# Designing with Robots

## Navigating the Unknown to unlock Creativity and Innovation

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*Integrating robotic technologies into architectural education offers significant potential beyond technical skill development. Applied as a pedagogical medium, robotics in architecture can foster creativity, critical thinking, and innovation through experiential, open-ended learning experiences. While most applied teaching formats in architectural robotics prioritise pre-defined, task-specific assignments, they often neglect the value of exploratory design approaches that encourage innovative discoveries. This study presents an abductive design methodology that supports an exploratory design approach through navigating complex, ambiguous, and evolving problems. By embracing uncertainty, emergent processes, and material-driven responses, this approach enables the formulation of plausible hypotheses and innovative ideas, providing space for creative inquiry. Robotic systems become active agents within iterative design processes. Drawing on selected case studies, the paper demonstrates how robotics can be meaningfully integrated into exploratory architectural education and reimagined as a transformative component within open-ended design environments.*

**Keywords:** *Architectural Robotics, Abductive Reasoning, Exploratory Design Process, Architectural Education, Design Innovation.*

## INTRODUCTION

Recent innovative building projects highlight the significance of robotic technologies within the construction industry and illustrate how robotic processes evolve from educational settings to industrial applications. As robotics becomes integral to architectural practice, integrating these technologies into architectural education is increasingly relevant and gaining attention from pedagogical perspectives.

Architectural Robotics offers a broader perspective beyond its traditional association with Digital Fabrication and Automated Construction. As defined by Mostafavi (2021), it refers to the emerging field concerned with the creative application and innovative development of robotic systems in architecture. Within this framework, robots are not solely regarded as instruments for precise and efficient automated fabrication, but increasingly as assistive and creative catalysts in exploratory design and construction processes. In response, pedagogical questions arise regarding appropriate methodological practice. Against the backdrop of changing environmental conditions and accelerating technology, marked by uncertainty, growing complexity, and dynamic transformation, skills such as creative problem-solving, critical thinking, and innovative action are becoming central cognitive competencies in the 21st century.

There is an interrelated relationship between creativity and innovation, emphasizing that creativity flourishes more in low-pressure, open-ended environments (West, 2002). Thus, integrating robotic technology into architectural education must go beyond technical knowledge transfer to foster creativity as an essential driver of innovation. However, many current educational formats for Architectural Robotics focus on restricted pre-defined, task-specific applications (Jenny et al., 2022; Shi et al., 2020; Yi, 2021), leaving limited opportunities for open-ended experimentation and creative technology exploration. Furthermore, its potential as a pedagogical medium to cultivate such creative and future-oriented competencies, especially at undergraduate level remains underexplored.

The study presents an abductive design model as a methodological approach to foster students creative and open-ended engagement with robotic systems. The aim is to investigate the extent to which exploratory, creativity-enhancing teaching formats in Architectural Robotics foster innovation and design thinking among students and how these approaches position themselves in relation to established, technological-driven models of instruction. Rather than emphasizing technical mastery, the pedagogical abductive design approach centers on navigating the unknown, embracing uncertainty, emergence, and material responsiveness through iterative observations and testing of hypothetical ideas.

## Research method

The study follows a qualitative-exploratory research design to examine the potential of abductive learning methods within architectural robotics. Based on three case studies from different academic institutions, the analysis focused on didactic structure, integration of robotic technologies, task openness, and student engagement. Data sources included course documentation, student prototypes, video recordings, feedback sessions, and observational notes.

To contextualize the findings, a comparative literature review was conducted, focusing on recent international publications related to Digital Fabrication, Abductive Reasoning in design education, and the integration of design thinking in technological learning environments.

The research goal is to identify recurring patterns and educational potentials that can inform exploratory design-driven, future-oriented teaching formats. A central element is the introduction of an abductive design model as both conceptual and pedagogical framework. This model emphasizes knowledge generation through interaction with materials, technologies, and uncertainty, supporting the positioning of Architectural Robotics as a catalyst for creative and speculative thinking.

## ROBOTS IN ARCHITECTURAL DESIGN

Over the past two decades, the use of robotics in architecture has progressed from exploring and automating fabrication processes to a more collaborative integration across all stages of the architectural design and production workflow. Despite robotics' rising institutional presence in architectural education, divergent interpretations persist regarding its scope, terminological boundaries, and pedagogical objectives. However, it is recognizable that robots integrated into the design process are becoming catalysts for new ways of designing, thinking, and learning, driving innovative ideas and further developments. The distinction between industrial and collaborative robots within an architectural design process is increasingly blurred, as is the separation between stationary and mobile robotics, especially when robots operate as collaborative assistants and creative operating agents. Furthermore, the integration of robotics with emerging technologies extends the range of potential design applications and collaboration, thereby enhancing the field's suitability for diverse explorations within educational contexts. At the same time, the complexity of handling and creatively operating such individually developed robotics systems challenges students to gain respective technical competencies. Therefore, these educational formats and technical specifications are often positioned on high-level architectural studies, like postgraduate masters. Within such formats, a strong technological-centered and research-driven methodology is usually applied, aiming towards technical advancements. In many of such educational settings, robotic applications are constrained by predefined workflows and task-specific procedures. These constraints can significantly narrow the design space available to students and avoid innovative discoveries. As a result, the potential for experimentation and innovation may be limited, particularly when the robot is treated solely as a tool for executing pre-scripted operations, aiming to reach predefined outcomes. By scaling down technical complexity and encouraging intuitive explorations of robotics within a design process, this educational approach seems more appropriate at the undergraduate level (Luque, 2021; Tvede Hansen, 2023; Yazar et al., 2023). However, robotic technologies offer significant educational value when positioned as active co-creative agents within the design process. Their integration allows the exploration of novel design strategies, real-time feedback loops and the digitally controlled manipulation of material behaviours that are difficult to access manually. Beyond imparting technical foundations, actively engaging in robotics offers students opportunities to develop critical and cognitive competencies, as similarly investigated in the related discipline of Educational Robots (Gubenko et al., 2021). In this way, robots in architectural design become a pedagogical medium for exploring complexity, fostering interdisciplinary collaboration, and rethinking the relationship between design, process, material, and tool. This offers a fertile ground for innovation, not only in what and how we build but also in what and how we learn to design.

## Complementary pedagogical concepts

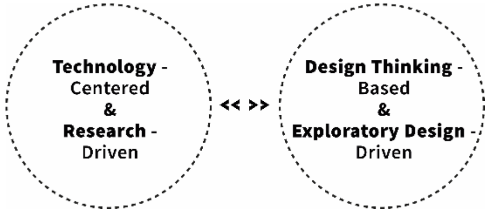



Figure 1
Complementary pedagogical concepts

From the pedagogical perspective, integrating robotics into architectural education represents two significant complementary concepts: a technological-centred and research-driven approach and a design-thinking and exploratory-based approach, each reflecting their educational priorities and epistemological foundations (see Figure 1). While in the first approach, institutional research directions push educational settings and outcomes, the second approach follows a student-centred design method, where individual research directions can emerge.

Both pedagogical approaches share a practice-based methodology, where experiential and "hands-on learning" grounded in constructivist learning theory are essential for the educational setting.

The technological-centered approach focuses highly on technical knowledge transfer, process optimization and performance-based outcomes. Rooted in engineering logic and digital fabrication practices, this approach prioritizes precision, efficiency, and controlled automation. It often involves pre-defined tasks and structured objectives, fostering deep engagement with pre-tested robotic procedures for construction, its programming, and material behaviour through procedural and project-based learning (Stuart-Smith, 2023). It often aligns with design-build studio methodology in reaching a 1:1 physical prototype in the end, serving as proof of concept of the technical advancements.

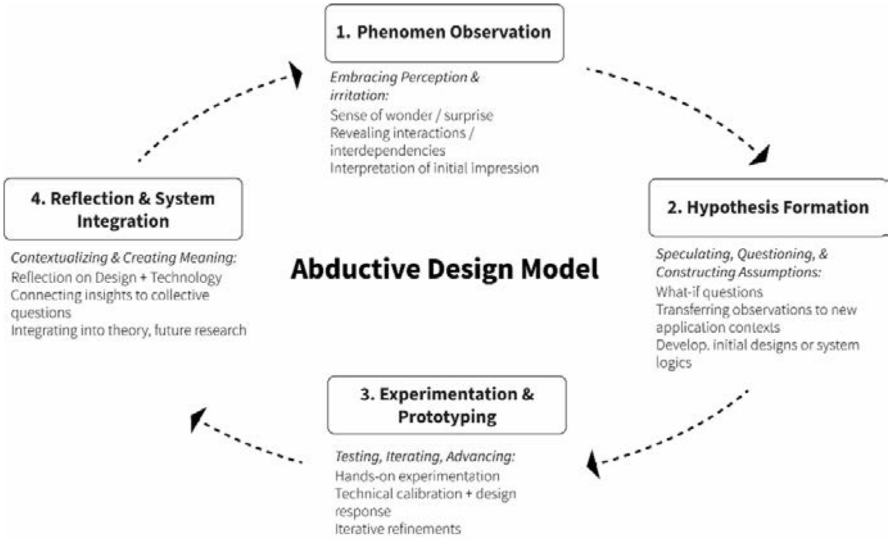
In comparison, exploratory design-driven projects vary in robot applications from interactive installations and assistant procedures to model-scale prototypes. Here, the creative design process driven by hypothetical ideas describes the educational output rather than the physical result. The approach is characterized by its exploratory and open-ended nature. Technological experimentation, creative inquiry, and the development of critical design intelligence describe the educational intention. Drawing from design thinking principles, it encourages abductive reasoning, iterative prototyping, and contextual reflection in the face of complex design challenges.

## ABDUCTIVE REASONING METHODOLOGY

When referring to an abductive reasoning methodology, we understand it as a theoretical framework for the design process grounded in abductive Reasoning. Abductive Reasoning represents a core concept in design cognition, serving as a strategy for navigating uncertainty through an iterative interplay between problem framing and solution generation. In essence, abduction can be understood as a form of informed hypothesis-making grounded in observation and creative inference (Engholm, 2023).

Introduced by philosopher Charles Sanders Peirce, abduction refers to inference in which a plausible explanation is derived from observation and prior knowledge. In contrast to deduction (from the general to the specific) and induction (from the specific to the general), abduction is the "logic of what might be" (Schön, Donald and Martin, 1994). It marks the beginning of creative inquiry, often pointed to as the key moment in the design process, constituting the moment in which ideas or hypotheses are generated. Accompanied by a prototyping activity in which the proposed hypothesis is tested, a simultaneous reflection occurs (Schön, 1983) in direct dialogue with materiality, emergent behaviour, and observed patterns, whether through a specific material reaction to environmental conditions or the intuitive sense of a skilled design facilitator recognizing alignment with a promising strategic direction. In an exploratory design process, we traverse a landscape of possibilities, temporarily grounding ourselves in specific contexts without fixed objectives - creating space for unexpected insights to emerge (Galdon, Haal and Ferrarello et al., 2021). The precondition for such serendipitous discoveries is the ability to remain present within open-ended situations while productively engaging with the input, data, and stimuli encountered (Engholm, 2023). Abductive Reasoning mediates between rapid technological advances and existing design and engineering education practices, enabling the generation of novel design ideas (Galdon, Haal and Ferrarello et al., 2021).

Figure 2
Abductive Design Model




## Abductive design model

Inspired by Koskela, Paavola and Kroll´s (2018) framework to conceptualize abduction in design, we propose an abductive design model (see Figure 2) grounded in iterative cycles of inquiry and discovery. This model consists of four interrelated phases. *1. Phenomenon Observation – Embracing Perception and Irritation:* The process begins with engagement in an open design situation, where students encounter unexpected conditions, material responses or behavioural phenomena through open-ended exploration of technologies, often without a clear problem definition. This phase fosters attention to anomalies and cultivates curiosity, laying the foundation for abductive reasoning. *2. Hypothesis Formation- Speculating, Questioning:* In response to initial observations, students formulate plausible hypotheses to explain or explore what they have encountered. These hypotheses are not yet solutions but speculative interpretations that guide further investigation. This phase supports the development of creative reasoning and encourages risk-taking.
3. Experimentation & Prototyping – Testing, Iterating, Advancing: The hypotheses are tested through physical experiments, prototypes, or digital simulations. Emphasis is placed on working deliberately with ambiguities, failures, and emergent effects. Design results arise not from deterministic planning but through the interaction of system parameters, material behaviour, and control logics. Knowledge emerges through process, not linearly. 4. Reflection & System Integration - Contextualizing and Creating Meaning: Experiences gained through experimentation are systematically reflected upon. Which hypotheses were confirmed or disproved? What new questions arose? The findings are embedded within a broader design, technological, or societal context. Students articulate design principles and strategic guidelines.

The abductive design model facilitates an open, non-linear and inquiry-based learning situation, where the process itself becomes the primary venue for knowledge production.

## CASE STUDIES

### Mobile Robotics – Co-Creative Autonomous Agent

(Leibniz University Hannover, SoSe 2021, in cooperation with Victor Sardenberg)

In a two-week workshop, master's students explored the potential of a semi-autonomous mobile robotic platform (MIR) within an architectural context. The initial Phenomenon Observation phase involved open-ended engagement with the robot through light-based motion studies (see Figure 3), aimed at understanding its behavioral patterns, control mechanisms, and autonomous decision-making. These explorations revealed unexpected spatial and behavioral phenomena that sparked curiosity and critical inquiry. In the Hypothesis Formation phase, students developed speculative assumptions about the robot's role, not as a mere tool, but as a co-creative design agent. These hypotheses opened new perspectives on its performative and spatially interactive capacities (see Figure 4). During Experimentation and Prototyping, students iteratively tested their assumptions by expanding the MIR with a custom-designed end-effector (a winding module), transforming it into a concept-based robotic system for spatial installation (see Figure 5). The process emphasized experimentation with uncertainty, emergent learning, and non-deterministic system responses, leading to design outcomes shaped by control logic, spatial constraints, and co-creative robotic autonomy (see Figure 6). The final phase, Reflection and System Integration, focused on evaluating which hypotheses held and contextualizing the results within broader architectural and technological frameworks. The workshop concluded with the articulation of design-relevant strategies and principles, demonstrating the robot's potential as a catalyst for creative exploration in architectural design.

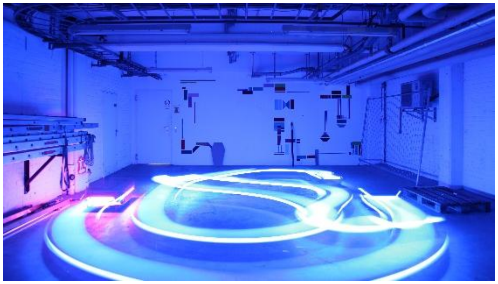


Figure 3
Light-based motion studies with semi-autonomous mobile robotic agent

Figure 4
Testing hypothetical ideas

Figure 5
Semi-autonomous robotic system for spatial installation

Figure 6
Weaving structure, installed in human-machine collaboration

## Spatial Composition

(Technical University Braunschweig, WiSe 2016)

The six-week teaching format (Bachelor/Master) investigates how “unthinkable” architectural space can emerge from experimental, material-driven, and non-deterministic processes. The course follows a process-oriented design methodology in which students act not as authors of final forms, but as observers, initiators, and moderators of creative transformation. In the Phenomenon Observation phase, Students observed diverse material groups, focusing on inherent properties and unexpected behaviours that emerged under varying environmental conditions (see Figure 7). They examined physical, chemical, and biological reactions, such as deformation, reactive behaviour, and crystallization, under variable environmental conditions. Unexpected phenomena acted as irritations, sparking curiosity and further inquiry (see Figure 8). In the Hypothesis Formation phase, students developed speculative assumptions about the form-generating potential of these processes. They served as conceptual frameworks to explore spatial dynamics (see Figure 9). The Experimentation and Prototyping phase involved iterative setups, including formulations, reactive substrates, and adaptive systems. Emphasis was placed on the interplay between material behaviour, structural constraints, and environmental variables (e.g., temperature, humidity, airflow). Form emerged through systemic interaction, not predefinition (see Figure 10). In the Reflection and System Integration phase, students investigated digital control strategies to modulate material transformation. Material was reconceptualized as a dynamic system. Results culminated in spatial design proposals, ranging from speculative scenarios to prototypical material systems, highlighting transitions, atmospheres, and emergent logics.

The aim was to engage with the intrinsic logic and generative potential of the material.

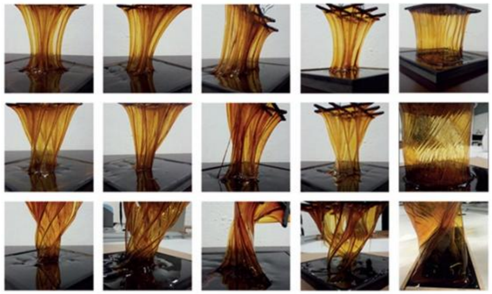


Figure 7
Sugar-form study with various grid-plates, movement speed and

Figure 8
Material consistency after cooling

Figure 9
Iterative spatial system development

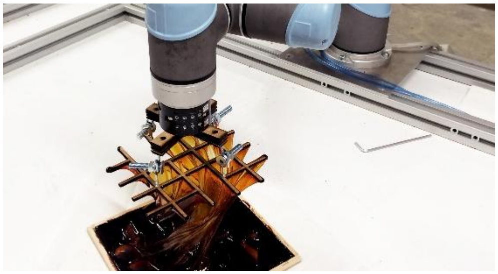


Figure 10
Robotic sugar-forming process with supporting grid-plate

## Creative Coding – Physical Reality

(Technical University Braunschweig, SoSe 2016)

The course (Bachelor/Master) explores how digital control, dynamic force, and algorithmic logic interact with material conditions to drive open-ended, process-based form generation in exploratory architectural design. In the Phenomenon Observation phase, students explored how robotic motion, combined with material responsiveness, could produce non-determined spatial formations. By systematically varying parameters (speed, impulse duration, frequency, directional change) they examined the effects on thermoplastics, casting compounds, and viscoelastic substances (see Figure 11). The Hypothesis Formation phase was shaped by the speculative assumption that a liquid material A (plaster) could be injected into a stabilizing material B (gel) through digitally controlled motion (see Figure 12). This setup aimed to generate semi-controllable forms and investigate the reactive interplay between fluid dynamics and structural suspension (see Figure 13). The observed phenomena, ranging from turbulence and diffusion to entrapped layering, highlighted the material agency of the injected substance within the viscous medium. During Experimentation and Prototyping, students developed algorithmically defined workflows that synchronized robotic motion with material conditioning parameters. These processes were iteratively tested and refined through prototypes, revealing how form emerges from the systemic interaction between material behaviour, environmental factors, and programmed movement (see Figure 14). In the Reflection and System Integration phase, results were contextualized within architectural discourse. Material was reconceptualized as an active system, and form generation as a temporally emergent process. The results gave rise to visionary structural concepts, proposing new directions for novel construction methods.

Figure 11
Material study with viscoelastic substances

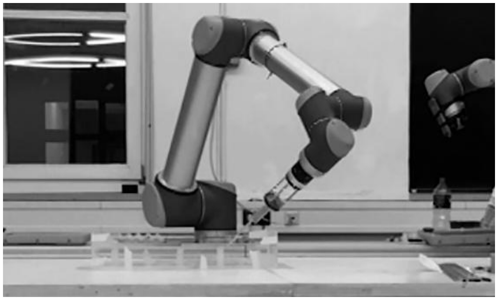


Figure 12
Robotic injection process within suspension

Figure 13
Injection-based model

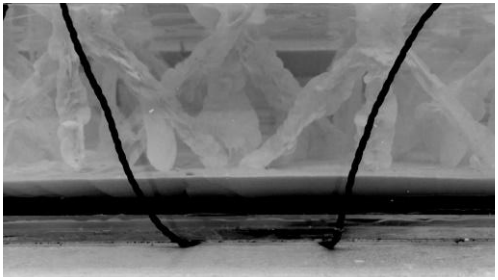


Figure 14
Injected structural system in suspension

## DISCUSSION

Despite the varying conceptual orientations of case studies in Architectural Robotics, recurring patterns have emerged regarding student behaviour, engagement, and learning outcomes. These patterns offer generalizable insights into design-driven, technology-integrated education.

A common observation is students' initial scepticism toward the abstract, open-ended nature of the design brief and its robotic components. This hesitation typically diminishes during the early, observation-focused phase, which allows students to engage without pressure for immediate outcomes. This aligns with West's (2002) assertion that creativity thrives in low-pressure environments. The approach appears to facilitate access to complex, technology-mediated design scenarios and fosters exploratory engagement. Intrinsic motivation is often sparked when students encounter unexpected or architecturally compelling emergent behaviours, what Engholm (2023) terms "abductive serendipity." These moments trigger hypothesis formation and deeper investigation into robotic behaviour, control, and material interaction, actively cultivating abductive reasoning through situated discovery. Although robotics is inherently complex, the teaching formats reduce entry barriers by minimizing reliance on technical prior knowledge. The use of intuitive interfaces and open-ended experimentation supports accessibility and fascination with semi-controlled, hypothesis-driven processes. The iterative development of hypotheses enhances students' capacity for abstraction and innovation, suggesting that Architectural Robotics supports both technical knowledge and cognitive agility. This aligns with Koskela, Paavola and Kroll's (2018) call for the integration of abductive reasoning in interdisciplinary design education. A key strength of this study lies in its theoretical reflection on recurring pedagogical patterns. A limitation remains in the difficulty of assessing students' creative development.

## CONCLUSION

The pedagogical inspiration for the study roots first in the related discipline of Educational Robotics and its underlying pedagogical concept and second from the conclusions of radical pedagogies (Colomina et al., 2022), where various analogies are seen towards Architectural Robotics, particularly in its embrace of diverse strategies, cross-disciplinary thinking, and openness to experimentation. As radical pedagogies once questioned architectural norms through social and political lenses, Architectural Robotics now provokes similar inquiry through technological means, inviting students to reimagine spatial agency, materiality, and human-machine collaboration in the built environment. The study highlights the innovative potential of a design-thinking and exploratory, design-based approach, particularly at the undergraduate level, as a foundation for developing multiple theoretical frameworks in the emerging field of Architectural Robotics. The identification of recurring patterns in student engagement and learning suggests that integrating abductive reasoning, situated discovery, and intuitive interaction with complex systems fosters both technical understanding and creative speculation. As part of broader doctoral research, further empirical work is underway. A targeted student survey will address current limitations in evaluating students' creative and critical thinking outcomes, while expert interviews are already providing valuable insights into the broader discussion on the educational value of Architectural Robotics. These steps aim to complement the theoretical framework with empirical depth and reinforce the relevance of Architectural Robotics within Architectural Education.

## REFERENCES


Colomina, B., Galán, I.G., Kotsioris, E. and Meister, A. M. (2022) *Radical pedagogies*. 1st ed. Cambridge, MA: MIT Press.

Engholm, I. (2023) *Design for the new world: From human design to planet design*. New ed. Bristol: Intellect Books.

Galdon, F., Hall, A. and Ferrarello, L. (2021) 'Enhancing abductive reasoning in design and engineering education via probabilistic knowledge: A case study in AI', in *DS 110: Proceedings of the 23rd International Conference on Engineering and Product Design Education (E&PDE 2021)*, Herning, Denmark: VIA Design, VIA University, 9–10 September 2021, pp. 1–6.

Gubenko, A., Kirsch, C., Smilek, J.N., Lubart, T. and Houssemand, C. (2021) 'Educational robotics and robot creativity: An interdisciplinary dialogue', *Frontiers in Robotics and AI*, 8, Article 662030. Available at: https://doi.org/10.3389/frobt.2021.662030

Jenny, D., Mayer, H., Aejmelaeus-Lindström, P., Gramazio, F. and Kohler, M. (2022) 'A pedagogy of digital materiality: Integrated design and robotic fabrication projects of the Master of Advanced Studies in Architecture and Digital Fabrication', *Architecture, Structures and Construction*, 2(4), pp. 649–660. Available at: https://doi.org/10.1007/s44150-022-00040-1.

Koskela, L., Paavola, S. and Kroll, E. (2018) 'The role of abduction in production of new ideas in design', in Vermaas, P.E. and Vial, S. (eds.) *Advancements in the philosophy of design*. Cham: Springer, pp. 153–183.

Luque, R.M. (2021) 'Craft-based methods for robotic fabrication: A shift in architectural education', *JIDA21 – Journal of Innovation in Digital Architecture*. Available at: https://www.academia.edu/68303931

Mostafavi, S. (2021) 'Hybrid intelligence in architectural robotic materialization (HI-ARM): Computational, fabrication and material intelligence for multi-mode robotic production of multi-scale and multi-material systems', *A+BE | Architecture and the Built Environment*, 12, Article 12.

Shi, X., Fang, X., Chen, Z., Phillips, T.K. and Fukuda, H. (2020) 'A didactic pedagogical approach toward sustainable architectural education through robotic tectonics', *Sustainability*, 12(5), 1757.

Stuart-Smith, R. (2023) 'Towards technically progressive and speculative design education: Penn MSD-RAS's collaborative and interdisciplinary pedagogy'. Unpublished manuscript or institutional publication.

Tvede Hansen, F. (2023) 'Human–material dialogues through the use of robotics: Embodied craft learning in an architectural educational context exploring patterns in clay', *FormAkademisk*, 16(4). Available at: https://doi.org/10.7577/formakademisk.5442.

West, M.A. (2002) 'Sparkling fountains or stagnant ponds: An integrative model of creativity and innovation implementation in work groups', *Applied Psychology*, 51(3), pp. 355–387.

Yi, H. (2021) 'Robotics application for the advanced integration of design and technology in architecture', *Computer Applications in Engineering Education*, 29(5), pp. 1282–1294. Available at: https://doi.org/10.1002/cae.22370