

**RAE2026**

**Exploring Phygitalisation**

**The Synergetic Role of Interactive  
Materials and Digital Information in  
Design Participation Enhancement**

**MCO 2**

Prof. Sky Lo Tian Tian

UoA38

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# Contents

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# 1 Descriptor

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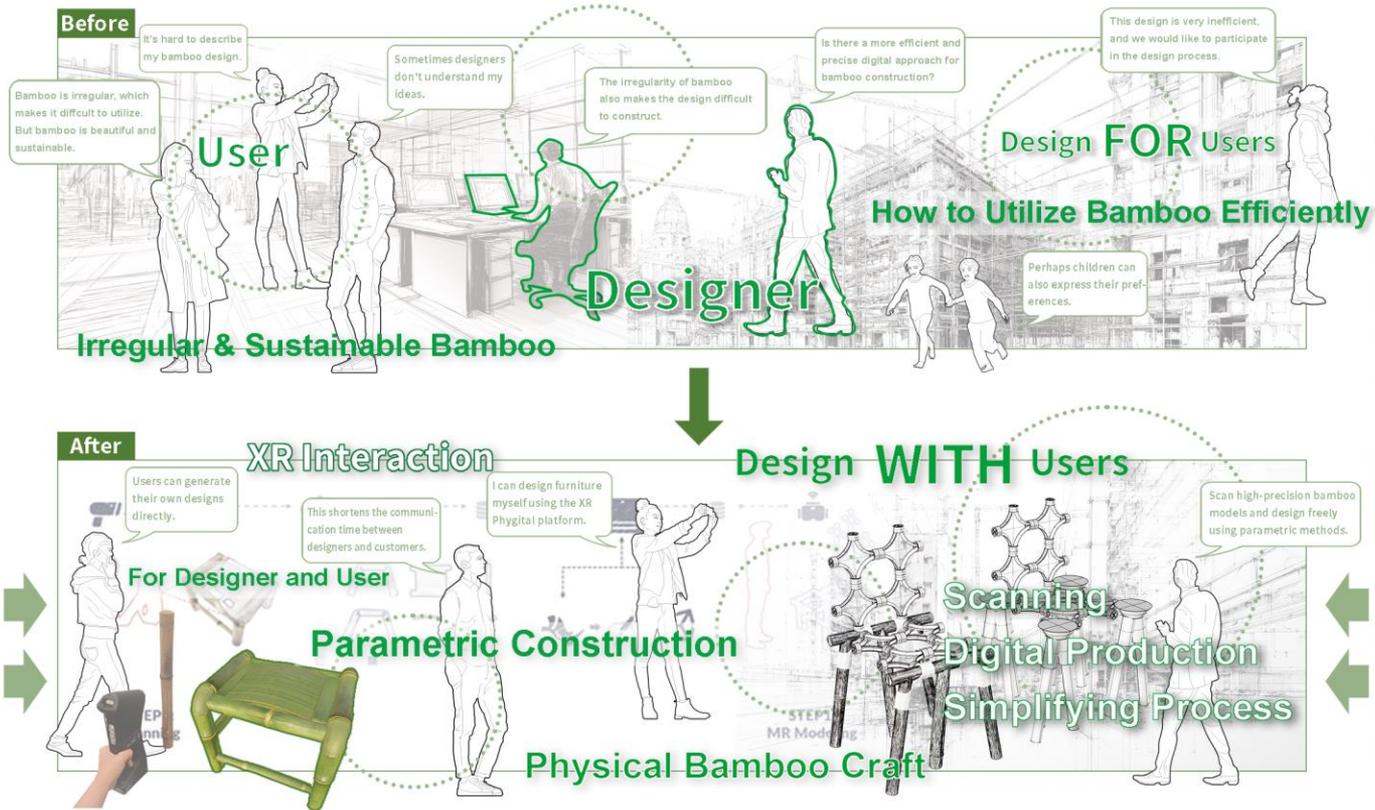
This research centers on examining how the fusion of digital and physical tools and knowledge (Phygitalisation: Physical-Digital Interaction) might inform the future deployment of indigenous materials (e.g. bamboo) in both manufacturing and construction projects. The aim is to improve traditional construction which is an inefficient, un-systematic way of making complex parts, without real-time, context-aware visualization of design or feedback, often resulting in resource-wasteful construction practices. By utilising design methods and combining virtual technologies, this cluster of experimental projects examine how to construct parameters for material use and how these can be digitally modelled and adapted while engaging clients, makers and users equally in the participatory and co-design processes and thereby increasingly shift the design agency into a more accessible, responsive and dialogic relationship.

This research comprises a sequence of five experimental projects, including a successful GRF (Ref. No. 15604423), value HK\$1,200,000, focusing specifically on the use of indigenous bamboo and exploring modelling parameters for bamboo (see outputs 3, 4 and 5 in this body of work). This sequence of projects and practices associated with 'Phygitalisation', specifically the design and combination of software applications and processes, has the potential to unlock new opportunities for forms of public, user and client engagements, and how this immersive modelling of products and spaces remains responsive and adaptive in real time to optimise flexibility and efficient material use.

The methods and methodology of this research combine 3D scanning, discrete design, topology optimisation and Extended Reality (XR) techniques augmented in dialogue with professionals, clients, users and makers. The research results are promoted through academic sharing and commercial collaboration. Future research aims to focus on knowledge dissemination and how these processes reposition design professional in the shaping of physical and virtual environments.

# 1 Research Map: Relationships of Different Outputs

## Physical Bamboo Furniture



## Bamboo Craft Work



### Prototype



Research Output 1 - < The Green Woven Corridor >

### Research Output - Basis Technology Development

Research Output 2 - < Enhancing Immersion in Virtual Spaces: PhytualBlend - a real-time interaction system for seamless physical feedback >

Research Output 3 - < PACS: Phygital-Aided Construction System based on Modular Customizable Timber Fabrication >

### Continue Research Output - GRF Project

Research Output 4 - < iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological >

Research Output 5 - < Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow >

## 2 Personal Profile: Prof. Sky Lo Tian Tian



Prof. Lo's research investigates spatial 'phygital' interactions and the relationships between virtual and physical spaces through transdisciplinary methods that combine design, virtual reality technologies, gamification and digital tools. His research emphasises multilevel sharing and collaboration, from basic data to deep intelligence, using mixed reality technologies to enhance interaction and knowledge transfer, and foster innovation in the design process. In his research, he uses the IoT and virtual visualisation to advance interactive fields and human VR interaction (HVRI), and open up the potential for future hybrid interactive experiences. MCO 1 (gamified recycling) and MCO 2 (XR Bamboo) demonstrate the outcomes of his research.

Prof. Lo joined The Hong Kong Polytechnic University as an assistant professor in 2022. He has organised workshops for DigitalFuture, CCD-ASC and POLAR, and published articles on transdisciplinary research and interactive design. He contributes to the leadership of organisations including CAADRIA (The Association for Computer-Aided Architectural Design Research in Asia), eCAADe (Education and research in Computer Aided Architectural Design in Europe), WORLD16 (a working group of 16 professors from around the world that engage in collaborative research on VR technologies) and World CAAD PhD (<https://research.polyu.edu.hk/en/activities/world-caad-phd-forum-2/>).

## 3 Research Questions

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### **1. How can the construction of irregular bamboo be optimised through digital technology to enhance the efficiency and sustainability of traditional materials in architecture and landscape design?**

The irregular geometric properties of bamboo limit its standardised application in construction. This study will examine how digital techniques (e.g. 3D scanning, parametric design and topology optimisation) can be used to transform irregular bamboo materials into efficient and sustainable building components.

### **2. How are the material properties of bamboo combined with the digital construction process, and how is XR technology used to achieve more accurate design-construction interactions and thus enhance the overall building performance and user experience?**

The properties of traditional materials, such as bamboo (e.g. flexural strength and air permeability), provide unique advantages for buildings, but traditional construction methods fail to fully utilise them. XR technology can integrate these properties with digital construction processes to achieve real-time interactions and optimisation.

### **3. On the basis of John Wood's synergy orders framework, how can knowledge dissemination and wisdom sharing contribute to the transformation of traditional materials from conventional to digital construction methods?**

John Wood's synergy orders provide a theoretical basis for innovation in the construction industry. This research will investigate how digital construction techniques for traditional materials can be extended to a wider range of application scenarios to promote sustainable development in the construction industry.

## 3 Research Questions

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### **4. How can the physical properties of bamboo be combined with virtual information through XR technology to present bamboo at different levels of immersion and thus test its impact on the user's understanding of physical space?**

In traditional architecture, the physical properties of bamboo are difficult to fully utilise. However, to these properties, XR technology can add virtual information on the physical space. This study tests the effects of different immersion levels on users' understanding of physical space through comparative experiments and examines how to optimise users' perception of bamboo architectural space through the presentation of virtual information.

### **5. In testing phygitalisation technologies in the design and learning process, how can phygitalisation technologies enhance user engagement and creativity in the manufacturing process by integrating the physical properties of traditional materials with digital information?**

This research will evaluate the effectiveness of phygitalisation technology in the design and learning process; examine how it can enhance users' understanding, engagement and creativity in the manufacturing process of traditional materials through the fusion of the virtual information and physical properties; and analyse it in comparison with traditional methods.

## 4 Research Outputs

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### (2021) The Green Woven Corridor

This research, a hands-on project for 2021, realises the phygitalisation of bamboo architecture by developing collaborative workflows that integrate augmented reality (AR), 3D scanning and robotic construction technologies.

### (2024) Enhancing Immersion in Virtual Spaces: PhytualBlend—A Real-Time Interaction System for Seamless Physical Feedback

Peer-reviewed paper, DOI: [https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024\\_116](https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_116)

### (2025) T: Phygital-Aided Construction System Based on Modular Customizable Timber Fabrication

Peer-reviewed paper, CAAD Futures, <https://research.polyu.edu.hk/en/publications/-phygital-aided-construction-system-based-on-modular-customiz>

### (2025) iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological. Electronics 2025, 14, 1116.

Peer-reviewed paper, DOI: <https://doi.org/10.3390/electronics14061116>

### (2025) Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow

Peer-reviewed paper, eCAADe 2025, <https://research.polyu.edu.hk/en/publications/parametric-and-modular-design-for-bamboo-chairs-in-extended-reali>



## 4 Research Context

**Phygital** is a portmanteau combining the words **'physical' and 'digital'**. It was coined by Chris Weil, the chairman and CEO of the Australian marketing agency Momentum Worldwide, to describe the seamless integration of the physical and digital worlds (What is phygital marketing?, 2024). *Phygital* was first used in the field of marketing to describe how brands integrate online and offline experiences. Its core concept is to break down the boundaries between the virtual and real worlds and create immersive, data-driven interactive experiences. The 'phygital' system is an interactive platform that amalgamates physical sensors and virtual reality technology to facilitate bidirectional real-time interaction between the virtual and real worlds.

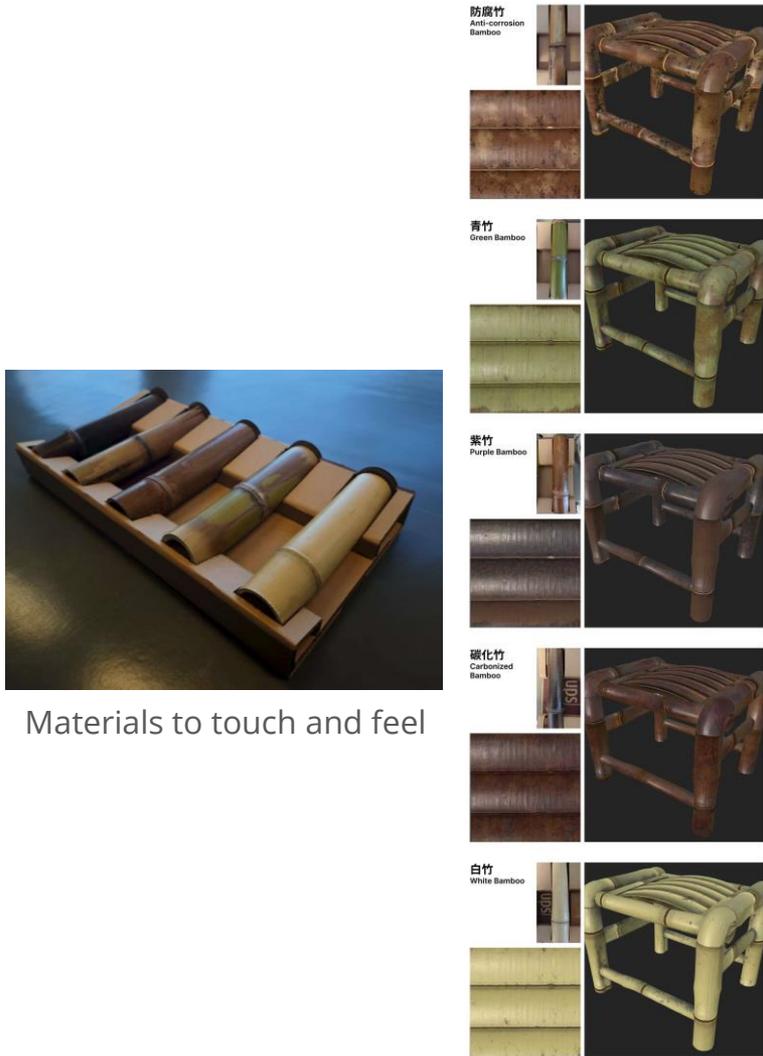
This research engages communities and stakeholders through a bottom-up design to meet their needs. It examines how phygital technology enhances the design, experience and perception of physical spaces, focusing on the role of **phygitalisation**. By leveraging sustainable materials, such as bamboo, and overcoming traditional workflow limitations, this research aims to promote sustainable development in construction through phygitalisation technology. Hence, it delves into the potential of digital-physical fusion in architecture and landscape design through a sequence of projects, emphasising the roles of material, manufacturing and construction technologies in human-space interaction.

The Green Woven Corridor in 2021 is a prototype of the combination of the phygitalisation concept and traditional materials that validates the digital efficiency and sustainability of bamboo. 2024 Opt2 demonstrates how XR and sensing technologies can provide physical feedback support for traditional material construction, representing a technical refinement of the parametric utilisation of irregular bamboo. The GRF funded a three-year (2024–2026) research project (Currently Outputs 3–5). Building upon previous practices and technical research, the GRF project developed digital modelling parameters for the irregular geometry of bamboo and engaged clients, manufacturers and users in participatory co-design. Opt3 is a foundational framework for the GRF project development and technical testing. Opt4 integrates 3D scanning, topology optimisation and XR to propose a digital workflow for bamboo applications. Opt5 refines the platform and feasibility design of the digital workflow.

What is phygital marketing? (2024).

<https://advertising.amazon.com/library/guides/phygital#:~:text=Phygital%20is%20a%20term%20invented,exciting%20and%20unique%20customer%20experiences.>

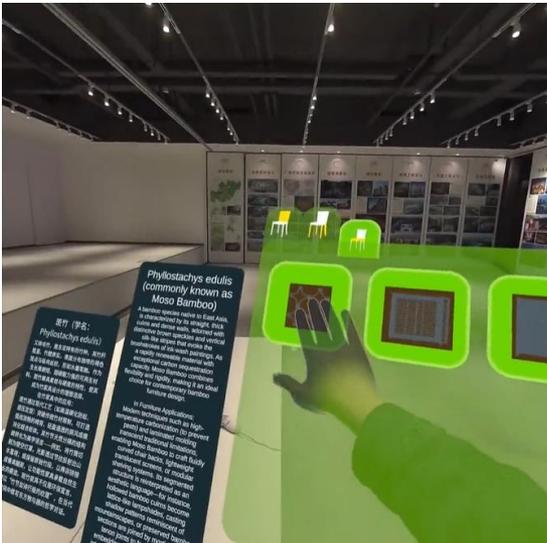
# 4 Research Context: Phygitalisation Process of the Project



Materials to touch and feel



MR pops up the digital information of the material that is touched



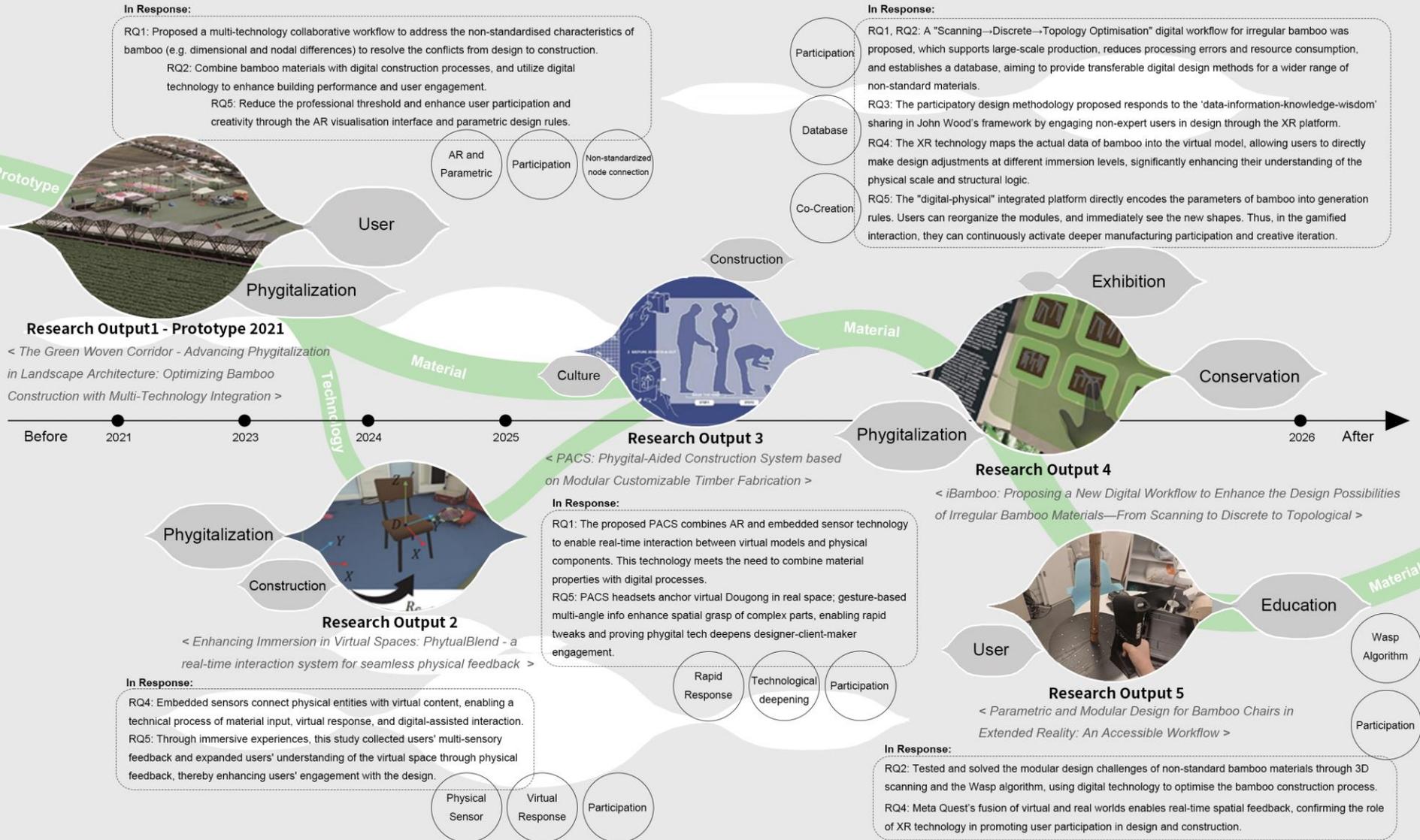
MR allows changes to the design and simulated result

Video Link:  
<https://ira.lib.polyu.edu.hk/video.jsp?id=115343>



Final product design to be built

# 4 Research Timeline



## 4 Research Output 1

### The Green Woven Corridor—Advancing Phygitalization in Landscape Architecture: Optimizing Bamboo Construction with Multi-Technology Integration (2021)

This is a 2021 teaching practice project for a green woven corridor designed and built in Chaozhou, China, using digital technology combined with traditional bamboo.

The project optimises the **parametric design and construction process** of bamboo through the integration of multi-technology methods, which is the **initial tangible practice** of the concept of phygitalisation in architecture. It aims to improve the utilisation of **non-standardised bamboo components** in parametric design to solve the **contradiction between nonlinear parametric design and irregular bamboo materials** from design to construction and to enhance the **construction efficiency and sustainability** of bamboo buildings.

This study aims to upgrade the construction process of traditional bamboo buildings by introducing an advanced parametric design system and digital construction process. By analysing the problems in traditional bamboo building construction methods, solutions are proposed to improve the construction efficiency and sustainability of bamboo buildings using a combination of digital tools.

Five major constraints were identified: 1) difficulty in positioning the supporting structure, 2) low efficiency of material selection and matching, 3) manual processing of materials, 4) non-standard node and 5) low utilisation rate of non-standard waste materials.



## 4 Research Output 1

### The Green Woven Corridor—Advancing Phygitalization in Landscape Architecture: Optimizing Bamboo Construction with Parametric Integration (2021)

Traditional construction methods rely on specialised intuition and construction experience for material selection and processing, making it difficult to ensure material suitability and coordination.

We established a multi-technology collaborative workflow that includes 3D Scanning for bamboo data selection, Grasshopper defining modularisation rules, AR-assisted construction and robotic construction complemented with 3D printing. Customised non-standard connectors are used to compensate for differences in bamboo shape.

The results of this research could improve the efficiency of bamboo construction, shorten the design cycle and facilitate structural innovation. AR technology preserves the perception of physical space, conforms to the core concept of phygital and facilitates the synergy between design and manufacturing.



Design and manufacturing process under the phygitalisation system

From left to right:

Stage 1: The builder builds according to the drawings.

Stage 2: HoloLens is used to show the model.

Stage 3: The builder's understanding and the designer's original intention were compared.

Stage 4: The design is revised.

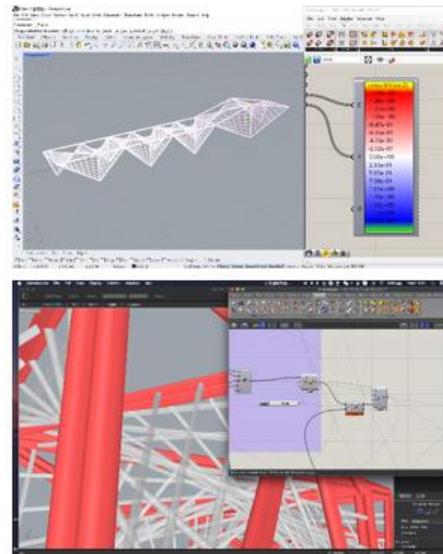
## 4 Research Output1

### The Green Woven Corridor—Advancing Phygitalization in Landscape Architecture: Optimizing Bamboo Construction with Parametric Integration (2021)

#### Relationship between the research content and questions:

This is the initial research prototype of this series of research results. Through the collaborative use of multiple technologies such as "3D scanning + Grasshopper parameter rules + AR positioning + robot/3D printing", the irregular properties of bamboo are transformed into real-time digital modules that can be assembled. Customized non-standard nodes are used to eliminate geometric errors, enabling precise on-site construction.

The AR interface enables non-professionals to adjust the module through gestures, instantly seeing the structural response. Thus, in landscape construction, the "bamboo material physical properties - parameter model - on-site perception" loop is achieved, and the "design - manufacturing - experience" integrated phygital prototype is initially realized.



(1) Grasshopper 3D model

(2) Physical design effects



## 4 Research Output 2

### Enhancing Immersion in Virtual Spaces: **PhytualBlend**—A Real-Time Interaction System for Seamless Physical Feedback (2024)

This research was published in volume 2 (pp. 129–138) of the proceedings of the eCAADe 42 conference titled ‘42nd Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2024)’, held in Nicosia in 2024. This study shows how providing physical feedback support through XR and sensing technology might be applied for the construction of traditional materials.

As an extension of physical space, VR and MR technologies provide convenient solutions for spatial and product designs by providing immersive user experiences. However, these technologies are limited in their ability to provide physical feedback, which can lead to a perceived disconnection between visual, auditory and bodily sensations. Thus, this paper introduces PhytualBlend, a real-time interaction system designed to enhance the physical feedback experience in virtual environments.

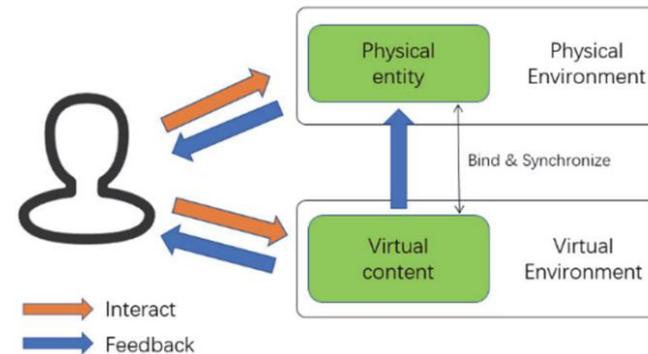


Figure 1: Interaction mechanism of the PhytualBlend system

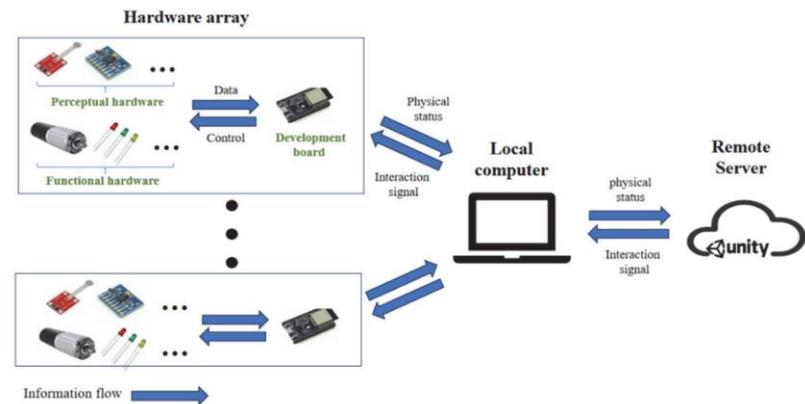


Figure 2: Overall structure of the PhytualBlend system

(2024) Enhancing Immersion in Virtual Spaces: PhytualBlend—A Real-Time Interaction System for Seamless Physical Feedback  
Peer-reviewed paper, DOI: [https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024\\_116](https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_116)

## 4 Research Output 2

### Enhancing Immersion in Virtual Spaces: PhytualBlend—A Real-Time Interaction System for Seamless Physical Feedback (2024)

The system employs perceptual and executive hardware driven by development boards as its hardware components. The user's operation on physical entities can be synchronised to a server-based virtual world through a local information hub, including position, orientation and haptic interaction. Diverse interaction modes in the virtual world can then trigger corresponding feedback in the physical space, encompassing tactile vibrations, thermal sensations, visual illumination and object deformations. This prototype demonstrates positive performance, achieving a frame rate exceeding 60 frames per second with an imperceptible network latency. The modular design of PhytualBlend potentially enables an efficient and scalable expansion of various physical feedback, interactive modes and new virtual environments. PhytualBlend bridges the gap between the virtual and physical worlds, enabling remote collaboration participants to experience and interact with virtual contents in a more tangible and realistic manner.

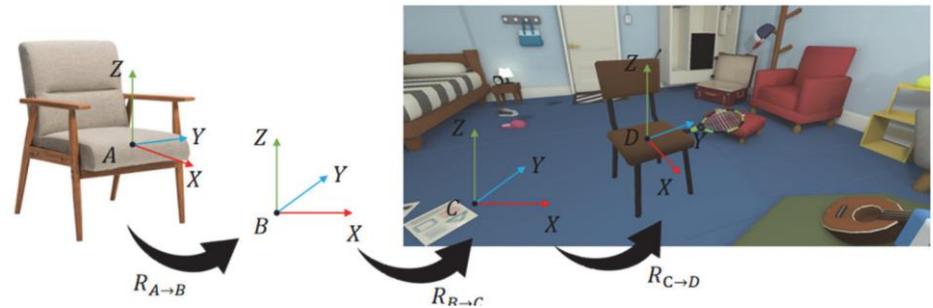


Figure 3: Rotation relationships: The mathematical relationship between the local coordinate systems in the physical and virtual worlds

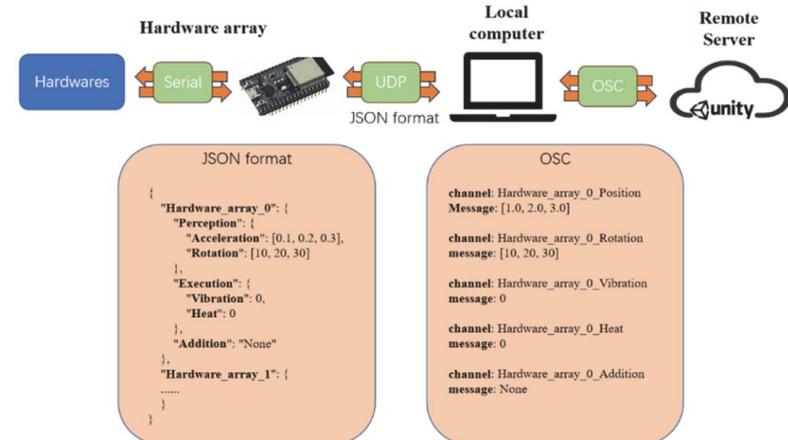


Figure 5: Data transmission mechanism of PhytualBlend

## 4 Research Output 2

### Enhancing Immersion in Virtual Spaces: PhytualBlend—A Real-Time Interaction System for Seamless Physical Feedback (2024)

#### Relationship between the research content and questions:

This study used embedded sensors to link physical entities with virtual content, realising a technical process of material input, virtual response and digitally assisted interaction. The system developed in this research is designed to collect users' multisensory feedback, and users' understanding of virtual space is efficiently extended through physical feedback. This demonstrates the impact of phygitalisation on the immersive experience, thereby enhancing user engagement with the design.

This research has broken through the previous limitations of XR bamboo structures, which were only focused on the visual level or single sensory stimulation. It has pushed the "local material properties - multi-sensory feedback - collaborative design" into the real-time closed-loop stage, laying a key technical foundation for the overall research to leap from "prototype verification" to "quantitative assessment of immersive performance and user cognition".



Figure 6.1: The sofa rotated as the physical entity was rotated

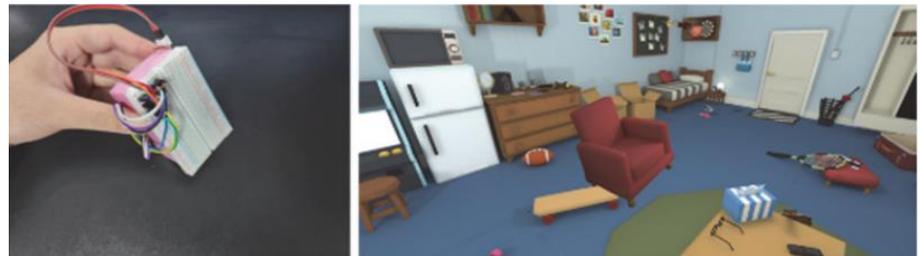


Figure 6.2: Vibration occurred when the sofa collided with something

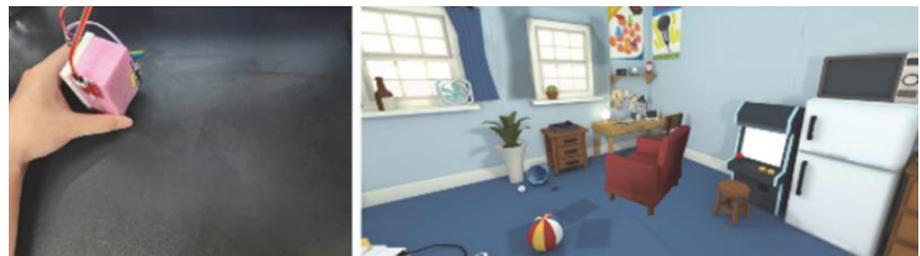


Figure 6.3: Heat was triggered when the sofa was placed in an inappropriate area

## 4 Research Output 3

### PACS: Phygital-Aided Construction System Based on Modular Customizable Timber Fabrication (2025)

This research is accepted and will be published in the proceedings of the CAAD Futures 2025 conference in Hong Kong. It aims to develop a system called PACS (phygital-aided construction system), which combines AR and pressure sensor technology to help lay participants, clients or learners efficiently and accurately assemble complex building structures. This research forms part of the basis for the development and technical testing of the GRF project.

As construction complexity increases in the architecture, engineering and construction industry, traditional paper plans struggle to clearly and conveniently provide adequate installation information and have poor interactivity and limited feedback guidance. This system streamlines the construction learning process, addresses the issue of low precision in traditional construction methods and leads to better-matched manufactured components.

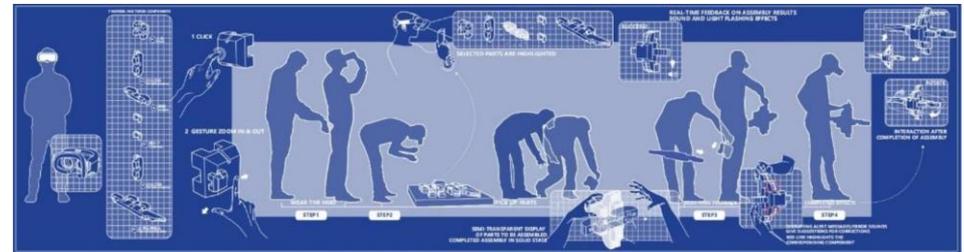


Figure 1: General PACS process, where workers can carry out construction activities with the assistance of virtual elements

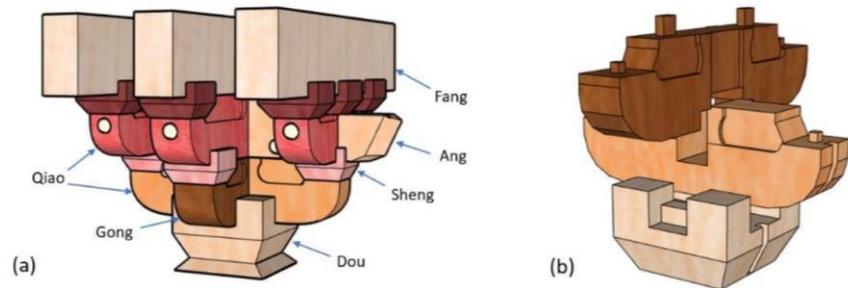


Figure 2: Structure of Dougong (the construction object of this study)

(2025) PACS: Phygital-Aided Construction System Based on Modular Customizable Timber Fabrication. Peer-reviewed paper, CAAD Futures, Accepted/In press. <https://research.polyu.edu.hk/en/publications/pacs-phygital-aided-construction-system-based-on-modular-customiz>

## 4 Research Output 3

### PACS: Phygital-Aided Construction System Based on Modular Customizable Timber Fabrication (2025)

The PACS proposed in this paper is based on an AR user interface and spatially anchored virtual models to help participants review information before construction and provide real-time feedback to unskilled workers on assembly location, method and results during the various steps of the construction. We designed modular structures called 'capsule'. The 'capsule' is used to carry hardware and sensors, which are placed within the Dougong components at designated recognition points to support triggering virtual feedback through physical actions.

The hardware combination (pressure sensors, magnetic sensors, etc.) and placement can be selected according to different sensing needs. The capsules merge with the structural components into a unified whole and provide long-term condition tracking to meet building maintenance needs. This research expands the application scenarios of BIM in on-site construction and user engagement through a low-cost, highly interactive approach, providing the construction industry with a more intuitive, real-time physical-digital collaborative construction solution.

We used HoloLens as the display device and Unity as the customised AR environment carrier, allowing the experimenter to assemble a wooden Dougong model with 16 components. The experiment shows that the participants mastered the use of the system after simple and quick training. The system reduced the assembly time and errors compared with the paper instructions. In addition, the results of the questionnaire survey indicate that the system helped improve the users' sense of participation and concentration in the assembly process. PACS has the potential to reduce the construction threshold, time and errors of complex buildings.

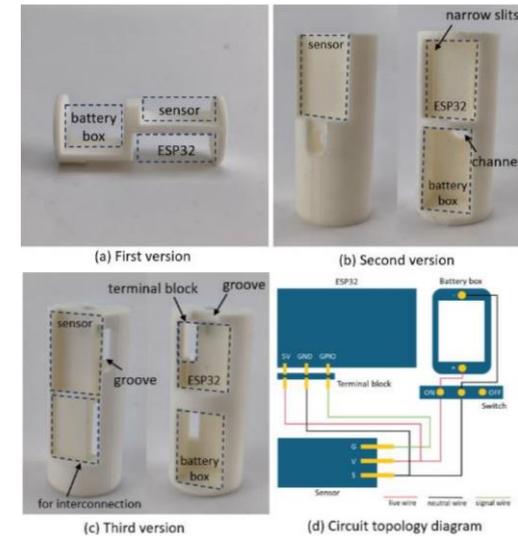


Figure 3: Capsule versions and the final circuit topology diagram

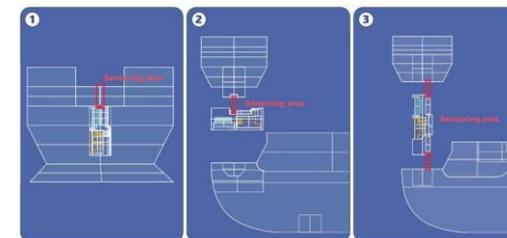


Figure 4: Capsule types

## 4 Research Output 3

### PACS: Phygital-Aided Construction System Based on Modular Customizable Timber Fabrication (2025)

#### Relationship between the research content and questions:

The proposed PACS combines AR and embedded sensor technology to enable real-time interaction between virtual models and physical components. PACS uses headsets to anchor virtual Dougong models in real space, allowing users to view component information from multiple angles through hand gestures, demonstrating that high immersion can enhance users' spatial understanding of complex structures. Users can make adjustments quickly based on the PACS.

This research has created a scalable construction closed-loop system integrating "local raw materials - embedded sensors - AR real-time correction", breaking through the previous on-site interaction bottleneck in digital construction. It has pushed "phygital creation" from prototype verification to the stage of "site-level accuracy and human factor quantification", laying a hard and soft integrated platform for the subsequent batch customization of bamboo structures.

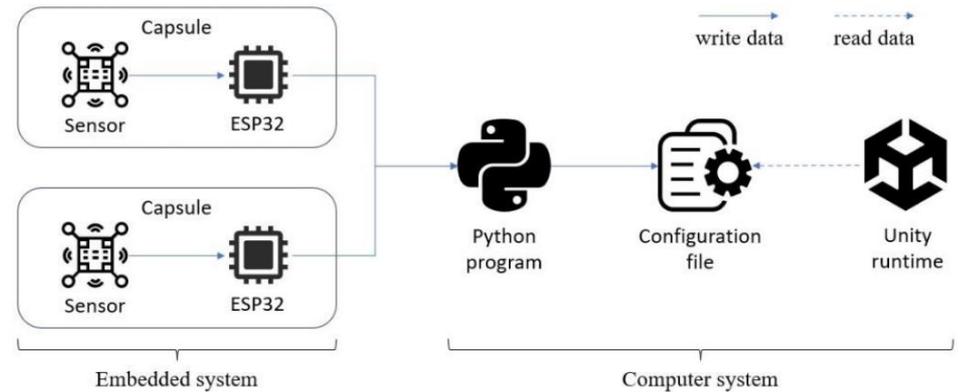


Figure 5: Software structure of the PACS

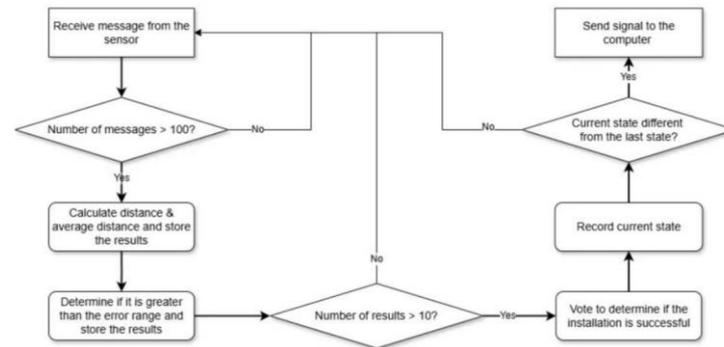


Figure 6: Flowchart of the embedded system

## 4 Research Output 4

### iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological (2025)

Opt4 is an exploration and technological integration of digital workflows for irregular bamboo materials, which is funded by the GRF. The research aims to improve the efficiency and sustainability of the use of traditional bamboo materials in Hong Kong architecture and to explore the potential of 'blending physical with digital' in architectural and landscape design.

This research proposes a new **digital workflow** to transform irregular bamboo materials into efficient building materials through **3D scanning, discrete design and topology optimisation techniques**. The basic logic of this technology can be summarised in three key steps: discrete unit design, definition of connection rules and aggregation of components. This process begins with an in-depth study of the simplest raw bamboo rods. This allows for the study of the discrete generation of bamboo rods, addressing the material limitations of bamboo and providing corresponding solutions (Figure 1).

(2025) iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological. *Electronics* 2025, 14, 1116.

Peer-reviewed paper, DOI: <https://doi.org/10.3390/electronics14061116>

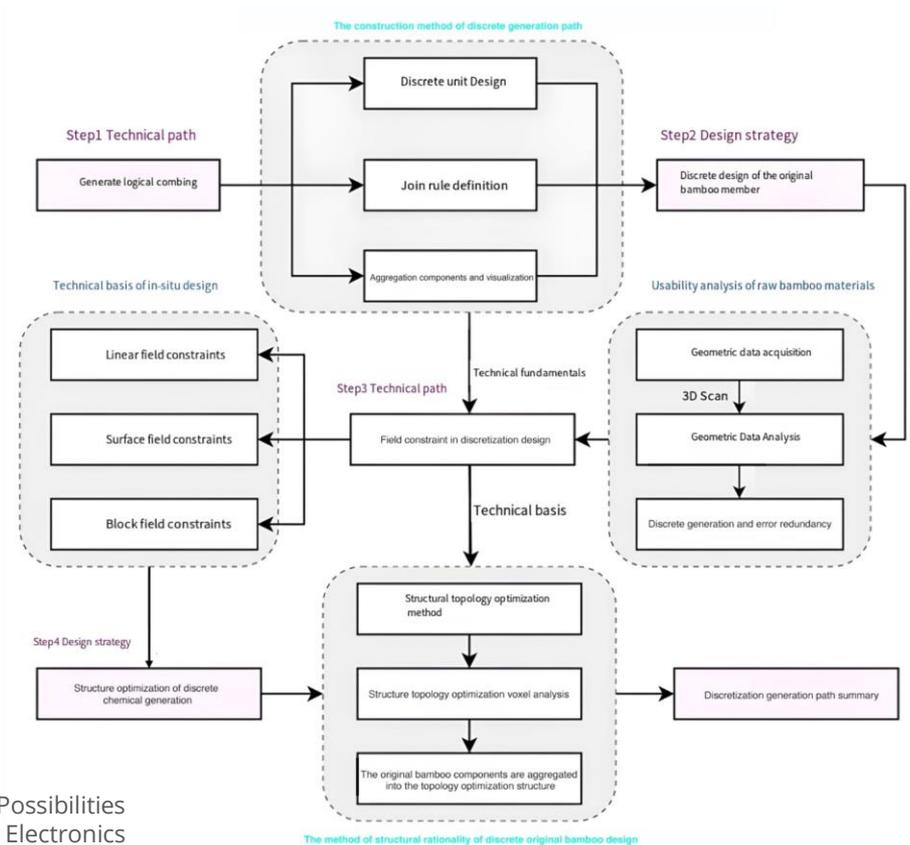


Figure 1: Workflow of a new aggregation approach for a discrete bamboo component

## 4 Research Output 4

### iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological (2025)

#### 3D Scanning Technology

3D scanning helps obtain digital information about bamboo materials, enabling designers and engineers to utilise non-standardised bamboo materials. However, accurately capturing the geometry of bamboo materials is difficult using 3D scanning.

#### Discrete Algorithm Enhanced Design

The discrete bamboo structure consists of repetitive and reconfigurable units that can be assembled by traditional connection methods, but the structural rationality of these polymeric bamboo units must be further verified.

#### XR Technology

XR platforms enhance collaboration and iterative capabilities in the design process, optimise the digital manufacturing process and provide educational and training opportunities.

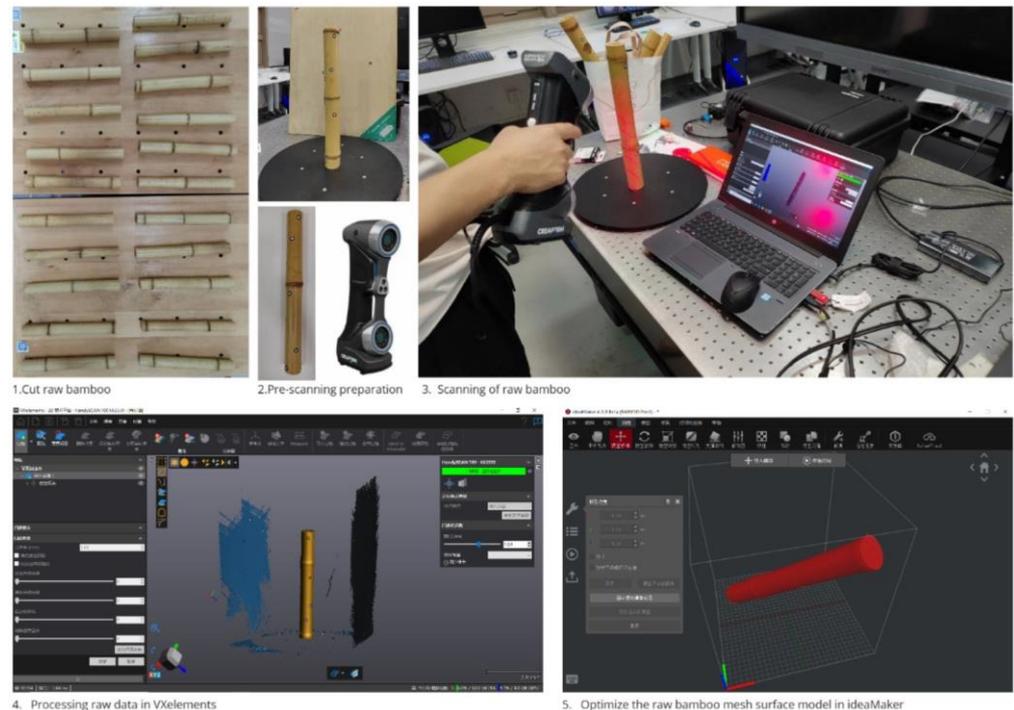


Figure 2: The non-standardized nature of bamboo materials limits their application in sustainable construction. This study initially addressed the challenge of non-standardised bamboo and established a database through 3D scanning, discrete algorithms and XR techniques, which require future enhancement of physical fabrication integration.

# 4 Research Output 4

## iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological (2025)

### Relationship between the research content and questions:

In this section, a digital workflow of ‘Scanning→Discrete→Topology Optimisation’ for irregular bamboo is proposed to transform non-standardized indigenous materials into computable modular components. This method not only aims to support scaled production and reduce processing errors and resource consumption but also strives to provide a transferable digital design methodology for a broader range of non-standard materials.

The participatory design methodology proposed responds to the ‘data-information-knowledge-wisdom’ sharing in John Wood’s framework by engaging non-expert users in design through the XR platform.

This research marks the transition of the overall study from "single technology verification" to the "systematic methodological output" stage.

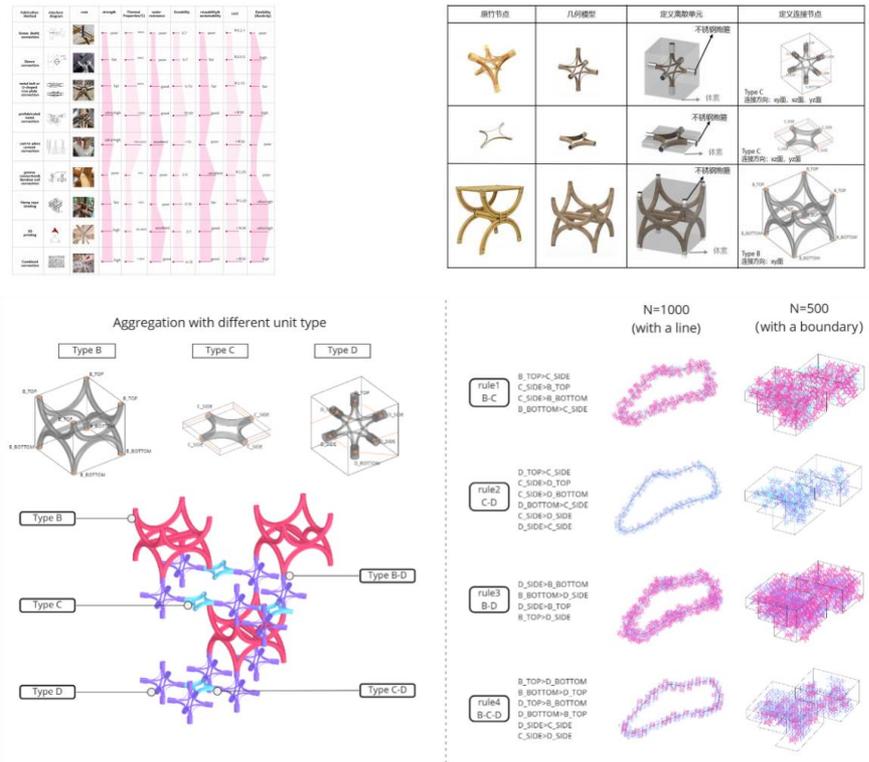


Figure 3: Database containing the characteristics of different fabrication methods, kinds of original bamboo discrete units and aggregate components of linear region constraints

## 4 Research Output 5

### Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow (2025)

This research was published in the proceedings of eCAADe 2025 Ankara (September 2025).

Bamboo is a renewable and biodegradable material with a potential to advance sustainable design. However, its natural irregularity and non-standard geometry present challenges for modularity, standardisation and digital fabrication. This study proposes an XR platform that enables intuitive, parametric designs of bamboo chairs through immersive interactions. Built in Rhino as the modelling core, the platform integrates Grasshopper for parameter control and Wasp for modular aggregation, allowing for a rule-based assembly of bamboo components that reflects their real-world irregularities.

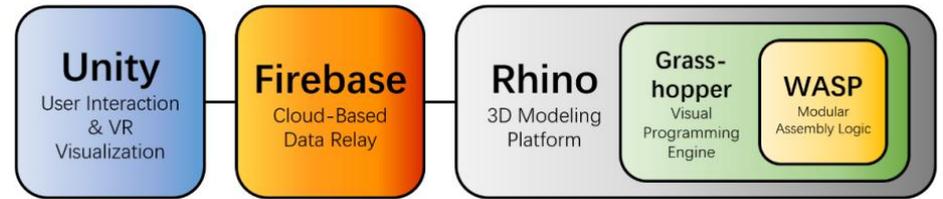


Figure 1: System architecture and component relationships of the development process

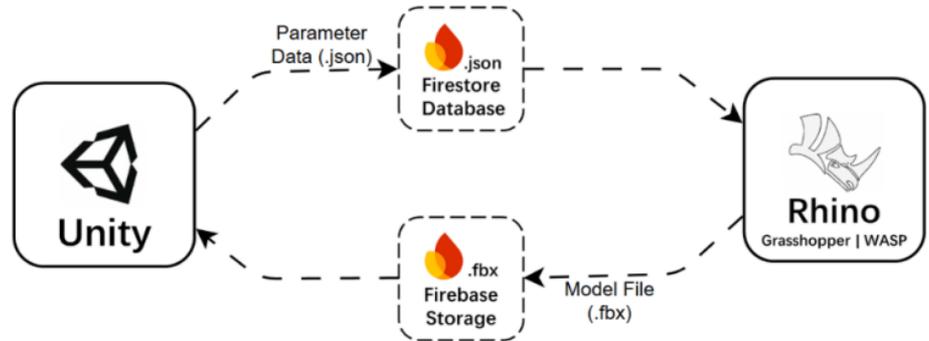


Figure 2: Data flow

(2025) Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow. Peer-reviewed paper, eCAADe 2025, Accepted/In press

## 4 Research Output 5

### Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow (2025)

Users can already interact with chair modules in real time using hand tracking in Meta Quest 3, adjusting parameters and visualising configurations directly in physical space. The system supports both basic and advanced design modes and uses scanned bamboo elements to ensure fabrication feasibility. Finalised models will be stored and prepared for production, bridging virtual design with traditional craftsmanship. By combining XR technology with computational design tools, the platform potentially offers a sustainable and accessible workflow for bamboo furniture customisation.

The study chose WASP to manage the non-standard geometric structure of bamboo, leveraging XR technology to enhance users' spatial perception, thereby lowering the threshold for design participation and creating a participatory design platform suitable for different users.

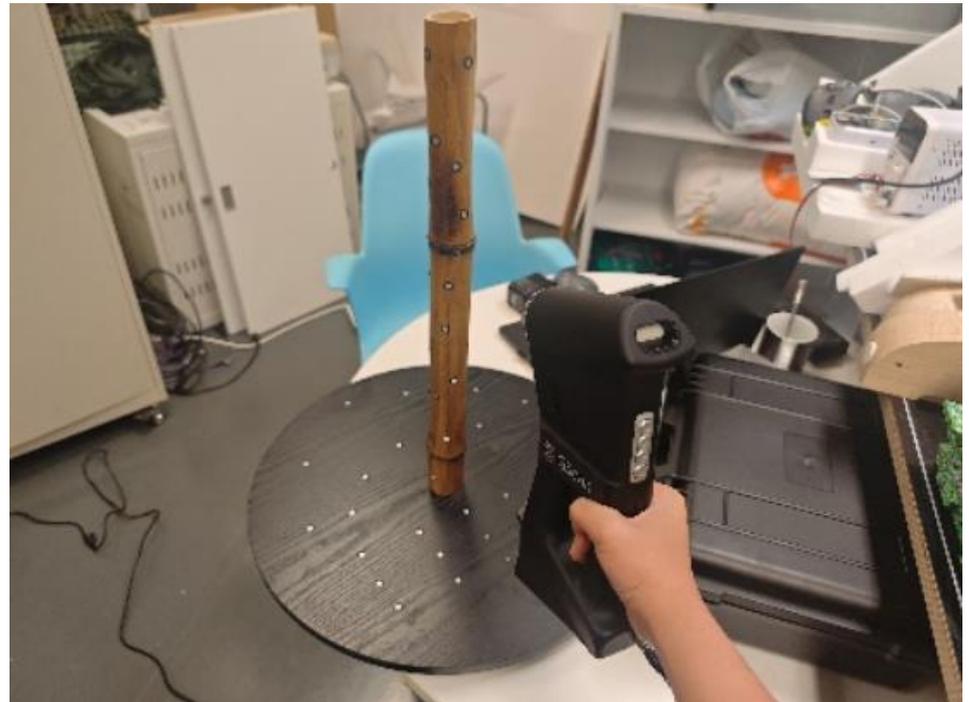


Figure 3: GScan scanning bamboo

## 4 Research Output 5

### Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow (2025)

#### Relationship between the research content and questions:

This study tested and solved the modular design challenges of non-standard bamboo materials through 3D scanning and the Wasp algorithm, using digital technology to optimise the bamboo construction process.

Meta Quest's fusion of virtual and real worlds enables real-time spatial feedback, confirming the role of XR technology in promoting user participation in design and construction.

This research fully integrate the "scanning - modularization - immersive interaction" concept down to the furniture scale. It breaks through the previous limitations of the bamboo-structured XR, which only remained at the level of visual exploration or one-way display. It pushes "local materials + real-time parameters + multiple immersive levels" into the stage of commercialization and personalized customization, providing the terminal scenarios and data foundation for the overall research loop of "technology - performance - shared intelligence".

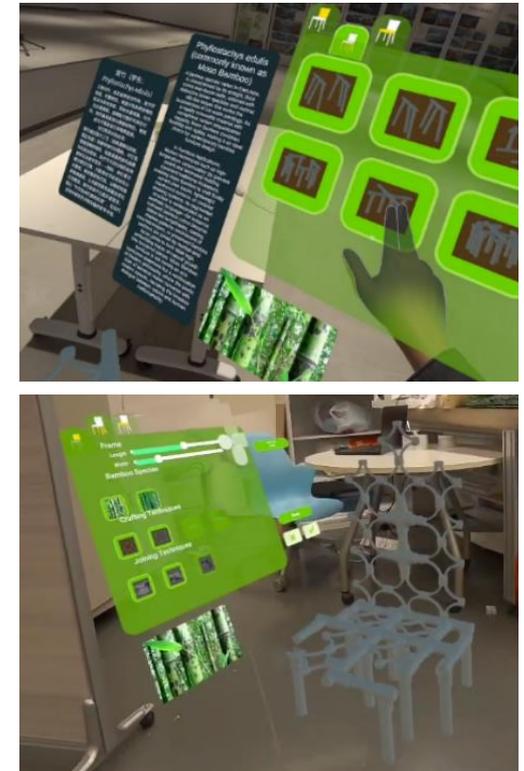


Figure 4: XR digital interactive interface design using Meta Quest

## 5 Research Field and Key References

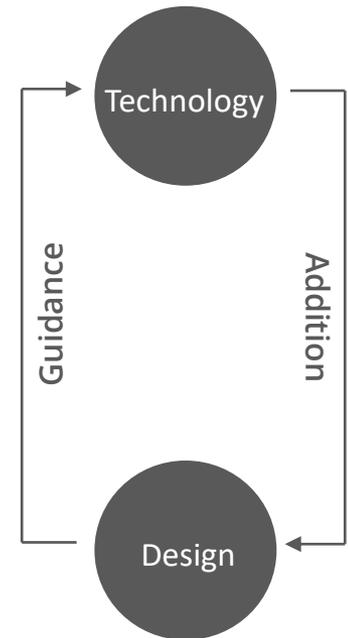
### Cross-Disciplinarity: Design and Technology

Phygitalisation research uses cross-disciplinary approaches that aim to combine design and technology to re-coordinate the interaction between people and space.

Key References:

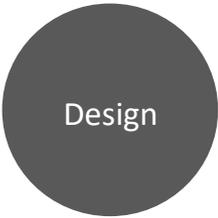
- Zhao, J.; Riecke, B. E.; Kelly, J. W.; Stefanucci, J.; Klippel, A. 2023. Virtual reality technology, due to its immersive interactive capabilities, is being integrated into traditional design processes, focusing on how technological advancements influence users' experiences.
- Mimendi, L.; Lorenzo, R.; Li, H. 2022. Digitizing bamboo structural units enables bamboo structures to integrate with modern data management platforms, while leveraging BIM technology to coordinate structural design, construction, and maintenance operations more efficiently.
- Zhu, J.; Zhou, H.; Wang, C.; Zhou, L.; Yuan, S.; Zhang, W. 2020. Topology optimization was developed as an advanced structural design methodology for generating innovative, lightweight, and high-performance structures that are difficult to obtain through conventional concepts.
- Hyde, R.; Filippidis, F. 2021. Discrete algorithms enhance prefabricated assembly design systems for bamboo structures, helping overcome limitations associated with 3D scanning.

In these experiments, technology is utilised experimentally to improve user and design participation, facilitate new forms of user interaction with space and enable rapid iteration of design concepts and practice developments. Design as a creative and practical discipline for addressing user needs and problems will drive the research. Technology, as an aid to design, will facilitate the development of design in a sustainable direction.



## 5 Research Field and Key References

### Cross-Disciplinary: Design and Technology



#### Design

- The interdisciplinary approach aims to overcome the non-standardised characteristics of traditional bamboo materials, enhance their application efficiency and sustainability in architecture and design, and promote innovation through knowledge sharing and user participation.
- Participatory design dominates the entire research process, which is a form of research based on user participation and feedback that help to develop design outcomes that fulfil user needs. Design is not only the construction of physical space but also the creation of spatial narrative and experiential perception. The research methodology includes problem analysis, technology testing, programme design, user experimentation, data analysis and design results analysis. Technology is an iteration on the physical environment and enhances the user's understanding of the design space. It also facilitates reflection on the design outcome.



#### Technology

- Virtual reality technology has redefined the role of participatory design in the creation of spaces, involving technology development, behavioural research and example applications. The technologies applied include VR application development, Unity 3D, VR device application deployment and smart wearables. Technology facilitates design innovation, provides new forms of practice for design and promotes design interactivity and inclusivity.

This MCO workflow and design methodology framework originated from practical project validation and academic conference exchanges, and was advanced through collaboration with professional designers, manufacturers and interdisciplinary teams. This research is dedicated to transforming research outcomes into industry-usable reference models, thereby making unique knowledge contributions in the areas of 'digital transformation of non-standard materials' and 'practical integration of participatory design technologies'.

## 6 Research Methods, Prototypes and Materials

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Phygitalisation research is a cross-disciplinary research methodology centred on participatory design with the addition of virtual reality technology, enabling the integration of hardware and software.

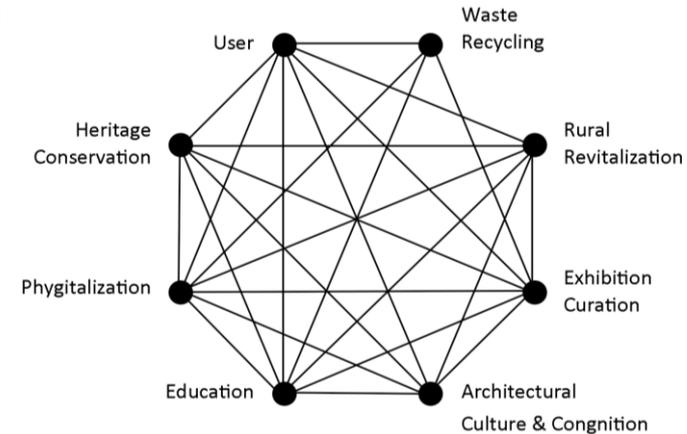
Specific research methods:

1. Integration of existing virtual reality technologies, virtual participatory design methodology and practice-based collation
2. 3D scanning, digital modeling, parametric design, discrete generation techniques and topology optimisation
3. Comparative experiments applied to simulations of different scenarios, data collection and behavioural observation
4. Data collation, analysis of experimental results and evaluation of interaction results

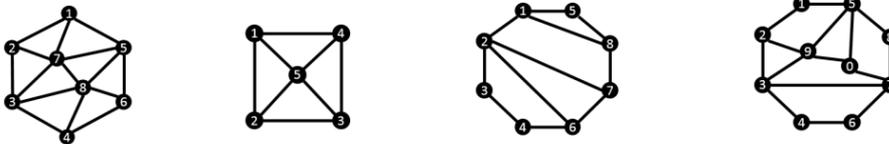
# 6 Research Methods, Prototypes and Materials

## A - Theoretical Foundation: John Wood's Synergy Orders Framework

Nodal Diagram	Feature	Comprehensiveness	Implications
	2 players 1 relationship	Very high	Minimum collective potential
	3 players 3 direct relationships	High	With more players, relationships starts to become indirect
	4 players 4 direct relationships 2 intersect relationships	Comprehensive enough	Team misunderstanding may build up if collaborators have to also deal with intersecting relationships which is confusing
	5 players 5 direct relationships 5 intersect relationships	Exceeds the scale of exclusively direct relationships	Going beyond the average person's conscious grasp
	6 players 6 direct relationships 9 intersect relationships	Very rich but increasing hard to manage and more dependent on intuitive management	Increasingly relies heavily on experiences, and/or intuitive skills and insights



Addition possible configuration with only direct relationships



- Relationship between the various contexts, the technology and the users

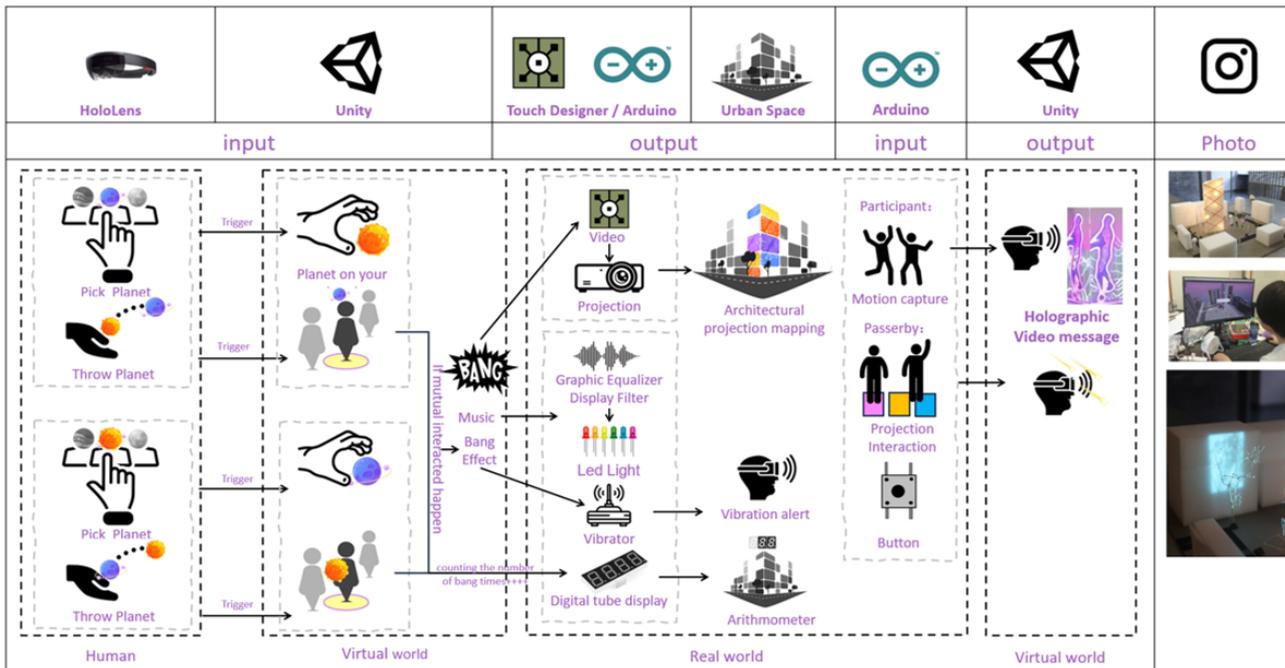
- Nodal diagram showing the number of players and the implications to comprehend the relationships (Wood, 2007)

Currently, the research on participatory design in phygitalisation technology involves various fields, including heritage conservation, virtual and reality interaction, education, architectural cognition, culture, exhibition and rural revitalization. Synergy is the core of participatory design, which is dynamic, stimulates innovation through multilevel collaboration and promotes the sustainable development of design and bidirectional communication between designers and users. Based on John Wood's synergy orders theoretical framework, this study found that multilevel collaboration and innovation—from data sharing to knowledge sharing—play a significant role in advancing the design process.

Wood, J. (2007). Design for Micro-Utopias: Making the Unthinkable Possible. England: Gower.

# 6 Research Methods, Prototypes and Materials

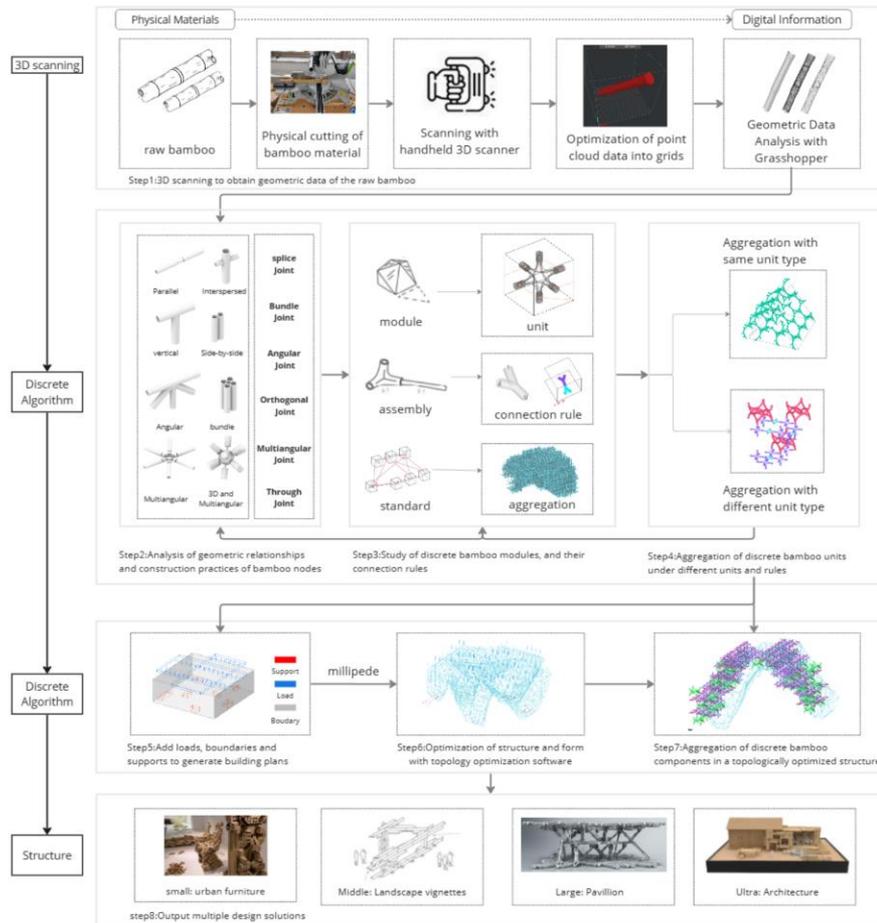
## B - Technology Foundation: The Significance of Phygital Interaction in Participatory Design



- This diagram shows the immersive phygital (physical-digital) interaction technology path of the MCO project and represents a deepening of John Wood's synergy orders framework.
- Users trigger virtual feedback through real-world interactions, achieving immersive learning and participatory design through multisensory stimulation.
- Phygitalisation technology represents a deepening of participatory design, successfully integrating communities and stakeholders into the design process while emphasizing the empowerment of individuals to provide solutions that meet their needs.

# 6 Research Methods, Prototypes and Materials

## B - Technology Foundation: Digital Manufacturing Technology Promotes the Innovation and Efficient Utilisation of Traditional Bamboo Materials



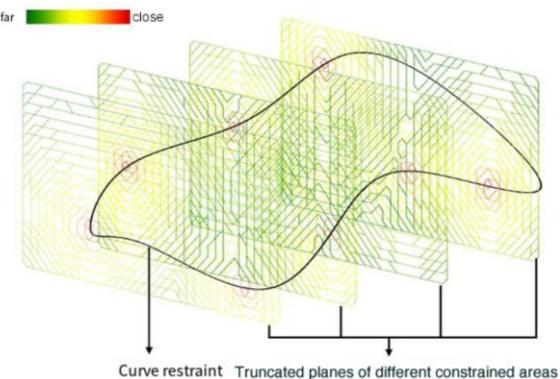
- Step 1 - 3D Scanning and Digitisation: Use laser 3D scanners to scan primary bamboo and capture their surface model data. Then, obtain precise digital 3D models of bamboo and extract key geometric parameters (e.g. diameter and node spacing) to provide a data foundation for subsequent design work.
- Step 2 - Discrete Design and Connection Rules: Decompose complex bamboo structures into repeatable, reconfigurable discrete basic units. Research and classify various traditional bamboo jointing methods (e.g. binding, metal fittings and 3D-printed connectors), and analyse their strength, durability, cost and sustainability characteristics to establish a digital library of jointing rules.

Digital workflow to design raw bamboo:

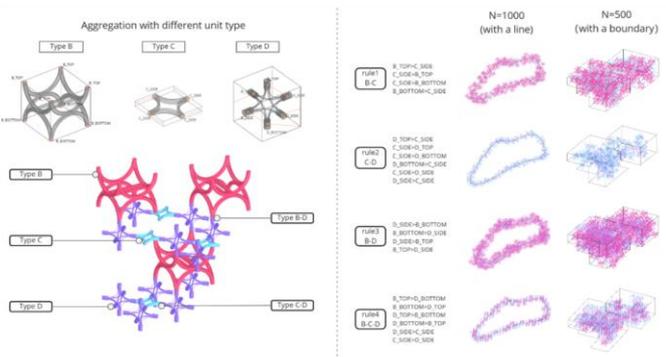
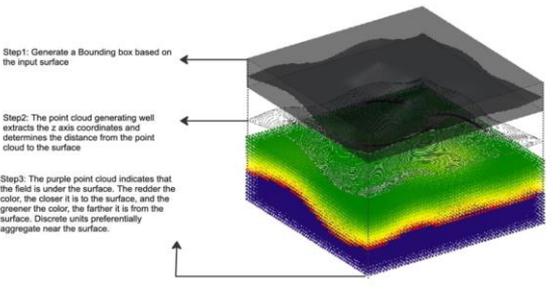
From scanning to discrete to topological

# 6 Research Methods, Prototypes and Materials

## A - Theoretical Foundation: Discrete Design and Topology Optimization in Bamboo Construction



Original bamboo node	Geometric model	Define discrete elements	Define connection nodes
		Stainless steel hoop voxel	Type C Connection direction: xy,xz,yz
		Stainless steel hoop voxel	Type C Connection direction: xz,yz
		Stainless steel hoop voxel	Type B Connection direction: xy



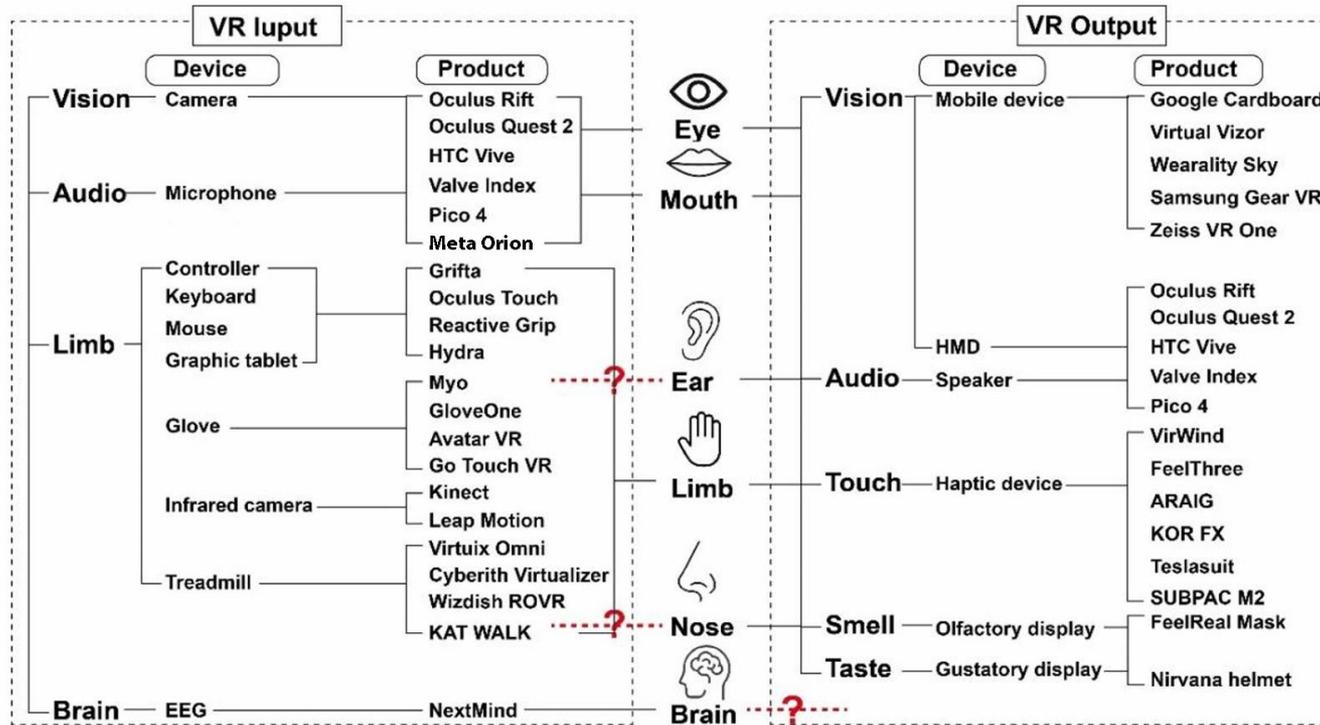
- Section plane of the curve-constrained area
- Field generation with surface area constraints

- Three kinds of original bamboo discrete units
- Aggregate components of linear region constraints

- Step 3 - Aggregation Under Field Constraints and Topological Optimisation: The aggregation process is driven by an algorithm (Wasp) applied to discrete units. Curved paths, surfaces and 3D space are defined to constrain and control the aggregation pattern. Subsequently, structural performance optimisation is applied to the aggregated form to achieve structural rationality, resulting in an optimised bamboo structure that satisfies both design aesthetics and engineering logic.
- Step 4 - XR Visualisation: Building an immersive interactive platform using XR technology (developed on the Unity engine). Designers, clients and craftsmen can jointly view, operate and modify design proposals within XR environments, enabling participatory design.

# 6 Research Methods, Prototypes and Materials

## C - Technology Integration: Application of Bidirectional Interaction and Participatory Design in the MCO Project



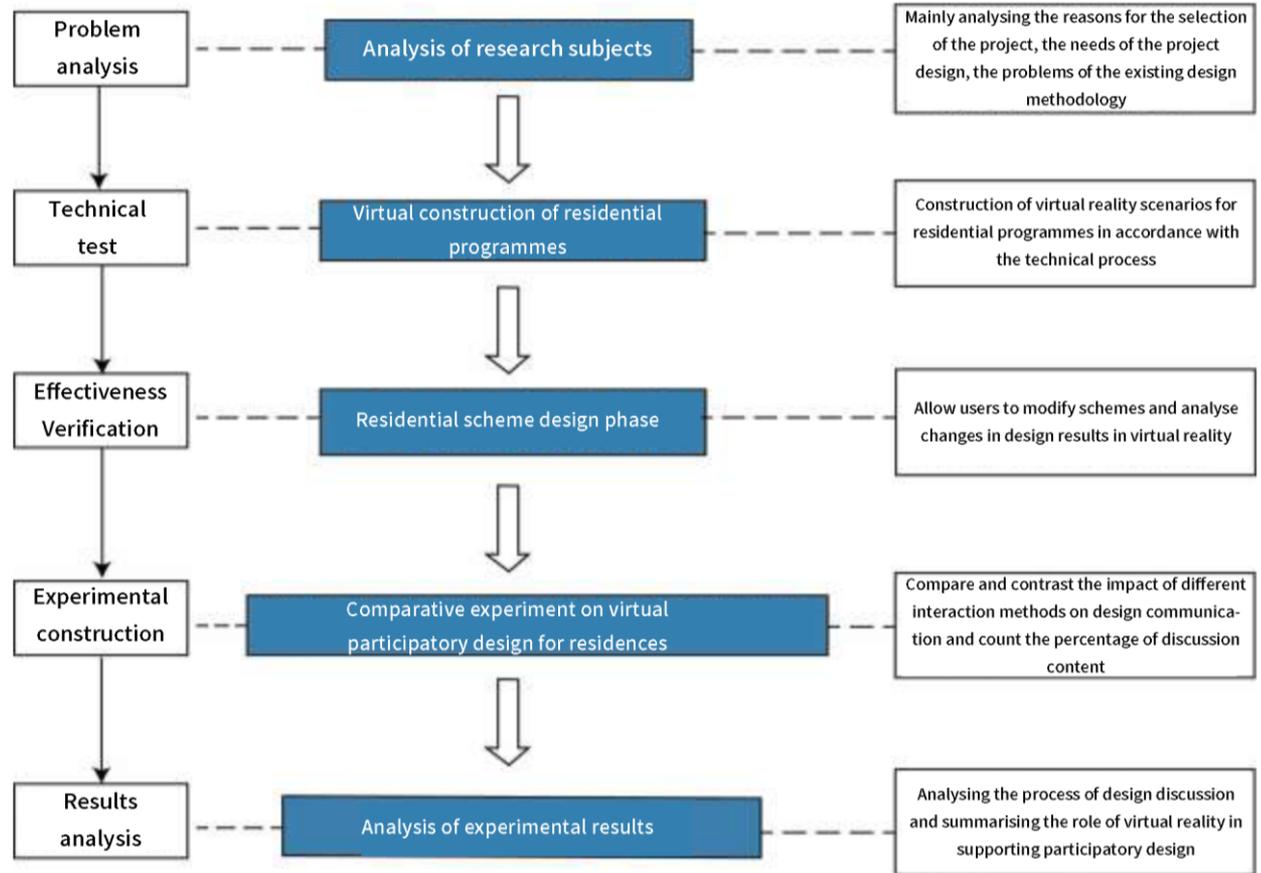
- Use multiple sensory channels. Multiple signal inputs can convey information accurately.
- Use 3D spatial interaction. Virtual reality presents a 3D world and invites interaction beyond 2D interfaces.
- Focus on the bi-directionality of interaction. The interaction input and output can be responsive.
- Focus on the realism of the interaction. A positive interaction mode would minimise the presence of the interface.

Integration of devices to be used in the technology development phase of an immersive participatory design

# 6 Research Methods, Prototypes and Materials

## D - Application Logic of the Research Subject Analysis Method of the Project

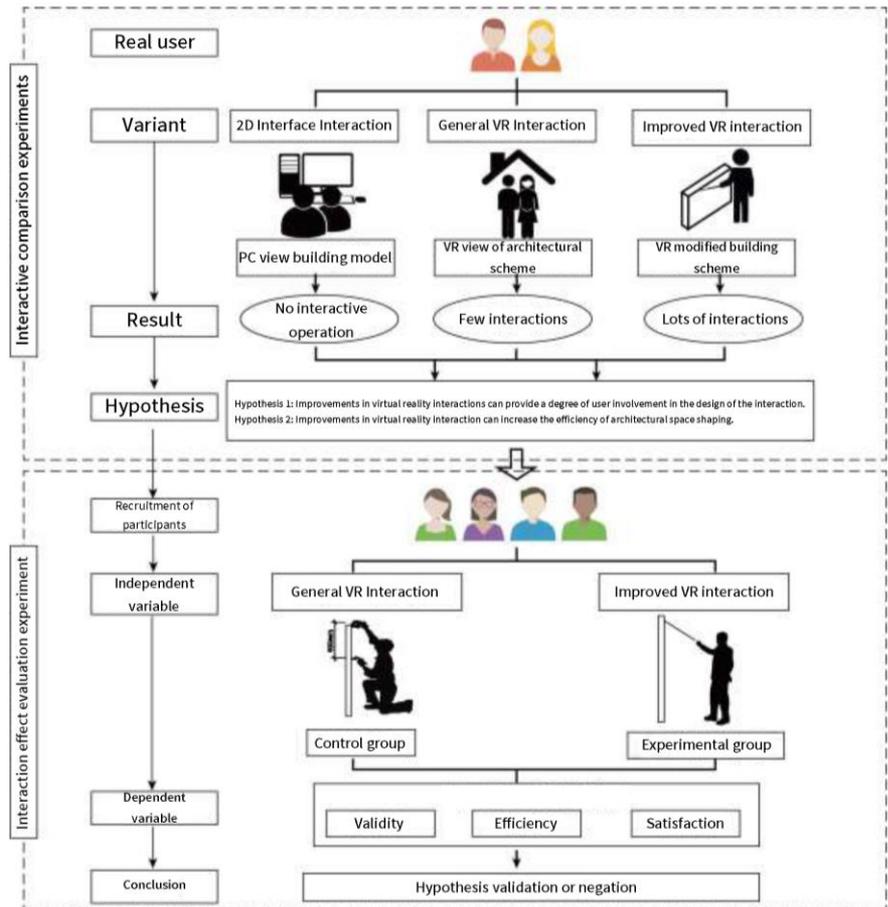
The logic of empirical research is problem analysis, technique testing, effect validation, experimental construction and result analysis.



# 6 Research Methods, Prototypes and Materials

## E - Comparative Experiments to Analyze the Impact of Different Levels of Immersive Technologies on Participatory Design

Comparative experiments can compare the facilitating effects of different interaction methods on participatory design and design communication using virtual reality technology. The interaction effect evaluation experiments use virtual reality interaction methods as independent variables to measure the user's interaction behaviour during the design process and analyse the interaction between the user and the building.



Comparative process of the MCO project

# 6 Research Methods, Prototypes and Materials

## F – Bamboo Prototypes of the Project

- Digital Prototype: Digital models generated through 3D scanning and parametric design tools, which can be used to simulate and optimise the structure of bamboo materials.
- Physical Prototype: Physical model manufactured through 3D printing and used to verify the feasibility of the design and optimise the manufacturing process.
- Modular Prototype: Modular units generated based on discrete design technologies.
- Topology Optimisation Prototype: Meeting the design requirements and maximising the structural performance of the material.



Fabrication Method	structure diagram	case	strength	Thermal Properties(°C)	water resistance	Durability	reusability& sustainability	cost	Flexibility (Elasticity)
Screw (bolt) connection			poor	350°C	poor	3-7	poor	¥0.2-1	poor
Sleeve connection			fair	550°C	poor	3-7	fair	¥0.5-5	high
metal belt or U-shaped iron plate connection			fair	900°C	good	5-10	fair	¥2-10	fair
prefabricated metal connection			ultra-high	1150°C	good	10-20	good	> ¥50	high
cast-in-place cement connection			ultra-high	700-1200°C	excellent	>15	poor	> ¥50	poor
groove connection& Bamboo nail connection			poor	70°C	poor	2-5	excellent	¥2-20	poor
Hemp rope binding			fair	150°C	poor	3-10	fair	¥5-20	ultra-high
3D printing			high	180-200°C	excellent	3-7	good	> ¥20	ultra-high
Combined connection			high	>180°C	good	4-10	good	> ¥50	high

## 7 Research Outcomes

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This study proposes a new digital workflow to transform irregular bamboo materials into efficient building materials through 3D scanning, discrete design and topology optimisation techniques. The workflow significantly improves the efficiency and sustainability of bamboo applications in architecture and landscape design.

This research verifies the effectiveness of multi-technology integration (including XR, 3D scanning, digitally assisted construction and 3D printing) in optimising the bamboo building construction process through several sub-projects (e.g. 'Green Woven Corridors' and 'Bamboo Landscape Architectural Design Methods Based on Discrete Generation Techniques').

Based on John Wood's synergy orders framework, this study establishes a multilevel collaboration system for XR construction from data sharing to wisdom sharing, which provides theoretical support for participatory design and digital innovation of traditional materials. Beyond providing a digital demonstration for the sustainable utilisation of irregular materials like bamboo, this study also developed an XR-based participatory design methodology to enhance engagement and design efficiency among users, designers and manufacturers throughout the design process.

## 7 Research Findings

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Research has shifted from an initial focus on bottom-up design engagement to the field of phygitalisation interactive technology, which explores the convergence of physical and digital experiences.

This shift reflects the blurring of the boundaries between the physical and digital worlds in the field of design research and provides new opportunities for innovation and impacts in immersive interaction technologies. Meanwhile, based on John Wood's synergy orders theoretical framework, this research found that multilevel collaboration and innovation from data sharing to wisdom sharing are important for driving the design process.

This research represents a deepening of participatory design that successfully integrates communities and stakeholders into the design process, emphasising the empowerment of individuals to contribute solutions that meet their needs. The approach potentially promotes innovation and ensures the sustainability and cultural relevance of the outcomes.

How phygitalisation is achieved and how it potentially presents new spatial contexts for human interaction by using a combinatory and immersive approach through the synergistic application of spatial design and virtual reality technologies are still to be realized professionally.

Phygitalisation has the potential to promote the seamless integration of the real and the virtual and meet stakeholders' needs.

This research approach brings new perspectives and methods to the design field and provides new directions for the integration of cross-disciplinary fields, emphasising the importance of sharing and collaborating from data to wisdom.

## 7 Research Findings

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This research achieves focus findings in integrating efficient bamboo utilisation with participatory design.

By developing a 'phygitalisation' digital workflow that combines 3D scanning, topology optimisation and XR technology, it facilitates rapid modelling of irregular bamboo and performance-driven structural adaptation, enhancing traditional material utilisation.

3D scanning and parametric modelling can effectively reduce the challenges posed by the non-standard characteristics of bamboo in design and construction, thereby enhancing its application efficiency in construction. XR technology in participatory design delivers immersive experiences and instant feedback while preserving the reality of the physical space, which helps optimise the design process.

Therefore, the multilevel collaborative participatory design framework effectively integrates manufacturer, user and community needs. This not only optimises the real-time responsiveness and adaptability of bamboo in building fabrication but also drives the evolution of design decision-making from 'data sharing' to 'wisdom sharing'. It provides a scalable tech-social collaborative pathway for highly sustainable, low-waste applications of local materials.

## 7 Further Research

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### **Further optimisation of digital workflows**

Continuous improvement of digital workflows, especially in terms of 3D scanning accuracy and discrete design algorithms for bamboo, to further increase design efficiency and build quality

### **Explore the combination of bamboo and other materials**

In-depth research into the ways in which bamboo can be combined with other sustainable materials (e.g. metals and synthetic fibres) to expand its application in architecture and landscape design

Deepening of interdisciplinary research

Enhance interdisciplinary research in architecture, computer science, sociology and psychology to address complex design challenges

Promotion and commercialisation of applications

Developing more advanced XR applications, promoting the commercialisation of research results and promoting sustainable construction by working with companies to integrate digital technologies with the bamboo construction process

### **Sustainable Development Goals (SDG17 Goals)**

To investigate how to more closely integrate phygitalisation interactive technology with the concept of sustainable development and to explore new methods of applying digital technologies in spatial and urban designs to achieve SDG17 goals for addressing global environmental and social challenges

## 8 Research Dissemination: The GRF Project

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Year	Project
2024– 2026	Principal Investigator - Developing an Extended Reality (XR) Gamified Participatory Urban Furniture Design System Using Discrete Bamboo Fabrication (2024–2026). Funded by the General Research Fund (GRF). HKD\$1,200,000.

## 8 Research Dissemination: Five Exhibitions

Year	Exhibition
2021	The Green Woven Corridor. Harbin Institute of Technology (Shenzhen).
2024	Phyigital Meta-Archive: An Immersive Alternate Hong Kong-Verse. The Hong Kong Polytechnic University.
2024	tPAC: Phyigital-Aided Construction System Based on Modular Customizable Timber Fabrication for Urban Housing. AI for Creative Innovation Design Joint Lab. The Hong Kong Polytechnic University.
2024	Exploring Dimensions: An Immersive Journey into Hong Kong's Realities, Life Lessons and History. MTALKS. Murry House, Stanley. <a href="#">Murray House   Evory Media Limited</a>
2024	Parklane X Laureus X PolyU Mind in Motion XR Sports Experience.

## 8 Research Dissemination: Five Media Reports

Year	Media Report
2024	PolyU bring reality check to its designs. <i>The Standard</i> .
2024	Combining virtual reality street scene to construct 'Meta-archive an immersive alternate Hong Kong-verse' - PolyU Students lead experiences in reinventing the cityscape. am730. <i>A8 Local News</i> . 2024.7.3 WED
2024	Sports photography exhibition with local athletes invited to unveil the exhibition. i-CABLE. <a href="https://www.i-cable.com/新聞資訊/274460/運動攝影展覽-多位本地運動員獲邀參與揭幕?utm_source">https://www.i-cable.com/新聞資訊/274460/運動攝影展覽-多位本地運動員獲邀參與揭幕?utm_source</a>
2024	U秀插班生：設計中的遊戲化體驗 . U秀幫. RTMK AM 621. <a href="https://www.rthk.hk/radio/pth/programme/uxiubang/episode/986205">https://www.rthk.hk/radio/pth/programme/uxiubang/episode/986205</a>
2025	U秀插班生：虛擬與現實的雙向交互. U秀幫. RTMK AM 621. <a href="https://www.rthk.hk/radio/pth/programme/uxiubang/episode/1003174">https://www.rthk.hk/radio/pth/programme/uxiubang/episode/1003174</a>

## 8 Research Dissemination: Publications

Year	Publication
2025	iBamboo: Proposing a New Digital Workflow to Enhance the Design Possibilities of Irregular Bamboo Materials—From Scanning to Discrete to Topological. <i>Electronics</i> 2025, 14(6), 1116. <a href="https://doi.org/10.3390/electronics14061116">https://doi.org/10.3390/electronics14061116</a>
2025	Parametric and Modular Design for Bamboo Chairs in Extended Reality: An Accessible Workflow, eCAADe 2025. (Accepted)
2025	PACS: Phygital-Aided Construction System Based on Modular Customizable Timber Fabrication. Peer-reviewed paper, CAAD Futures. <a href="https://research.polyu.edu.hk/en/publications/pacs-phygital-aided-construction-system-based-on-modular-customiz">https://research.polyu.edu.hk/en/publications/pacs-phygital-aided-construction-system-based-on-modular-customiz</a>
2025	Exploring Gamification: Playing and Learning through War-time Architecture, eCAADe 2025. <a href="https://research.polyu.edu.hk/en/publications/exploring-gamification-playing-and-learning-through-war-time-arch">https://research.polyu.edu.hk/en/publications/exploring-gamification-playing-and-learning-through-war-time-arch</a>
2024	Enhancing Immersion in Virtual Spaces: PhytualBlend—A Real-time Interaction System for Seamless Physical Feedback. <a href="https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_116">https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_116</a>

## 8 Research Dissemination: Publications

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Year	Publication
2024	Exploring Phygitalization in Architecture: Comparative Analysis of the Reality of Digital and Physical Experiences in Relationships of Humans and Space. <a href="https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_14">https://papers.cumincad.org/cgi-bin/works/paper/ecaade2024_14</a>
2023	Exploring the Application of the Digital Gamification Mechanisms to the Experience of Physical Architectural Exhibitions. <a href="https://papers.cumincad.org/cgi-bin/works/paper/caadria2023_80">https://papers.cumincad.org/cgi-bin/works/paper/caadria2023_80</a>