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Flexible Architecture: Designing Adaptive and Modular Spaces for Makerspaces in Urban Context

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Abstract

Flexible and collaborative workspaces have become increasingly common with the rise of the maker movement. Makerspaces are hubs for creativity, education, and innovation, yet many adopt rigid designs that limit diverse activities, user groups, and equipment learning. This research investigates Flexible Architecture for the creation of adaptable spaces in makerspaces, increasing their utility and resilience. The study seeks to design a framework for modular adaptive spaces that accommodate varied user needs and technological advancements over time. Using a mixed-methods approach, the research integrates site analysis, case studies of existing makerspaces, and validation of architectural solutions, alongside qualitative interviews and quantitative surveys of a broader user base. The study identifies key adaptive elements such as modular construction, multifunctional components, and reconfigurable layouts. The significance of this research lies in offering a new perspective on architectural design in innovative environments, emphasizing flexibility, sustainability, user engagement, scalability, budget considerations and community engagement. Findings contribute to understanding how makerspaces can be designed to remain future proof, that support collaboration, creativity, and technological development in urban contexts.

1.0 INTRODUCTION

In the context of makerspace, “makers” are individuals that engage in creating, building and changing objects, that is enhanced through collaborations. These communities emphasize hands-on learning, creativity, and innovation, forming environments that encourage experimentation and knowledge-sharing (Interaction Design Foundation, 2024). Recent studies show that makerspaces not only foster technical skills but also contribute to socio-intellectual development by integrating design, fabrication, and problem-solving into collective learning processes (Zhan, Chen, & Retnawati, 2022). Workspace paradigms have also evolved from individual-based models to activity-based settings, and more recently to team-based environments. Looking ahead, scholars predict a shift toward strategic-based approaches, where makerspaces and maker environments will play a key role in aligning creativity, innovation, and adaptability with long-term organizational and societal goals (Sargent & Nurse, 2017).

Zaharin et al. (2024) highlighted that one of the emerging concepts in workplaces is the provision of flexible arrangements designed for multiple occasions. Such spaces incorporate adaptable furniture, movable partitions, and multipurpose areas to support dynamic, inclusive environments conducive to participative practices. This requirement is particularly significant for makerspaces and innovation hubs that cultivate creativity, collaboration, and entrepreneurship among diverse user groups. Modular architecture supports this by providing flexible and scalable solutions that can be rapidly deployed and adapted to accommodate different types of makers and activities (Yavuz, Erdogdu, & Ozdemir, 2021; Vescovi et al., 2023). Building on this, adaptive design principles further enhance flexibility by allowing spaces to evolve over time in response to shifting technological and social requirements, ensuring long-term relevance and sustainability (Verma, 2023; Nguyen & Moere, 2024).

In Malaysia, innovation ecosystems are recognized as critical drivers of economic growth and technological advancement (MDEC, 2021). However, these efforts often face limitations due to rigid and inflexible physical infrastructure. Modular architecture addresses this gap by enabling quick deployment, reconfiguration, and expansion of makerspaces to support diverse needs (Yavuz, Erdogdu, & Ozdemir, 2021). This research explores how adaptive modular architecture can shape a holistic Malaysian maker hub that integrates digital, community, professional, and educational makers. By adopting modular and adaptive approaches, the study seeks to inform innovative spaces that are flexible, sustainable, and future-oriented (Nguyen & Moere, 2024).

The maker movement has rapidly expanded over the past decade, driven by open-access technologies, peer-to-peer collaboration, and experiential learning models (Interaction Design Foundation, 2024; Zhan, Chen, & Retnawati, 2022). In Malaysia, initiatives such as #mydigitalmaker provide vital platforms for fostering creativity, innovation, and resource-sharing across multiple user groups (MDEC, 2021). Adaptive strategies enhance these environments by tailoring spatial configurations to evolving user requirements, while modular systems allow for on-demand, scalable, and versatile layouts (Vescovi et al., 2023; Verma, 2023). Together, flexibility, affordability, and sustainability underpin the ability of makerspaces to respond to social and technological change—ranging from movable partitions to prefabricated components. These principles help democratize access to technology, promote learning-by-doing, and support the growth of novice entrepreneurship (Mauroner et al., 2023).

Potential for scalability and customization can be observed in references such as the Nagakin Capsule Tower and My Micro (Arch2O, 2023). By minimizing the waste of materials and adjusting flexibility for the needs of the dynamic process, prefabrication fits this demand perfectly (Harrison Clarke, 2023). Although adaptive design and modular architecture have great potential, they are still largely unutilized within developing contexts, such as Malaysia. This study explores the integration of the above to engage sustainable, flexible maker hubs that cater for digital, community, professional and educational makers, towards the digital economy of Malaysia (MDEC, 2021). This allows for flexibility to meet changing needs without sacrificing creativity and collaborative opportunities in physical, phycological members and virtual real**ity.**

Makerspaces encompass diverse environments ranging from woodworking to electronics and digital fabrication, which necessitates flexibility and resilience in their design (Interaction Design Foundation, 2024). Conventional static construction methods restrict makerspaces from adapting to changing user needs and technological developments, often resulting in underutilization and user dissatisfaction (Verma, 2023). Adaptive designing movable walls, flexible furniture, and modular components that can be reconfigured creates multi-purpose spaces that support both collaborative work and individual projects (Renovated Learning, 2023). Such strategies facilitate imaginative thinking, exploration, and innovation while minimizing spatial inefficiency. Scalability also allows makerspaces to expand or transform in cost-effective ways rather than relying on expensive renovations (Yavuz, Erdogdu, & Ozdemir, 2021). Furthermore, aligning spaces with user expectations and workflows through user-centric design increases the functional efficiency of spaces, fostering creativity and innovation while enhancing user engagement and satisfaction (Oktra, 2024).

Although makerspaces are increasingly recognized as hubs for creativity, education, and technological innovation, much of the literature continues to emphasize their educational, social, and technological roles such as fostering STEM learning, entrepreneurship, and digital fabrication while giving limited attention to their architectural dimension (Bobic, 2023; Zhan, Chen, & Retnawati, 2022). Few studies explicitly examine how spatial design, modular construction, and adaptive layouts shape user experience, long-term sustainability, and flexibility in makerspace environments (Yavuz, Erdogdu, & Ozdemir, 2021). While adaptive design principles such as flexibility, modularity, and reusability are increasingly discussed in architecture, there remains a lack of empirical data specific to makerspaces, particularly regarding architectural performance metrics like energy efficiency, space utilization, and adaptability over time (Nguyen & Moere, 2024; Vescovi et al., 2023). Furthermore, existing research tends to overemphasize technological integration for example, IoT systems, 3D printing, and augmented reality without adequately addressing how physical spatial frameworks enable or constrain these technologies (Thoring, Müller, Desmet, & Badke-Schaub, 2020). In the Malaysian context, this gap is even more pronounced, as research has primarily focused on digital innovation initiatives rather than localized architectural strategies for makerspaces (MDEC, 2021; Zaharin et al., 2024). Finally, although sustainability is a recurring theme in makerspace discourse, insights are often fragmented, with limited integration of circular design principles such as planned disassembly, material reuse, and scalable modular systems into a holistic architectural framework (Elwakil, Schroder, & Steemers, 2023; Vuylsteke et al., 2022).

This study aims to propose a systematic framework that combines adaptive design and modular architecture to improve the functionality, adaptability, and sustainability of makerspaces in Malaysia. The research envisions makerspaces as innovation hubs that promote creativity, collaboration, and technological development while advancing sustainable design practices. It also contributes to the international dialogue on sustainable building by presenting scalable and adaptable solutions that encourage material reuse and lifelong learning.

Research Objectives:

a. To examine how user-centric design impacts user engagement, satisfaction, and innovation.
b. To assess how adaptive design and modular architecture influence sustainability and cost-effectiveness.
c. To identify key components for integrating adaptive design principles with modular architecture in makerspaces.

Modular architecture and adaptive design thus act as catalysts for creating flexible, scalable makerspaces that enhance expandability, efficiency, and sustainability. Moreover, embedding user-centric approaches ensures that these spaces significantly improve user experience and stimulate creativity.

The research on adaptive design space and modular architecture for Malaysian makerspaces seeks to address the challenges of rigid and underutilized infrastructure by proposing sustainable, flexible, and future-ready innovation ecosystems. Malaysia requires such approaches to nurture creativity, innovation, and entrepreneurship across diverse communities, enabling makerspaces to evolve from facilities tailored to the needs of their own time into environments capable of meeting both present and future demands (Yavuz, Erdogdu, & Ozdemir, 2021). The findings of this research aim to guide architects, policymakers, and stakeholders in shaping context-specific frameworks for adaptable and sustainable maker hubs that promote collaboration, inclusivity, and resource sharing (Nguyen & Moere, 2024). By integrating adaptive design into modular systems, this study emphasizes economically and environmentally viable solutions that strengthen scalability and long-term resilience (Vescovi et al., 2023). Beyond the Malaysian context, its broader implications inform global innovation ecosystems, supporting Malaysia’s digital economy while advancing innovation and entrepreneurship (MDEC, 2021).

2.0 LITERATURE REVIEW

Combining these adaptive modular spaces with maker spaces creates spaces for innovation and learning. These adaptable, scalable spaces encourage creativity and activity-based learning, while providing functional sustainability due to their varied popular uses (Verma, 2023; Cleveland Modular, 2023).

2.1 Adaptive Design Principles

Adaptive integration in architecture is guided by several core principles that enable spaces to respond to their surroundings, inhabitants, and functions through both design and technology. These principles challenge the constraints of static, purpose-built environments by creating spaces that can evolve with shifting needs (Yavuz, Erdogdu, & Ozdemir, 2021). One of the most prominent is flexibility, which allows spaces to serve multiple purposes through movable partitions, mobile furniture, and modular layouts tailored to diverse user requirements (Soomro et al., 2023; Zaharin et al., 2024). Equally important is scalability, which ensures that makerspaces can expand or contract as demand changes, offering quick deployment, reconfigurability, and long-term viability (Vescovi et al., 2023). A third principle, responsiveness, leverages smart technologies and sensor systems to monitor environmental conditions such as energy use and occupancy, ensuring comfort, efficiency, and climate-conscious operations (Nguyen & Moere, 2024).

Adaptive design also fosters collaboration and knowledge-sharing by linking diverse user groups, turning these environments into hubs of innovation and discovery (Verma, 2023). However, challenges remain, particularly in the integration of automated control systems that balance efficient reconfiguration with user agency and participatory design (Furszyfer Del Rio et al., 2021). Moreover, adaptive architecture requires a culture of continuous feedback and collaboration between architects, designers, and users, reinforcing the importance of human-centered approaches in shaping resilient and future-ready environments (Mitchell Finnigan & Clear, 2020; Arvaniti, 2020). Taken together, adaptive and modular principles—flexibility, scalability, responsiveness, and collaboration—offer a comprehensive framework for designing makerspaces that are dynamic, sustainable, and aligned with evolving community needs.

2.2 Benefits of Modular Architecture

Modular design approaches have emerged as a key strategy for building flexible and adaptable makerspaces. Modular systems, composed of pre-made standardized components, enable rapid deployment, reconfiguration, and scalability in response to changing requirements (Yavuz, Erdogdu, & Ozdemir, 2021). This flexibility allows makerspaces to expand, adapt, or restructure layouts according to evolving project needs, user groups, or community events.

A central aspect of modular architecture is its reliance on prefabricated components, which can be assembled and dismantled efficiently, enabling spaces to adapt to future demands with minimal disruption (Harrison Clarke, 2023). Scalability further strengthens this adaptability by allowing spaces to expand or contract through the addition or removal of components, making it highly suitable for fluctuating user demands (Vescovi et al., 2023). Beyond adaptability, modular construction also advances sustainability by optimizing material use, minimizing waste, and reducing environmental impact during construction, aligning with broader goals of sustainable practice (Yavuz et al., 2021).

Moreover, modular architecture opens pathways for the integration of advanced technologies such as artificial intelligence, smart systems, and robotics. These technologies enhance adaptability by enabling responsive, data-driven operations and fostering specialized infrastructure that supports reconfiguration and user-centric functions—an essential feature for future-ready makerspaces (Nguyen & Moere, 2024).

2.3 Diverse Needs of Maker Groups

In Malaysia, the maker movement has experienced substantial growth, leading to diverse communities of makers with distinct spatial, technological, and collaborative requirements to foster creativity, innovation, and entrepreneurship (Soomro et al., 2023). At the forefront, digital makers work with emerging technologies such as IoT, AI, and blockchain, requiring high-performance tools and flexible environments to support advanced production processes (JAC Recruitment, 2023). National priorities also emphasize digital development, with agencies highlighting fields such as software development, data science, and cybersecurity as essential drivers of the innovation economy (MDEC, 2021; Zaharin et al., 2024).

Besides that, community and social makers, on the other hand, focus on addressing local needs and social issues, valuing inclusive spaces that encourage collaboration. An example is the KitaBina Maker Space, which provides semi-professional tools accessible to a wide range of users (KitaBina, n.d.). Professional makers often treat makerspaces as incubators for entrepreneurship, requiring access to prototyping facilities, mentorship, and networking opportunities, while educational makers benefit from hands-on STEM learning environments linked to initiatives such as #mydigitalmaker (MDEC, 2021; Zhan, Chen, & Retnawati, 2022).

Each type of makerspace is designed to meet varied demands, from providing equipment such as 3D printers and laser engravers to ensuring open collaborative layouts for communities, private prototyping zones for professionals, and flexible reconfigurable classrooms for education (Makerspace@UM, n.d.). Modular architecture, with its prefabricated and interchangeable elements, allows these spaces to be easily reconfigured to match evolving user requirements, supporting adaptability, efficiency, and inclusivity (Yavuz, Erdogdu, & Ozdemir, 2021; Vescovi et al., 2023). By accommodating these diverse needs, Malaysian makerspaces can remain innovative, responsive to their communities, and continue to drive creativity and entrepreneurship.

2.4 Adaptive Modular Spaces for Sustainable Community

Adopting adaptive design principles complements the viability of sustainable community maker hubs. Adaptive modular spaces demonstrate flexibility and scalability to optimize resource utilization, improve energy efficiency (Erdogdu et al., 2021; Yavuz et al., 2021), and integrate intelligent technologies such as sensors and IoT components to reduce operational costs and enhance environmental performance throughout their lifespan (Arvaniti, 2020). This adaptability supports the creation of robust local innovation ecosystems capable of evolving alongside technological and societal change.

Modular systems rely on prefabricated elements assembled on-site, reducing construction waste and improving efficiency, which makes them well-suited for sustainable development (Harrison Clarke, 2023). At the operational level, adaptive spaces respond to changing occupancy patterns, thereby lowering energy and maintenance costs. Smart technologies such as real-time energy monitoring, intelligent climate control, and renewable energy systems further enhance efficiency and sustainability (Nguyen & Moere, 2024). Additionally, the use of high-performance materials like advanced insulation and multi-glazed windows further contributes to long-term energy savings.

Adaptive modular spaces equipped with smart technologies can gather and analyze data on space usage, user behavior, and environmental conditions, ensuring continuous optimization and more user-centered design outcomes (Arvaniti, 2020). This data-driven approach guides future decision-making, resulting in highly functional, productive spaces. Beyond technical efficiency, modular design also enables sustainable business models. Its scalability attracts a variety of user groups, creating stable income streams to support initiatives such as renewable energy integration and community programs (Vescovi et al., 2023). Furthermore, features such as screw-pile foundations, mobility, and autonomy allow these spaces to adapt to shifting urban landscapes without the need for permanent infrastructure.

In Malaysia, encouraging progress can be seen in initiatives like Makerspace@UM, which incorporates modular components such as movable partitions, adjustable workbenches, and a wide range of fabrication tools to accommodate different user needs (Makerspace@UM, n.d.). Similarly, KitaBina Maker Space demonstrates the potential of adaptive principles in fostering community engagement, social innovation, and sustainability through collaborative projects (KitaBina, n.d.). With the rising maker movement in Malaysia, its frameworks are naturally evolving around adaptive design principles, modularity, and customizable on-site solutions.

3.0 METHODOLOGY

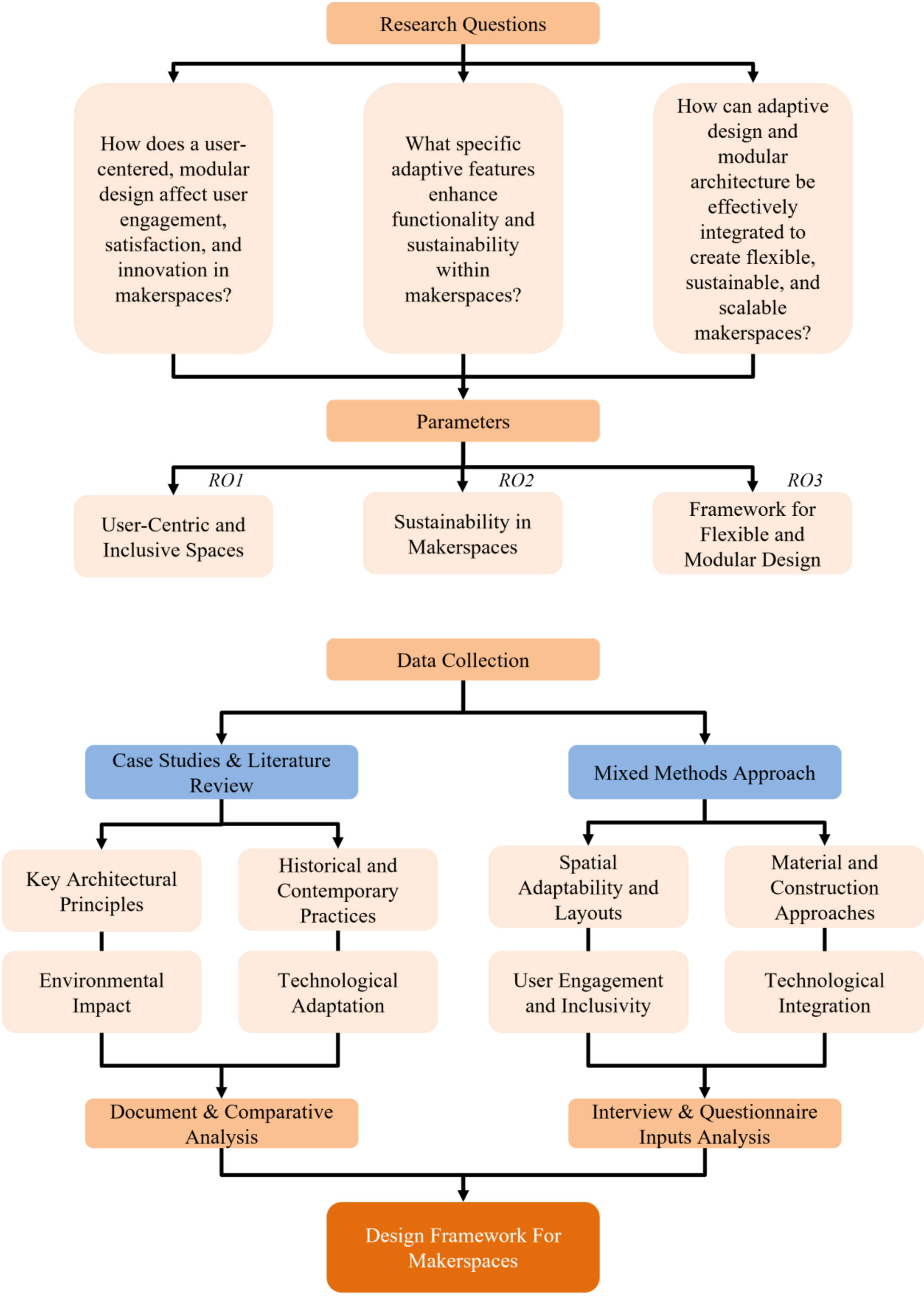
3.1 Research Framework

Table 1. Research Frameworks.

	Research Questions	Research Objectives	Research Methodology	Research Findings (Expected)	
The primary aim of this research is to explore and establish a framework for designing flexible and modular maker spaces that can adapt to diverse activities, user groups, and evolving technologies, thereby enhancing their functionality and responsiveness.	RQ1	RO1	RM1	RF1	A Framework for Designing Flexible and Modular Maker Spaces Adaptable to Diverse Activities, User Groups, and Evolving Technologies to Enhance Functionality and Responsiveness
	How does a user-centered, modular design affect user engagement, satisfaction, and innovation in makerspaces?	To assess the role of user-centered design in enhancing user experience and innovation within makerspace.	Document analysis	The enhancement of engagement and innovation within diverse maker groups as a result of user-focused, adaptive spaces, contributing to more vibrant and productive makerspaces.	
	RQ2	RO2	RM2	RF2	
	What specific adaptive features enhance functionality and sustainability within makerspaces?	To analyze the impact of adaptive, modular design on the sustainability and cost-efficiency of makerspaces.	Case Studies	The reduction of environmental impact and construction costs through the implementation of adaptive modular designs.	
	RQ3	RO3	RM3	RF3	
	How can adaptive design and modular architecture be effectively integrated to create flexible, sustainable, and scalable makerspace?	To identify key components for integrating adaptive design principles with modular architecture in makerspaces.	Mixed Research Approach	The identification of essential adaptive and modular components, including movable partitions and multifunctional modules, that facilitate flexibility within maker spaces.	

3.2 Data Collection Procedure

Table 2. Data Collection Procedure Flow Chart



3.3 Data Collection Method

3.3.1 Case Study by Desk Research

Case studies are widely recognized as effective for exploring contemporary phenomena within real-life contexts, especially when addressing complex "how" or "why" questions. They are particularly valuable when researchers have limited control over external variables, as they allow for a deeper understanding of subjects in their natural environment. Recent scholars emphasize that case studies provide a robust methodological framework for investigating architectural practices and innovation spaces, enabling the integration of contextual, technological, and user-centric perspectives (Thoring, Müller, Desmet, & Badke-Schaub, 2020; Zhan, Chen, & Retnawati, 2022). In adaptive and modular design research, case studies highlight practical applications of theoretical principles and illustrate how flexibility, sustainability, and user engagement are operationalized in practice (Nguyen & Moere, 2024).

Desk research: Gathering information from already existing papers, books, industry reports, and databases without going into the field to collect new data. Researchers use this approach to critically assess and integrate data supporting and verifying theories and findings related to their aims and research queries.

Desk research may explore existing literature and construct theoretical basis of study. By reviewing and analyzing free, high-quality material, researchers can also evaluate knowledge gaps within their area, compile existing supporting evidence and plan study designs. It helps in precise decoding this way without compromising the study as we are derived from known entities and brings them relevant information from the same vertical.

3.3.2 Document Analysis

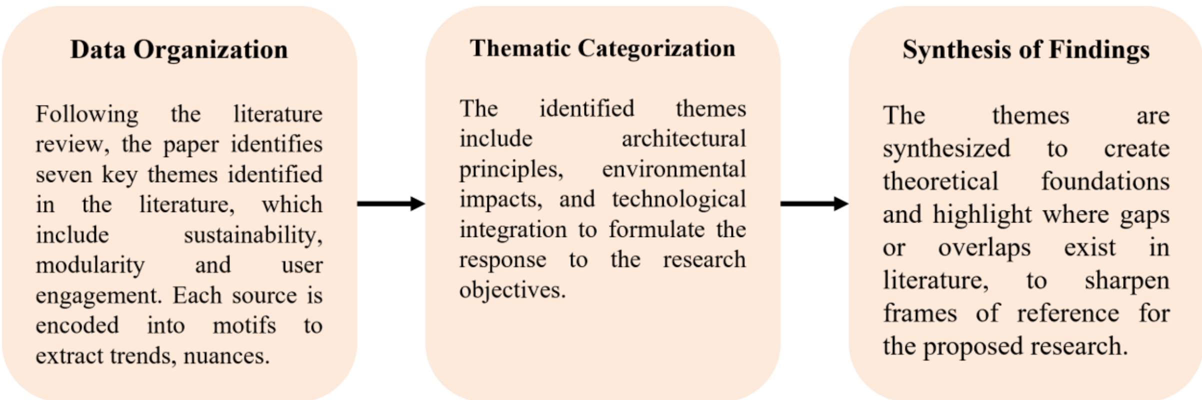
Document analysis serves as the primary data collection method for this research and is pulled from journal articles, books and design frameworks related to flexible architecture, modular architecture and adaptive architecture. These include wide-ranging topics such as architectural fundamentals, ecological viability, user interaction and technological adoption. By receiving different studies on innovation spaces and adaptive architectural practices, the analysis leads to relevant theories and practices that it will relate to the research objectives

The coding process is used to analyze the data sorts of concepts (such as flexibility, modularity, user-centered design) into specific categories to synthesize the key data. This forms a basis of its own to identify patterns, gaps or overlaps in the current literature. The analysis of these documents helps in synthesizing diverse sources, laying a comprehensive theoretical background for the study, that makes sure that the proposed framework complements both modern and past practices of adaptive architecture.

3.3.3 Data Analysis Method

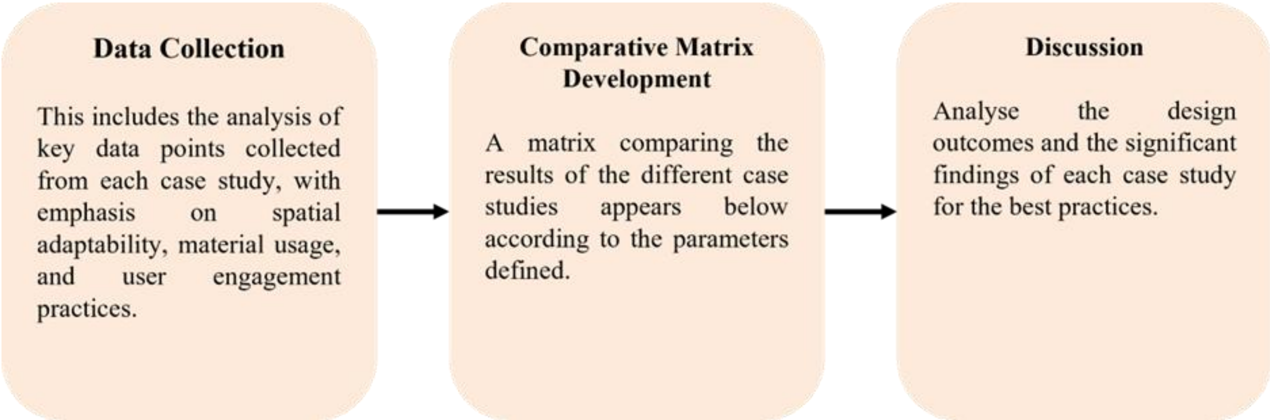
Document Analysis

Table 3. Flow of the document analysis



Comparative Analysis

Table 4. Flow of the comparative analysis

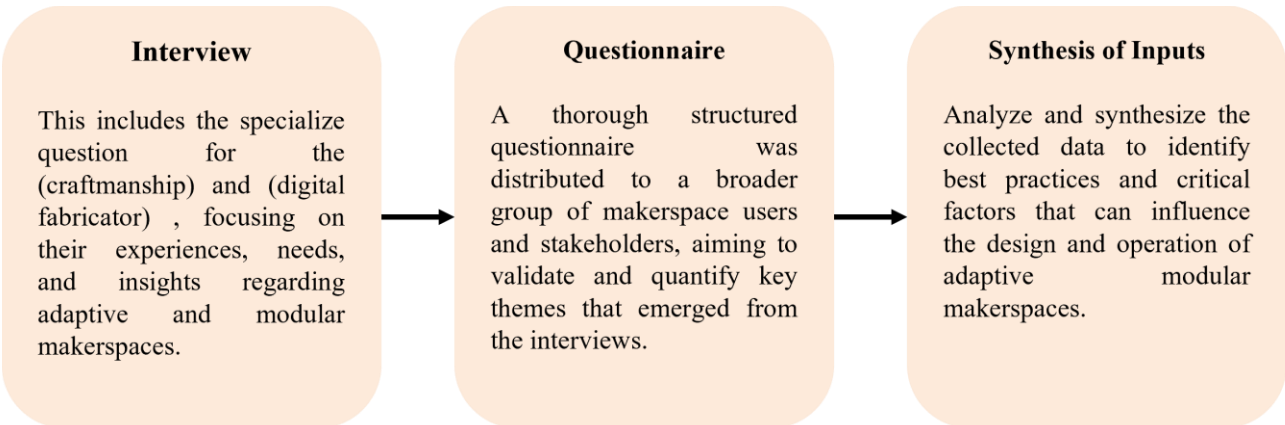


The document analysis organizes the literature, identifies topics such as sustainability and adaptability and summarizes the results. Comparative analysis involves collecting case study data, developing a comparative matrix and discussing the key findings to identify best practices for makerspaces.

3.4 Interview and Survey

The first phase is conducting specialized interviews with two personnels that represent two different maker groups, which are craftsmens and digital fabricators. The first personnels is named Ahmad Kamarul Husnain Bin Abdul Rashid and Azri Haziq Bin Ahmad Hilmi from Hues 9 Engineering & Services. The semi structured interview is designed to produce detailed insights into interviewee experiences and inputs on adaptive and modular makerspaces, more focus on spatial flexibility, material reuse, the incorporation of digital fabrication technologies, and the sustainability of the makerspaces. The second phase is on the structured survey questionnaire towards the broader population comprising general people and other makerspace users, involving 105 respondents. The topics is like the interview, includes the user needs, space adaptability, environmental sustainability, cost – efficiency and satisfaction with makerspace facilities. Furthermore, the synthesis of inputs from both interviews and questionnaires was conducted, this consist of cross – referencing the data to identify overlapping themes, best practices and critical success factors for the design and operation of adaptive modular makerspaces. This combined analysis allows the formulation of insights aimed at forming a design for future makerspaces.

Table 4. Flow of the Survey approach



3.5 Case Study Selection

3.5.1 Case Study 1: MIT Toy Lab, Cambridge, United States, 2017

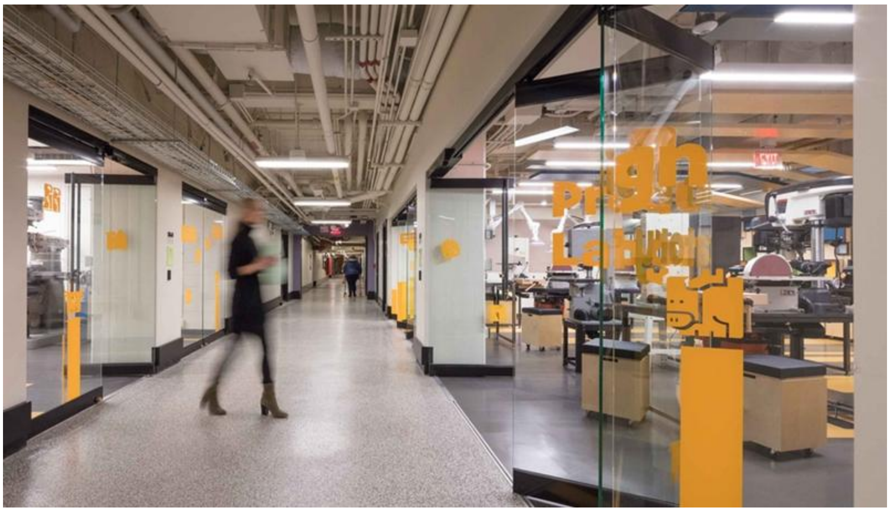


Figure 1. MIT TOY LAB (Source: https://architizer.com/projects/mit-toy-lab/)

The MIT Toy Lab, designed by Merge Architects and completed in 2017 within the Massachusetts Institute of Technology (MIT), is a specialized educational facility that supports the 2.00b Toy Product Design course. This course helps guide first-year students through the product design process, focusing on creativity and hands-on learning by creating toys.

i. **Flexible Design**: The lab features an open concept with movable partitions and modular furniture to easily configure the space to suit the activities and size of groups. This flexibility is built to accommodate the fluid process of toy design and prototyping.
ii. **Custom Millwork**: A modulated plywood grid system serves as storage, seating and organizational guides. The grid is punctuated by colorful steel-framed niches that serve as display areas for toys, both finished and unfinished.
iii. **Technological Integration**: With tools like 3D printers, CNC machines, and electronics workstations, the lab allows students to integrate advanced technologies into their toy designs.
iv. **Innovative Space**: The lab's location, with glass walls along MIT's 'Infinite Corridor,' shows visitors ongoing projects and encourages students from different departments to work together.
v. **Energy Sustainability**: Aesthetic Considerations: Grounding the overall design in MIT's historical architectural qualities. Sustainability Considerations.

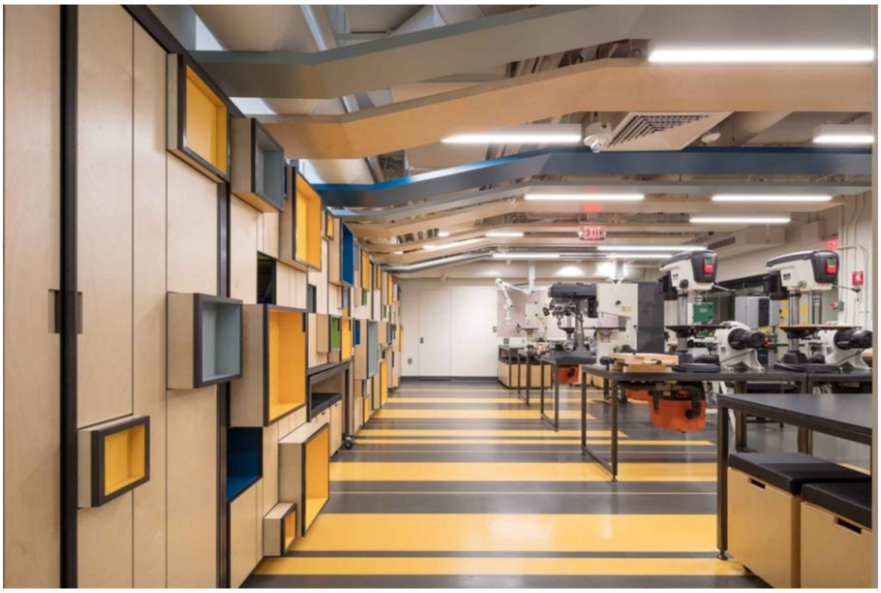


Figure 2. Not in Use Space (Source: https://architizer.com/projects/mit-toy-lab/)

Figure 3. When in Use Space (Source: https://architizer.com/projects/mit-toy-lab/)

3.5.2 Case Study 2: Sydney Modern Museum, Sydney, Australia, 2022

Figure 4. Sydney Modern Museum (Source: https://www.archdaily.com/995295/sydney-modern-sanaa)

The Sydney Modern Museum designed by SANAA Architects is an architectural extension of the Art Gallery of New South Wales, the site is within the natural topography overlooking Sydney Harbor, this project demonstrates a thoughtful marriage of art + architecture + nature. Additionally, the architecture facilitates cultural and public engagement, through interconnected pavilions, flexible spaces and sustainable design.

i. **Spatial Adaptability**: The museum includes a series of linked pavilions stepping down along the landscape, providing seamless integration between indoor and outdoor spaces. The flexible design allows for different programs, including large-scale art exhibitions, workshops, and events. Open-plan layout and flexible spaces can evolve with changing needs to support a dynamic cultural program

ii. **Sustainable Material and Construction:** The structure features sustainable and regionally sourced materials. Highlights include a 250-meter rammed earth wall, made from soil that was sourced from right across New South Wales, as well as hand-laid limestone blocks that deliver organic aesthetics with an environmental focus. The materials emphasize durability and ecological responsibility.

iii. **Technological Integration:** The project consists of using beyond sustainability approaches, the use of solar panels installed on the Entrance Pavilion roof. And there's an inventive reuse of a WWII fuel tank in the "The Tank" exhibition space, where modern design intersects with historical infrastructure. This integration makes for a careful choreography between technology and adaptive reuse.

iv. **User Engagement and Inclusivity:** Designed to be accessible to the public, the museum includes accessible features throughout its galleries and outdoor areas. Visitors are invited to activate art with the surrounding terrain through public terraces, roof gardens and courtyards designed for communion with nature. This open and welcoming design gives a nod to the commitment to community and user experience.

4.0 RESULTS AND DISCUSSION

The results from the document analysis of the literature review, combined with the comparative analysis of selected case studies, are used to answer the research questions and objectives. The two case studies chosen a makerspace (MIT Toy Lab, Cambridge, 2017) and a cultural institution (Sydney Modern Museum, Sydney, 2022) demonstrate practical applications of adaptive and modular design within different contexts. By examining their spatial adaptability, material strategies, technological integration, and user-centered design, the analysis provides a comparative lens against the theoretical principles and strategies identified in the literature review.

This synthesis highlights how adaptive design principles translate into practice, showcasing their significance in achieving flexibility, sustainability, and user engagement. The findings reinforce the argument that adaptive and modular approaches can enable makerspaces in urban contexts to remain relevant and future-ready, supporting innovation, collaboration, and resilience in response to constantly evolving societal and technological demands.

4.1 Document Analysis of Literature

i. Data Organization

In the literature, three of the four criteria were consistently identified as critical to the design and development of makerspaces: architectural principles, historical and contemporary practices, and environmental and technological adaptation. Fine-grained architectural principles emphasize flexibility, modularity, and reusability as fundamental strategies. Flexible layouts support adaptability to changing user requirements, while modular systems provide interchangeable elements that can accommodate diverse activities and emerging technologies. Durability and sustainability are also integral, with adaptive modular design enabling robust material use and long-term structural resilience while reducing environmental impact (Yavuz, Erdogdu, & Ozdemir, 2021).

From a historical perspective, makerspaces have evolved from industrially inspired production rooms to dynamic community-driven hubs for collaboration and innovation. This trajectory reflects broader shifts in spatial design and participatory practices, as identified in research on creative environments and collaborative planning (Thoring, Müller, Desmet, & Badke-Schaub, 2020). Contemporary makerspaces now embody these lessons by embedding adaptability and collaboration into their spatial frameworks.

Finally, environmental considerations and adaptability to technological change are central to the contemporary makerspace model. The use of sustainable materials prefabricated modular systems, and smart technologies can revolutionize production in urban contexts, aligning with broader goals of circular urban design and climate-conscious development (Elwakil, Schroder, & Steemers, 2023). These findings reinforce the importance of adaptive and modular principles in shaping sustainable, flexible, and future-ready maker hubs.

ii. Thematic Categorization

The expanded criteria become rich with attributes that describe their role in makerspace design. Flexibility, central to architectural principles, requires reconfigurable spaces that can adapt to changing user needs through features such as movable walls and modular furniture (Bobic, 2023). A modular approach ensures that systems are composed of interchangeable components that can be easily upgraded or replaced, minimizing waste and maximizing long-term adaptability. Durability reinforces these attributes by encouraging the use of sustainable materials capable of withstanding repetitive reconfiguration without compromising structural performance (Yavuz, Erdogdu, & Ozdemir, 2021).

While historical practices emphasized industrial efficiency, modern makerspaces integrate advanced technologies such as 3D printers, CNC machines, and laser cutters to enable diverse fabrication processes, positioning them as contemporary hubs for creativity and innovation (Thoring, Müller, Desmet, & Badke-Schaub, 2020; Zhan, Chen, & Retnawati, 2022). Environmental impact is equally critical, with energy efficiency, material reuse, and waste minimization at the heart of circular economy strategies that are increasingly applied to urban makerspace development (Elwakil, Schroder, & Steemers, 2023).

Scalability further supports these objectives by enabling modular systems to expand and integrate new digital technologies, such as IoT-driven controls, smart sensors, and augmented reality interfaces that facilitate user interaction and co-design processes (Nguyen & Moere, 2024; Vescovi et al., 2023). These thematic attributes—flexibility, modularity, durability, environmental responsibility, and technological responsiveness—form the foundation for resilient and future-ready makerspace design.

iii. Synthesis of Findings

Adaptive and modular design is key to creating environments that enable diverse users to innovate, collaborate, and reconfigure spaces according to evolving needs, from digital fabrication to community workshops (Nguyen & Moere, 2024). These findings confirm that sustainability is a recurring theme, with research showing how circular design principles can minimize environmental degradation through strategies such as recycled materials, planned disassembly, and reduced energy consumption (Elwakil, Schroder, & Steemers, 2023).

At the same time, learning-oriented makerspaces require open, cooperative layouts and educational programs that prioritize inclusivity and participant-centered engagement (Bobic, 2023). This balance between architectural adaptability and pedagogical inclusivity is central to the growth of innovation hubs. Ultimately, technology adaptation ensures that makerspaces remain future proof. By integrating advanced tools such as IoT systems, 3D printing, and augmented reality, modular makerspaces can continually evolve with technological progress while supporting diverse forms of maker activity (Vescovi et al., 2023).

Altogether, these results highlight how adaptive design principles, modular strategies, sustainable practices, and technology integration converge to form the foundation of user-centric, future-ready makerspaces in urban contexts.

Table 5. Analysis of Documentation

Criteria	Attributes	Description	Key Preferences
Key Architectural Principles	Flexibility	Flexible layouts enable adaptability to changing user needs and diverse activities through movable partitions and multipurpose furniture.	(Bobic, 2023; Zaharin et al., 2024)
	Modularity	Modular systems provide interchangeable components that can be added, removed, or reconfigured to support multifunctional spaces and evolving technologies.	(Yavuz, Erdogdu, & Ozdemir, 2021; Vescovi et al., 2023)
	Durability	Sustainable and durable materials ensure robustness over time, supporting long-term usability and resilience in reconfigurable systems.	(Yavuz et al., 2021)
Historical and Contemporary Practices	Industrial Roots	Early makerspaces mirrored industrial production systems focused on efficiency and systematic workflows.	(Thoring, Müller, Desmet, & Badke-Schaub, 2020)
	Community Driven Evolution	Makerspaces transitioned into community-driven collaborative hubs emphasizing participatory and creative activities.	(Zhan, Chen, & Retnawati, 2022)
	Innovative Integration	Contemporary practices integrate digital tools (e.g., CNC, 3D printers) with sustainable methods to bridge traditional production and modern design.	(Nguyen & Moere, 2024)
Environmental Impact	Energy Efficiency	Incorporation of energy-efficient systems, smart monitoring, and renewable energy to reduce carbon footprint.	(Elwakil, Schroder, & Steemers, 2023; Nguyen & Moere, 2024)
	Material Reuse	Adoption of recycled and eco-friendly materials aligns with circular economy principles.	(Elwakil et al., 2023; Vuylsteke et al., 2022)
	Waste Management	Strategies such as planned disassembly and modular reuse minimize construction waste and maximize sustainability.	(Elwakil et al., 2023; Vescovi et al., 2023)
Technological Adaptation	Advanced Tool Integration	Makerspaces now integrate digital fabrication technologies such as 3D printing, CNC, robotics, and augmented reality for diverse user needs.	(Vescovi et al., 2023)
	Scalability for Evolving Tech	Modular and scalable systems ensure spaces adapt to continuous technological advancements.	(Yavuz et al., 2021; Verma, 2023)
	Digital Interfaces	IoT systems, AR/VR platforms, and smart interfaces enhance user experience, collaboration, and operational efficiency.	(Nguyen & Moere, 2024; Bobic, 2023)

Architecture	Reconfigurable Spaces	Modular layouts enable diverse activities such as digital fabrication, workshops, and educational programs.	(Thoring et al., 2020; Zhan et al., 2022)
	Modular Systems	Interchangeable modular units allow flexibility, rapid reconfiguration, and scalability for evolving user needs.	(Yavuz et al., 2021; Vescovi et al., 2023)
Sustainability	Circular Design Principles	Makerspaces adopt recycled materials, planned disassembly, and renewable systems to minimize environmental degradation.	(Elwakil et al., 2023; Vuylsteke et al., 2022)
	Material Reuse	Use of recycled and reclaimed materials supports waste reduction and sustainable construction.	(Elwakil et al., 2023)
	Energy Efficiency	Real-time energy monitoring, intelligent climate control, and renewable energy systems ensure long-term sustainability.	(Nguyen & Moere, 2024)
User-Centric Design	Open, Cooperative Layouts	Flexible floor plans encourage collaboration, creativity, and inclusivity across diverse user groups.	(Bobic, 2023; Zaharin et al., 2024)
	Participant-Cantered Programs	Learning and innovation programs foster user engagement, skill-building, and community ownership.	(Zhan et al., 2022; Bobic, 2023)

4.2 Comparative Analysis

Table 6. Comparative Analysis of Case Study

Description	MIT Toy Lab, Cambridge, United States	Sydney Modern Museum, Sydney, Australia
Location	Cambridge, Massachusetts, USA. Located within the MIT campus.	Sydney, Australia. Part of the Art Gallery of New South Wales.
Building Function	Educational makerspace supporting toy product design.  *Figure 1. MIT TOY LAB (Source: https://architizer.com/projects/mit-toy-lab/)*	Public art museum for exhibitions, events, and community engagement.  Figure 2. Exhibition Space (Source: https://www.archdaily.com/995295/sydney-modern-sanaa)

<table>
<tr><th></th><th></th><th></th></tr>
<tr><td>Spatial Adaptability</td><td>Open-concept layout with movable partitions and modular furniture.

Figure 3. Open Space Layout (Source: https://architizer.com/projects/mit-toy-lab/)</td><td>Interconnected pavilions with flexible, reconfigurable exhibition spaces.

Figure 4. Indoor, Outdoor Spaces (Source: https://www.archdaily.com/995295/sydney-modern-sanaa)</td></tr>
<tr><td>Material and Construction</td><td>Plywood grid system for storage and display. Sustainable materials.</td><td>Rammed earth wall, hand-laid limestone, and regionally sourced materials.</td></tr>
<tr><td>Technological Integration</td><td>3D printers, CNC machines, and electronics workstations.</td><td>Solar panels, reuse of WWII fuel tank (The Tank), energy-efficient systems.</td></tr>
<tr><td>Sustainability Practices</td><td>Durable and modular materials for long-term usability.</td><td>6-Star Green Star rating, sustainable construction, renewable energy systems.</td></tr>
<tr><td>User Engagement and Inclusivity</td><td>Glass walls encourage interaction and collaboration across groups.

Figure 5. Space Interactions (Source: https://architizer.com/projects/mit-toy-lab/)</td><td>Accessible galleries, public terraces, and outdoor spaces enhancing inclusivity.

Figure 6. Interconnected Gallery (Source: https://www.archdaily.com/995295/sydney-modern-sanaa)</td></tr>
<tr><td>Design Outcome</td><td>Supports creative, hands-on learning and prototyping activities.</td><td>Creates cultural engagement through art, nature, and adaptive spaces.</td></tr>
</table>

Comparing specific types of makerspaces such as the MIT Toy Lab and museums like the Sydney Modern Museum allows for a greater understanding of how adaptive design works in specialized versus public-driven spaces. They tackle similar challenges — flexibility, sustainability and integration of technology — providing transferable strategies. Such a comparison helps to spotlight what innovations they can implement to design adaptable, inclusive, and sustainable urban makerspaces.

4.3 Comparison of Findings from Interview and Questionnaire

Aspect	Interview Findings (Craftsmanship & Digital Fabricators)	Questionnaire Findings (General Users)
Flexibility & Adaptability	The interviewees specified that the makerspace needs to have spaces that can adapt quickly to different kinds of projects and needs of the makers. The movable partitions, adjustable workstations, and adjustable cubicle are important to accommodate plethora of needs and the user preferences.	87% of the survey respondents rated that the flexible spaces (movable furniture, modular walls) inside a makerspace is crucial that will enable them to enhance exploration capability.
Sustainability and Cost Efficiency	For an effective long term operational savings, the construction of the makerspace is crucial in having recycling facility for the makers but also use sustainable material for the building, also plan for maximizing energy efficiency and cost-effective modular constructions.	79% of the respondents agreed that environmental sustainability and lower operational costs are important to become a successful makerspace design.
User Experience & Engagement	The Interviewees highlighted that personal comfort, space ownership, and ease of access are essential to have in maximizing and enable the makers to explore their creativity and engagement with other makers.	82% of the respondents say that user focus design (comfortable furniture, accessible layout) can increase their engagement and innovative input inside the makerspace.
Technological Adaptability	Digital fabricators specifically pointed out the need for spaces that can accommodate new technologies (CNC machines, 3D Printer, Laser Cutting Machine, etc.) with proper and flexible infrastructure (power, ventilation, circulation).	85% of the respondent's responses were more general but they say that the makerspace needs to have a more "future-proof" (Autonomous Transportation System, Integrated Track System) spaces that can make use of the evolving technology
Community and Collaboration	The interviewees emphasize the value of communal and relaxing spaces inside the makerspace to enhance the knowledge sharing and collaborative projects.	78% of the users stated that the collaboration space is important in creating an environment that can enable them to share and increase their knowledge from other makers with different kinds of specialties.

The data from both the interviews and the questionnaire survey validated flexibility as one of the most critical priorities for makerspaces, although the interviews showed what this very flexibility comprised in the context of some making activities. The two groups are still well aligned concerning sustainability and cost-effectiveness, though interviewees suggested many more specific strategies such as systems prefabrication and the use of renewable materials. Another aspect mentioned throughout both types of investigation is a user-centric design as a very critical factor determining user engagement and creativity. What the interviews managed to do is, however, provide nuanced insights into the technology requirements and to give much stronger emphasis to the social and community dimensions of makerspaces, thus suggesting quite a more holistic understanding of user needs in comparison to the more general survey responses.

The findings and the analysis from the document analysis of literature; and the comparative analysis of the two case studies, the MIT Toy Lab and Sydney Modern Museum, the comparison of findings from Interview and Questionnaire. The research discusses the pivotal aspects of spatial adaptability, sustainability, technological integration, and user-centric design to prove the adaptability and modularity framework for makerspaces. The research findings demonstrate common strengths across modular layout, advanced technologies and sustainable practices, identifying gaps in scalability, inclusivity and circular design principles. Such learnings stress the need to bring together flexibility, durability, and cutting-edge technologies to design future-ready, sustainable, and inclusive urban makerspaces.

5.0 CONCLUSION

5.1 Limitation

This research has several limitations. Firstly, adaptive modular architectural designs with specific and measurable performance indicators are rarely established, meaning that findings often need to be drawn from generalizations of similar projects or theoretical frameworks, which may reduce their direct applicability to the Malaysian context (Yavuz, Erdogdu, & Ozdemir, 2021). Furthermore, technological advancement progresses so rapidly that some findings risk becoming obsolete shortly after publication, highlighting the need for continual investigation across different strands of adaptive and modular design research (Nguyen & Moere, 2024). Finally, while much of the current literature emphasizes the successes of adaptive and modular practices, it often overlooks the challenges and complexities of change, which are equally important for supporting meaningful learning and long-term resilience in workplace and makerspace environments (Zaharin et al., 2024).

Future research should aim to validate the proposed framework through practical applications in real-world contexts. While this study establishes a conceptual foundation for adaptive and modular makerspace design, its potential can be more effectively demonstrated through simulations or prototype spaces. A prototype incorporating modular construction, reconfigurable layouts, and smart technologies would enable evaluation of adaptability, energy efficiency, and user experience. Simulations could further test ergonomic comfort, spatial efficiency, and technological integration under different user scenarios, generating measurable data to refine the framework. Longitudinal studies would also be valuable, capturing how adaptive makerspaces evolve over time with technological and social change. Such validation would not only strengthen the framework's reliability but also provide architects, policymakers, and stakeholders with concrete strategies for implementing sustainable, user-centric makerspaces in Malaysia and beyond.

5.2 Proposed Framework

The table shows the summary of main recommendations based upon the research findings. These recommendations help bridge gaps highlighted in the areas of flexibility, sustainability, technological integration, scalability, and inclusivity. The recommendations point the way to future makerspaces that are adaptable, community-oriented, and sustainable to address city and tech issues going forward.

Table 8. Recommendations On Designing Adaptive and Modular Spaces for Makerspaces

Category	Recommendation	Justification
Flexibility and Modularity	Utilize scalable modular systems that can configure into varying layouts, allowing for changing components.	Increases capability to cater to diverse user needs and dynamic technologies in makerspace environments.
Sustainability	Embed the principles of circular design, sustainable energy systems and waste reduction.	Compatible with sustainable development goals on a global scale and helps minimize environmental footprint while assuring sustainability.
Technological Integration	Implement the Internet of Things (IoT) systems, augmented reality, digital fabrication tools, and other advanced technologies.	Helps makerspaces remain relevant with seamless interaction to innovate and serve its users more effectively.
User Engagement and Inclusivity	Creating access environments inclusive to groups that use spaces both individually and with others.	It promotes community participation, stimulates creativity, and fills the gap between various user demographics.
Scalability	Create systems and technologies that can grow in accordance with ever-rising user demands and urbanization.	To keep the makerspace useful and relevant as the user base and activities grow.
Budget Considerations	Look for low-cost solutions for implementation — open-source tools, sustainable materials, etc.	Financial constraints as well as maintaining the quality and functionality of adaptive and modular designs.
Community Integration	Collaborate with local communities and stakeholders, using participative design processes to arrive at adaptable, sustainable designs	Local, directed by locals, relevant to locals encourages community ownership, fosters collaboration, and ensures that the makerspace meets the local need.

6.0 ARTIFICAL INTELLIGENCE (AI) USAGE DECLARATION

Artificial intelligence (AI)–assisted tools were employed in this study to improve the clarity of language, grammar, and overall readability. To maintain academic integrity, the manuscript was subsequently reviewed and refined by the authors and subject to human oversight to ensure accuracy and quality.

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