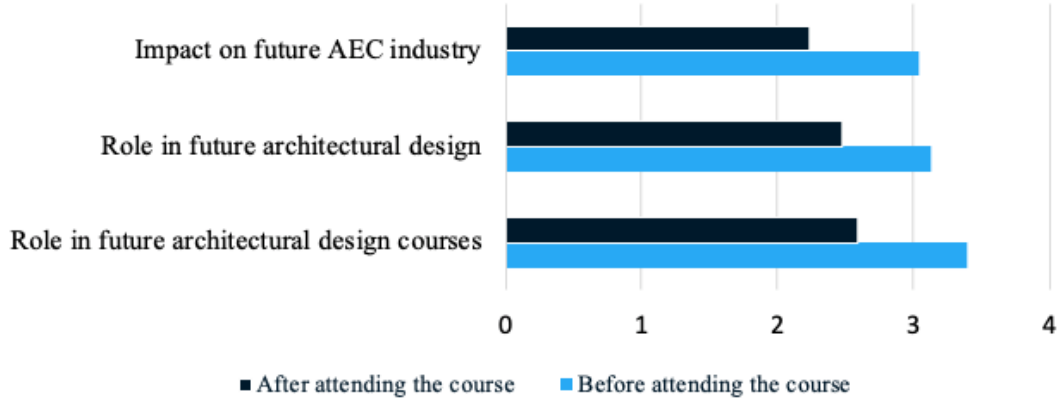


Fig. 39 Comparative analysis between before and after attending the course

Period	Before attending the course			After attending the course		
Options	Impact on future AEC industry	Role in future architectural design	Role in future architectural design courses	Impact on future AEC industry	Role in future architectural design	Role in future architectural design courses
1: No influence / An optional approach	7 (5.19%)	3 (2.22%)	2 (1.48%)	1 (0.74%)	1 (0.74%)	0 (0.00%)
2: Small influence / An auxiliary approach	92 (68.15%)	66 (48.89%)	64 (47.41%)	17 (12.59%)	4 (2.96%)	4 (2.96%)
3: Great positive influence / A dominant approach	33 (24.44%)	61 (45.19%)	57 (42.22%)	93 (68.89%)	102 (75.56%)	74 (54.81%)
4: Revolutionary influence / A necessary approach	3 (2.22%)	5 (3.70%)	12 (8.89%)	24 (17.78%)	28 (20.74%)	57 (42.23%)

Table 11 Empirical results' list by comparative analysis between before and after attending the course

Before attending the course					
Items of experience before class	Mean	Standard deviation (SD)	Number of participants	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Impact on future AEC industry	2.24	0.576	135	0.306	0.286
Role in future architectural design	2.50	0.609	135	0.155	0.536
Role in future architectural design courses	2.59	0.673	135	0.362	0.152
Summary of internal consistency	Grand mean	Number of options	F-test	Significance level	Cronbach's alpha
	2.44	4	14.682	0.000	0.442

After attending the course					
Items of experience before class	Mean	Standard deviation (SD)	Number of participants	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Impact on future AEC industry	3.04	0.578	135	0.559	0.803
Role in future architectural design	3.16	0.492	135	0.653	0.703
Role in future architectural design courses	3.39	0.548	135	0.701	0.64
Summary of internal consistency	Grand mean	Number of options	F-test	Significance level	Cronbach's alpha
	3.20	4	34.027	0.000	0.791

Table 12 The internal consistency assessment by Cronbach's method (Notes: Value labels from 1 to 4 correspond to the answer to the question from a to d.)

The comparative analysis of the results of the questionnaire before and after the course (Fig.39 and Table 11) shows that the students have obvious views on the impact of the "Robotic Tectonics" in the AEC industry, the position in the future architectural design and the necessity as the content of the architectural design course. Among them, the proportion of students who believe that “Robotic Tectonics has a great positive influence or plays a dominant approach” has increased from 24.44%, 45.19% (before attending the course) and 42.22% to 68.89%, 75.56% and 54.81% (after attending the course). Similarly, the proportion of students who believe that “Robotic Tectonics has

a revolutionary influence or plays an essential decisive approach” has increased from 2.22%, 3.70% and 8.89% to 17.78%, 20.74% and 42.23%, respectively. Then, from the results of internal consistency analysis, the grand mean values of the above set of questions changed a lot from 2.44 to 3.20 and the values Cronbach's alpha increased from 0.442 to 0.791 (Table 12). It means that after experiencing the course learning, the students recognized with more uniform consistency. Most students’ opinions have changed from “Robotic Tectonics has a small influence or plays an auxiliary approach" to "that has a great positive influence or plays a dominant approach" on the relevant dimensions of industry, architectural design or professional curriculum.

Moreover, overall 98.52% of students reported that the four stages of the course are helpful not only focus on the specific operation of a certain stage but also gain an overall view of the construction process.(Fig.40) Overall 97.78% of students reported that they can experience and clearly understand through the study of the course that “Robotic Tectonics” is composed of 4 linear and integrated stages of "Parametric Design", "Multi-data Simulation", "Robotics application" and "Robotic Construction". The same percentage of students thought that compared with examination or other homework requirements, the practical task used in this course can help them understand the whole process of "Robotic Tectonics". The Cronbach's alpha value of these feedbacks of questionnaires is as high as 0.912, which shows a high degree of consistency in opinion. (Table 13)

Therefore, it can be considered that the conventional architectural design concept is necessary, but it will allow students to form an inherent thinking, which has

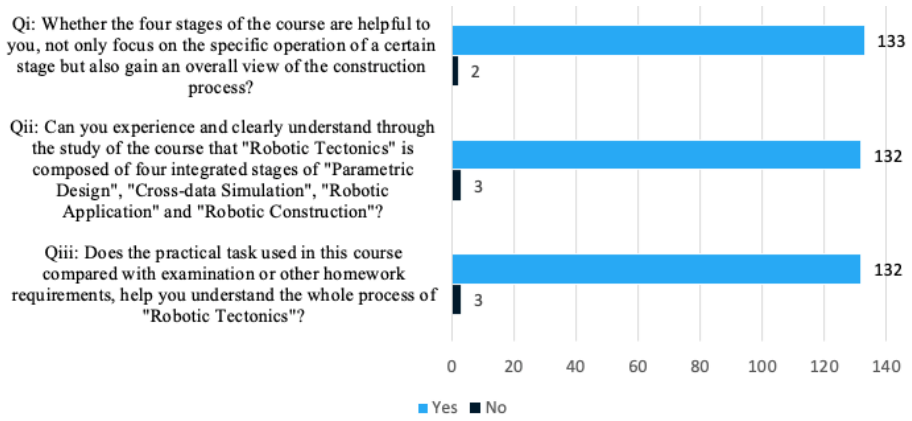


Fig. 40 The analysis of curriculum effect

Items of experience before class	Mean	Standard deviation	Number of participants	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Qi	1.02	0.148	135	0.911	0.798
Qii	1.03	0.170	135	0.829	0.887
Qiii	1.01	0.121	135	0.781	0.921
Summary of internal consistency	Grand mean	Number of options	F-test	Significance level	Cronbach's alpha
	1.02	2	1.506	0.000	0.912

Table 13 The internal consistency assessment by Cronbach's method

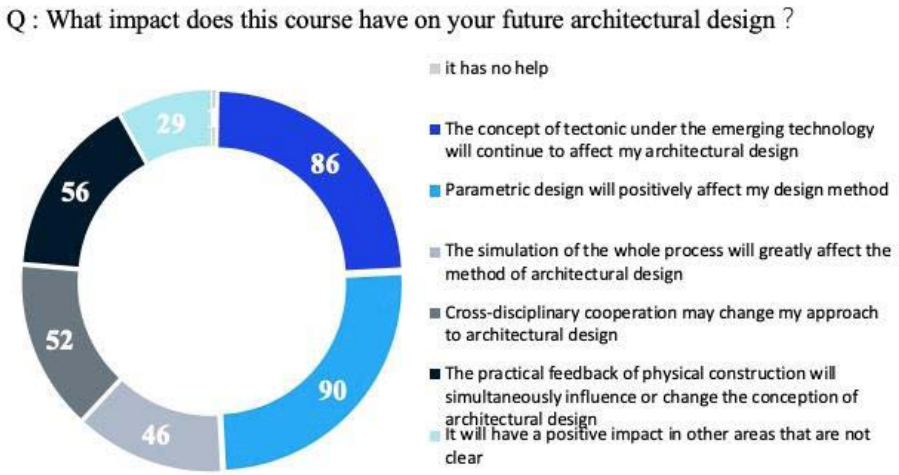


Fig. 41 The analysis of curriculum effect by the multiple-choice question

a negative effect on the acceptance of new technologies and concepts. Curriculum theory and practical education through reasonable process arrangements are effective for developing students' thinking and perceiving to adapt to the advanced architectural design concepts of the future era. The proposed pedagogical approach and its workflows are reasonable, which can make students fully understand the whole process from architectural design to construction through step-by-step teaching practices and effectively imparted advanced architectural design concepts. All analysis of the questionnaire results quantifies the beneficial effects of this course even are highly recognized and supported by students.

In order to further verify the effects of the course and the beneficial effects on the students through the course learning practice. The questionnaire specifically set up some multiple-choice and open-ended questions, so as to collect more gratifying feedback and helpful survey responses. (Fig.41) From the answer to the question "what impact does this course have on your future architectural design", the majority of students of (90 persons) indicated that parametric design will positively affect my design method. There are 86 students who reported that “the concept of tectonic under the emerging technology will continue to affect my architectural design”. There are 56 students considered that “the practical feedback of physical construction will simultaneously influence or change the conception of architectural design”. And 52 students thought that "cross-disciplinary cooperation may change my approach to architectural design". 46 students think that "the simulation of the whole process will greatly affect the method of architectural design". Few students (29 persons) have the view of "it will have a positive impact in other areas that are not clear" while only one student thought "it has no help."

The students’ open-ended responses to the survey questions overwhelmingly provided meaningful improved suggestions and personal reflections about the proposed course. Some specific comments include:

“I suggest that the course can add more kinds of structures or materials for teaching practice.”

“I hope the teacher can pay more attention to the participation of each classmate in the process.”

"Through the course, my design ability has been greatly improved. I hope that these new technologies and design methods can be combined into traditional design courses, as much as possible in the usual design and get professional guidance from teachers."

"This is the first time I have manipulated a robot. It is highly professional and requires more systematic learning. I suggest adding related auxiliary courses."

"Compared with the previous manual construction model, the accuracy of the robot construction is particularly high, and it can save labor time."

"For me, it is a magical and surprising experience to compile the design into the program and then let the robot build it into the real thing. I hope to have more opportunities in the future."

"We young people in the contemporary age should actively learn and master this new knowledge and new technology and prepare for the future in advance."

7.4. Future studies

Applying the pedagogical method of robotic tectonics into architectural curriculum has significant efforts for the future participants in the AEC industry. It can be considered that the conventional architectural design concept is necessary, but it will allow students to form an inherent thinking, which has a negative effect on the acceptance of new technologies and concepts. Curriculum theory and practical education through reasonable process arrangements are effective for developing students' thinking and perceiving to adapt to the advanced architectural design concepts of the future era. The proposed pedagogical approach and its workflows are reasonable, which can make students fully understand the whole process from architectural design to construction through step-by-step teaching practices and effectively imparted advanced architectural design concepts. All analysis of the questionnaire results quantifies the beneficial effects of this course even are highly recognized and supported by students. The paradigm of architectural education is changing with the integration of emerging robotics technology.

This study reveals a pedagogical approach for future architectural education towards interdisciplinary vision of future sustainable automated construction. All new technologies need widespread for fully acceptance and manipulation, where education always plays an important way. With the digitalization transforming of every field of our lives and societies, students as the future professional participates have somehow generated consciousness for creating brand new ideas of architectural design and construction methods, which could be read through the positive attitude towards future challenges, therefore, adapting to the trends of digitalization and interdisciplinary developing for architecture, engineering and construction industry is crucial. Searching for the proper pedagogical methods for this changing paradigm are necessary, also, creative and attractive approaches for both students and other participates are indispensable, which always be the future works for our further research.

Appendix

Teaching Questionnaire

In order to effectively analyze the teaching effect of this course, I hope you can take a few minutes to tell us your feelings and suggestions. We attach great importance and look forward to the valuable opinions of each participating student in this course. Let's start now!

A. Basic information

Student No.: Name: Gender:

B. Single-selection questions answering before attending the course

1. Please describe your experience on these aspects by choosing one from the options below.

(1) Your experience on 'Parametric Design' ( )

(2) Your experience on 'Multi-data Simulation' ( )

(3) Your experience on 'End-tool Application' ( )

(4) Your experience on 'Robotic Construction' ( )

a. Never touched.
b. Heard of but never tried.
c. Basically understood or occasionally tried.
d. Fully understood or mastered relevant skills.

2. Please describe your understanding of the impact of the "Robotic Tectonics" in the architecture engineering and construction (AEC) industry.

a. Robotic Tectonics has no influence on the AEC industry.

b. Robotic Tectonics has a small influence on the AEC industry.

c. Robotic Tectonics has a great positive influence on the AEC industry.

d. Robotic Tectonics has a revolutionary influence on the AEC industry.

3. Please describe your understanding of the "Robotic Tectonics" what role in the future architectural design.

a. Robotic Tectonics in the future architectural design.

b. Robotic Tectonics plays an auxiliary approach in the future architectural design.

c. Robotic Tectonics plays a dominant approach in the future architectural design.

d. Robotic Tectonics plays an essential decisive approach in the future architectural design.

4. Please describe your understanding of the "Robotic Tectonics" what role in the future architectural design course.

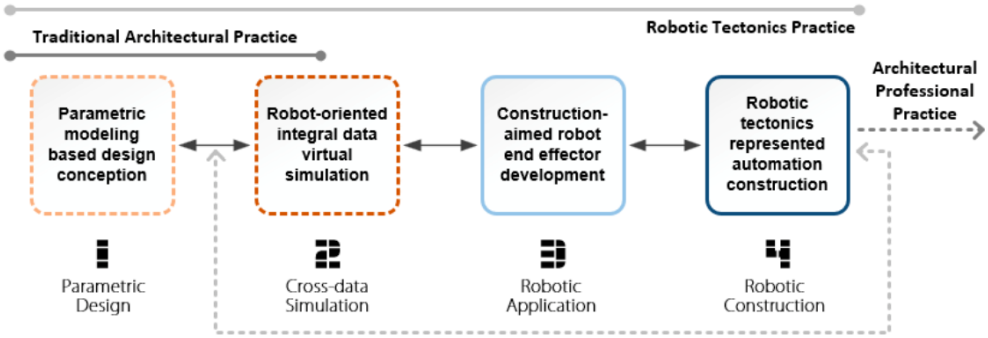
a. Robotic Tectonics in the future architectural design course.

b. Robotic Tectonics plays an auxiliary approach in the future architectural design course.

c. Robotic Tectonics plays a dominant approach in the future architectural design course.

d. Robotic Tectonics plays an essential decisive approach in the future architectural design course.

C. Single-selection questions for each stage answering after attending the course



As the figure shows, our study of this course composed of 4 integrated stages including: Stage 1-"Parametric Design", Stage 2-"Multi-data Simulation", Stage 3-"Robotics application" and Stage 4-"Robotic Construction". Please give values to the 6 questions (Q1-Q6) in each stage according to your personal situation. The score can be an integer score of 1-10. The higher the score, the higher the degree of approval of the corresponding question. The questions are as follows:

1. For Stage 1:

Q1-1. The degree of participation in each stage

1	2	3	4	5	6	7	8	9	10

Q2-1. The difficulty degree of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q3-1. The importance of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q4-1. The degree of understanding "Tectonics lays in the interaction between material and construction"

1	2	3	4	5	6	7	8	9	10

Q5-1. The degree of understanding "Tectonics means clear and logic structure"

1	2	3	4	5	6	7	8	9	10

Q6-1. The degree of understanding "Tectonics represents performative architecture"

1	2	3	4	5	6	7	8	9	10

2. For Stage 2:

Q1-2. The degree of participation in each stage

1	2	3	4	5	6	7	8	9	10

Q2-2. The difficulty degree of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q3-2. The importance of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q4-2. The degree of understanding "Tectonics lays in the interaction between material and construction"

1	2	3	4	5	6	7	8	9	10

Q5-2. The degree of understanding "Tectonics means clear and logic structure"

1	2	3	4	5	6	7	8	9	10

Q6-2. The degree of understanding "Tectonics represents performative architecture"

1	2	3	4	5	6	7	8	9	10

3. For Stage 3:

Q1-3. The degree of participation in each stage

1	2	3	4	5	6	7	8	9	10

Q2-3. The difficulty degree of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q3-3. The importance of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q4-3. The degree of understanding "Tectonics lays in the interaction between material and construction"

1	2	3	4	5	6	7	8	9	10

Q5-3. The degree of understanding "Tectonics means clear and logic structure"

1	2	3	4	5	6	7	8	9	10

Q6-3. The degree of understanding "Tectonics represents performative architecture"

1	2	3	4	5	6	7	8	9	10

4. For Stage 4:

Q1-4. The degree of participation in each stage

1	2	3	4	5	6	7	8	9	10

Q2-4. The difficulty degree of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q3-4. The importance of each stage to the overall workflow

1	2	3	4	5	6	7	8	9	10

Q4-4. The degree of understanding "Tectonics lays in the interaction between material and construction"

1	2	3	4	5	6	7	8	9	10

Q5-4. The degree of understanding "Tectonics means clear and logic structure"

1	2	3	4	5	6	7	8	9	10

Q6-4. The degree of understanding "Tectonics represents performative architecture"

1	2	3	4	5	6	7	8	9	10

D. Single-selection questions answering after attending the course

1. Please describe your understanding of the impact of the "Robotic Tectonics" in the architecture engineering and construction (AEC) industry.

a. Robotic Tectonics has no influence on the AEC industry.

b. Robotic Tectonics has a small influence on the AEC industry.

c. Robotic Tectonics has a great positive influence on the AEC industry.

d. Robotic Tectonics has a revolutionary influence on the AEC industry.

2. Please describe your understanding of the "Robotic Tectonics" what role in the future architectural design.

a. Robotic Tectonics in the future architectural design.

b. Robotic Tectonics plays an auxiliary approach in the future architectural design.

c. Robotic Tectonics plays a dominant approach in the future architectural design.

d. Robotic Tectonics plays an essential decisive approach in the future architectural design.

3. Please describe your understanding of the "Robotic Tectonics" what role in the future architectural design course.

a. Robotic Tectonics in the future architectural design course.

b. Robotic Tectonics plays an auxiliary approach in the future architectural design course.

c. Robotic Tectonics plays a dominant approach in the future architectural design course.

d. Robotic Tectonics plays an essential decisive approach in the future architectural design course.

4. Whether the four stages of the course are helpful to you, not only focus on the specific operation of a certain stage but also gain an overall view of the construction process?

a. Yes.

b. No.

5. Can you experience and clearly understand through the study of the course that "Robotic Tectonics" is composed of four integrated stages of "Parametric Design", "Multi-data Simulation", "Robotics application" and "Robotic Construction"?

a. Yes.

b. No.

6. Does the practical task used in this course compared with examination or other homework requirements, help you understand the whole process of "Robotic Tectonics"?

a. Yes.

b. No.

E. Multiple-selection questions answering after attending the course

What impact does this course have on your future architectural design?

a. It has no help.

b. The concept of tectonic under the emerging technology will continue to affect my architectural design.

c. Parametric design will positively affect my design method.

d. The simulation of the whole process will greatly affect the method of architectural design.

e. Cross-disciplinary cooperation may change my approach to architectural design.

f. The practical feedback of physical construction will simultaneously influence or change the conception of architectural design.

g. It will have a positive impact in other areas that are not clear.

F. Feedback or suggestions.

Please write down your feedback, idea, or suggestion about the course in the blank table below. Thank you very much for your active participation!

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