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Assessing the Potential of Robotic Fabrication in In-Situ Construction and Architecture Pedagogy.

Fosu Caleb[1], *Marfo-Yiadom Nana Kwame Boakye*[2], *Owusu Daniel*[3], *Ofori Edward*[4]*

Department of Architecture, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana.
Email; Khatecogh@gmail.com,fosucaleb.arc@gmail.com

ABSTRACT

The Architecture, Engineering, and Construction (AEC) industry is experiencing a profound shift from traditional methods to automation driven by digital technologies. This transformation, as highlighted by Papadonikolaki et al. (2020), has been steadily progressing over the past two decades, with computational design and digital manufacturing playing key roles in advancing architectural technology. Recently, there has been a noteworthy evolution in architecture and architectural education, aiming to reconnect the profession with materials and technology.This study explores the adoption of robotic fabrication in on-site construction and architectural pedagogy, employing a mixed-method approach. Interviews with industry and academia stakeholders shed light on the challenges and potential benefits of this transition. Findings reveal that factors like high labor costs, low productivity, and environmental concerns are driving forces behind the evolution of construction practices. However, significant barriers, including initial and operational costs, lack of expertise, and limited incentives, impede the integration of robotics into construction processes. To overcome these challenges, the study recommends early introduction of robotic fabrication in architectural education, promoting digital fabrication practices, establishing partnerships with institutions and professionals, retraining workers, raising awareness among stakeholders, and facilitating tax incentives for machinery imports. These strategies are crucial for realizing the potential of robotic fabrication in on-site construction

Keywords: Robotic fabrication, In-situ construction, Architecture pedagogy

1. Introduction

Modern architecture, is defined by the ability to capitalize on the distinctive triumphs of the same novelty - the advancements provided by modern technology and science - having abandoned the rhetoric of style (Kolarevic, 2001). The possibility of whole innovative aesthetic, as well as, functional possibilities is being brought up by the integration of robotics in architecture, which could fundamentally affect architectural design and the culture of construction as a whole (Architectural Design, 2014). Architecture constantly both informs and is informed through its means of representation and creation, perhaps never more so than presently, when emerging technology and digital media are rapidly expanding what we think is formally, spatially, and physically feasible. Digital manufacturing has sparked a design revolution, resulting in a plethora of architectural creativity and innovation (Iwamoto, 2009). New manufacturing improvements previously made in the automotive and aerospace industries, combined with the creative and generative potential of digital media, are allowing new perspectives in design and architecture to emerge. They created new opportunities by making it possible to manufacture and assemble incredibly complex forms that were previously impossible to create using conventional construction techniques (Kolarevic, 2001).

Traditional construction techniques are no longer able to meet the rising need for higher levels of safety, sustainability, standards and prolificacy (Pan et al., 2020). The building construction industry must dramatically increase productivity to satisfy current and future demand issues. According to projections and figures from the UN, the world’s population will increase from 7.7 billion in 2019 to roughly 8.5 billion in 2030 and 9.7 billion in 2050 (Gharbia et al., 2020). The Architecture, Engineering and Construction (AEC) industry is undergoing a significant transition from conventional labour-intensive methods to automation through the use of digital technologies (DTs), and has been a crucial element in this revolution (Manzoor et al., 2021). Papadonikolaki et al. (2020) suggests that construction, like other industries, has been undergoing a gradual but rapid digital transformation over the last two decades. The 'digital vortex' is cause significant disruptions to the built environment. One of the most promising approaches to changing the industry has been advancing the use and application of robotics (Pan et al., 2020)

Building construction with technologies represents a substantial shift from traditional methods. The usage of robotics is projected to create a wide range of new opportunities for structural design and construction (Gharbia et al., 2020). In a novel approach to the future requirements of construction, a mobile fabrication unit is aimed to be utilized forthwith on a building lot to carry out operations that were previously exclusively handled via prefabrication using specifically built machinery, often at a fixed, off-site location (Helm et al., 2014). The tight interplay between computational design and digital manufacturing has resulted in great improvements in digital technology in the realm of architecture (Helm et al., 2014). In the past, architectural designs were based on what could be built rather than what could be drawn (Dunn, 2012). However, new digitally drive design, manufacturing and construction processes are gradually posing a challenge to the traditional link between architecture and its production processes (Kolarevic, 2001).

1.1 Evolution of Robotics in Construction.

In recent years, there has been a resurgence of interest in the benefits that robots may provide to the building sector. Robotic building is making a comeback, and it looks like it'll be here to stay (Bechthold, 2010). Since the first attempts in the 1980s, when construction robotics was first discussed, a plethora of research and development eff (Pan et al., 2020). Large-scale prefabrication (LSP) building component manufacture (BCM) were introduced in the 1970s, reducing on-site difficulty and enabling the use of robotics during on-site construction of buildings. The accomplishment of automated off-site home construction in Japan inspired the invention of the first wave of on-site automated building construction robots in comparably simple single-task construction robots (STCRs) (Gharbia et al., 2020). The Japanese economy was booming in the 1980s, and building could hardly keep up with the demand (Bechthold, 2010). Working on construction sites, however, was not particularly appealing to a generation of young Japanese because of the '3 Ks': kiken (dangerous), kitanai (dirty) and kitsui (hard) (Bechthold, 2010). To address the growing expectations of the construction sector to lower project cost and schedule, large construction businesses in Japan started making significant investments in robots (Huang et al., 2022). Historically, the change and evolution of the construction can be divided into four phases

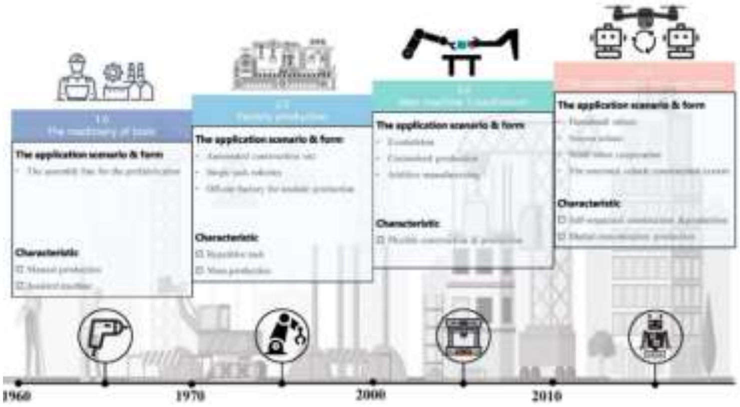

Fig. 1.1: The Evolution Phases of Robotics in Construction. (Huang, et al., 2022)

n the 1990s, the development of robot-assisted construction processes typically produced either highly specialized, expensive and only slightly flexible construction robots, or robot-assisted building factories with the same limitations (Architectural Design, 2014). Up until now, robots in the construction industry were solely utilized to improve (conventional) building procedures and increase production (Architectural Design, 2014).

Robotic fabrication in architecture has improved over the last decade where initial digital architecture fell short: it has been successful in fusing the intangible logic of computers with the physical reality of architecture, allowing for immediate reciprocity between digital systems and large-scale architectural development (Architectural Design, 2014). The emphasis on personalization has shifted today. The tools were custom made and the jobs were standardized in the 1980s, with little value added (Bechthold, 2010). The move from standardized to customized industrial production forms is presently underway. Architecture, arts and crafts, and industrial design, for example, have all changed. In the construction sector, robotics provides for new kinds of diversity and expression (Larsen, et al., 2016). Standard industrial robots are now capable of doing highly customized jobs that provide significant value. Industrial robots can now be purchased for a fraction of the price of a tailor-made robot from the 1980s (Bechthold, 2010). Industrial robots today have tremendous capabilities, and automated construction facilities can be set up in weeks as opposed to years (Bechthold, 2010). The concept of mass-customization was brought into building design and manufacturing with the capacity to mass-produce atypical building components with the same convenience as standardized ones (Kolarevic, 2001). Mass-customization is characterized by the mass production of individually personalized goods and services), allowing for a huge increase in range and modification without a significant cost increment (Kolarevic, 2001). Early incorporation of robotics in construction were driven towards pre-fabrication of building components in factories (Loveridge & Coray, 2017). Prefabrication typically takes place in production plant conditions, isolated from the weather and uncontrollable elements; such safe, controlled environments perfect for modern industrial robots. However, because final building takes place in place, there is a lot of unrealized opportunities for on-site robotic manufacturing in the architectural, engineering, and construction (AEC) industries (Loveridge & Coray, 2017).

Building prefabrication is being revolutionized by in-situ robotic fabrication (Helm et al., 2014). In-situ robotic fabrication makes possible direct operations on the jobsite and the construction of architectural structures according to particular geometric configurations, because the robotic system used transports and installs construction pieces precisely to their needed place (Helm et al., 2014). Again, in-situ robotic construction decreases the segmentation of huge building components by allowing the assembly of several smaller building elements. (Helm et al., 2014). Additionally, in-situ robotic manufacturing can accurately arrange and manipulate materials in accordance with a computer blueprint and operates in compliance with a digital architectural plan (Helm, et al., 2014). If digital fabrication can be done on-site, as envisaged, this removes the need for expensive and ecologically destructive movement of huge structural components. This would also effectively entail the extension and advancement of the digital fabrication chain of large architectural components (Helm et al., 2012).

To investigate the resulting advanced production requirements for design, a multipurpose fabrication laboratory using an industrial robot was set up – the first such in the field of architecture (Architectural Design, 2014). This was effected when the Gramazio & Kohler group established the first laboratory for industrial robotic fabrication prototyping, in 2005, for nonstandard architectural fabrication techniques at ETH Zurich, as part of the current shift towards digital technology in architecture. Ongoing developments in digital technologies have radically altered the relationship between design idea and fabrication (Dunn, 2012). As the capacity for innovation and unique creativity through robots is realized, the use of digital construction in the creative industries continues to rise (RobArch, 2016). In light of this, Bechthold (2010) is of the view that to complement traditional construction methods and craft-based fabrication, robotic fabrication is the way of the future. Chisels and robots are not mutually exclusive; each has its place.

1.2 Categories of Robotic Fabrication.

There are variations in robotic systems being deployed, and there is no consensus on a clear classification (Delgado et al., 2019). New technological advancements regularly redraw or obfuscate the boundaries between the classifications. The classification offered here aims to make it easier to comprehend an overview of the many system kinds (Delgado et al., 2019). There are four broad categories into which the robotic technology for building can be divided: Exoskeletons, drones and autonomous vehicles, on-site automated and robotic systems and off-site prefabrication systems.

1.2.1 On-Site automated and robotic systems.

Systems that can be used immediately on a construction site to manufacture structures and buildings are included in this category. Single tack construction robots (STCRs), which are capable of doing a single task repeatedly, were the first type of system deployed (Delgado et al., 2019). On-site construction robotic technologies are a growing application field, with additive manufacturing (AM), automated robotic assembly systems automated installation systems, autonomous robotic assembly and robotic bricklaying all appearing to have the potential to influence the development of robotics in the construction industry (Gharbia et al., 2020).

1.2.2 Drones and autonomous vehicles

This category covers terrestrial, aerial or nautical vehicles that can be controlled remotely or that are autonomous (Delgado et al., 2019). Unmanned aerial vehicles, or drones are becoming more common in the construction sector and their use has increased significantly in recent years (Bogue, 2018). It has been studied that conventional 100-acre survey assignment takes a staffed survey team about 7 weeks to complete, of 4 weeks are used to collect data. The necessary data can be gathered by a commercial drone service in about 9 minutes and the service can be completed in about 6 hours (Bogue, 2018). These autonomous vehicles may perform a wide range of tasks, including entering harsh and dangerous settings, so eliminating humans from high-risk locations, surveying and monitoring, automated excavating, demolition and material transfer (Delgado et al., 2019). In recent years, autonomous ground vehicles have been the focus of intense research and development (Bogue, 2018). Drillers and excavators have been mechanized and driverless vehicles with GPS are used to move the excavated material from one location to another. However, the relative simplicity of mining operations duties have facilitated the adoption of these technologies, as compared to conventional construction activities (Delgado et al., 2019)**..**

1.2.3 Exoskeletons

An exoskeleton is a motorised machine that is designed to fit on a person's body and is usually constructed of metal. The machine is designed to increase the wearer's strength and enable good body mechanics. It makes lifting objects easier and reduces body strain (Forestell, 2020). Exoskeletons can help construction workers move heavy loads, experience less tiredness and operate tools more easily when in awkward positions, reducing the negative impact of their work and enhancing productivity (Delgado et al., 2019). Construction workers wear exoskeletons to reduce exhaustion, increase production that might otherwise be lost due to fatigue and prevent injuries from overexertion or repetitive strain (Ekso Bionics, 2021). Industrial exoskeleton advocates refer to them as the "future of construction,". Furthermore, exoskeletons can deal with the problems brought on by an ageing construction workforce by enabling older personnel to continue working and performing physically demanding activities (Delgado et al., 2019).

1.2.4 Off-site automated prefabrication systems

This category encompasses a wide range of tools and technology for off-site manufacturing automation of building components. The technologies, which drew inspiration from robots employed in other sectors of production, were principally developed to improve the grade of prefabricated building components (Delgado et al., 2019). Building component manufacturing (BCM) techniques transform materials (concrete, bricks, wood, steel, and other low-level components) into high-level building components. High-level building components are integrated into finishes full building using large-scale prefabrication (LSP) techniques (Delgado et al., 2019).

1.3 Factors Influencing the adoption of robotic fabrication

The recent advancements and integration of robotic and automated systems in on-site construction processes are being driven by diverse factors, as explained below.

1.3.1 Economic Factors

At the landscape level, the economic climate is a significant factor that influences the real-world use of construction robots (Pan et al., 2020). Another important consideration is the cost of building. The construction industry is suffering from high labour expenses, thus any apparatus or technology that might reduce labour costs is welcomed (Pan et al., 2020). Contrarily, a significant economic driver at the niche level is the decline in investment by construction companies as a result of high capital costs and the absence of long-term economic justification for construction robots (Pan et al., 2020). Digital fabrication techniques can boost productivity in the construction industry not just because they save time on complex designs, but also because they allow design data to be transferred straight to 1:1 assembly procedures and automated construction (García de Soto et al., 2018). The integrated digital design and fabrication process (also known as a design-to-production process) allows for better control and flexibility during construction, allowing for late-stage alterations without significantly increasing construction costs (García de Soto et al., 2018).

1.3.2. Environmental Factor

Building and construction have negative consequences on the environment and the public in terms of carbon emissions, waste destruction, noise pollution and disruption of surrounding areas (Pan et al., 2020). The gradual decrease of harmful emissions and greening of the construction sector, as well as increased public awareness of construction operations, necessitates novel methods to construction, providing an ideal opportunity for robot adoption (Carra et al., 2018 & Pan et al., 2020).

1.3.3 Industry Factor

Many influencing elements at the regime level arise from the features of the construction industry. To begin with, the industry's fragmented nature makes it resistant to change and innovation (Pan et al., 2020). Robotic applications are challenging due to the multi-point responsibility. A well-organized and homogenous on-site environment is made possible by large-scale industrialization and prefabrication, which makes it easier to integrate robots for assembly tasks (Pan et al., 2020). The large-scale of prefabrication, on the other hand, may limit the economic benefits of using robots on-site. Diversity and greater architectural freedom are a driving force in the industry's use of robotics (Pan et al., 2020). In the face of population growth, resource constraint, and global warming, the construction industry must develop to produce more efficient, cleaner, faster and configurable building systems (RobArch, 2018).

1.3.4 Social-Cultural factors.

A significant challenge to obtaining innovative technology such as robots or other new technologies is a lack of innovation culture related to aversion to change (Pan et al., 2020). Another socio-cultural concern is the need to reduce human worker safety and health hazards on building sites, which is cited as a primary motivator for the usage of more automation and robotics (Pan et al., 2020). In 2005, the International Labour Organization estimated that more than 50,000 people die each year in the construction industry around the world, accounting for 17% of all workplace fatalities (Keating et al., 2017). Construction is being influenced to use automated fabrication to increase safety, speed, and quality, as well as to simplify complicated integrative fabrication procedures (Keating et al., 2017). Construction robots have a golden opportunity because of the challenges in work structure and organization. Meanwhile, education and training have a significant impact on the application of robots by improving the robotic knowledge and competence of the next generation as well as current workers (Pan et al., 2020).

1.3.5 Political and legal factors

Workplace safety and health are governed by government labour legislation, which also establishes regular working hours and wages (Pan et al., 2020). Changes in labour legislation may help or hinder the use of robots in terms of improved safety, health, and productivity. Strong policies and incentive programmes are typically effective in encouraging the use of cutting-edge technologies in the construction industry. Through its function as a client, the government has a significant impact on building construction and can encourage the use of robots in public procurement (Pan et al., 2020).

1.3.6 Technical Factors

The adoption of information and communication technology (ICT) such as BIM and the Internet of Things (IoT) across the construction sector lays the groundwork for automation and robotics (Pan et al., 2020). Due to the unpredictable and hazardous nature of building sites, robots utilized on construction sites should be durable, adaptable, mobile, and versatile. Improving the usability of construction robotics is a significant issue for future adoption in terms of increased technological understanding, simpler human-robot interface/interaction and control modes, flexible mobility and accurate analysis of the complex surrounding environment (Pan, et al., 2020).

1.4 The use of Robotics in In-Situ Construction

The early developments of in situ construction automation had been initiated by large contracting companies with the goal to increase the sector's efficiency and productivity (Dörfler, 2018). The intimate relationship that historically existed between architecture and building (what was once the fundamental nature of architectural practice) may resurface as an unintentional but positive result of new digital manufacturing techniques (Kolarevic, 2003). The six main stages of on-site construction that have the most potential for automation and robotics implementation are: earthworks, concreting, structural steelwork, painting / finishing, building assembly / lifting and positioning of components and total automation of the construction works, which includes the entire building process (Mahbub, 2011). Fabrication processes have evolved with design approaches and architectural styles, from adobe brick construction before 7500 BC to today's 3D printing technologies (Architectural Design, 2014). New design expressions have accelerated building technique innovation, while modern production procedures have motivated designers and architects to push the boundaries of design even further (Architectural Design, 2014). The adoption of digital technologies opens up a slew of new possibilities for conceptual design, dimensioning, detailing, and manufacture of concrete structures, with the potential to transform the construction industry (Mata-Falcón et al., 2018). As a result, various robotic technologies for on-site building construction have been evolved, ranging from single-task robots to integrated robotic sites (such as mobile and/or aerial robots for installing facades. These show how robotics can help with construction activities in a more effective, accurate and secure way (Pan et al., 2020).

Table *1*.1. Types of robotic technologies and their on-site applications.

Robotic Technology	Description	On-Site Application
Additive manufacturing (AM)	A robotic system with an articulated, gantry, Cable-Driven Parallel Robot (CDPR) that extrudes printing material in layers or manufactures the construction element on-site	Concrete structures, interior finishes
Automated installation system	A CDPR robotic system with suction devices on a mobile platform or connected to a gantry that allows automatic erection of construction components	Exterior envelope, interior finishes
Automated robotic assembly system	A robotic system of the scissor or gantry type with gripping and fastening tools for automating the assembly of building components	Steel structures, masonry walls, prefabricated buildings/components assembly
Autonomous robotic assembly	A humanoid robotic system that erects building components without the need for human assistance	Interior finishes, masonry walls, prefabricated buildings/elements
Robotic bricklaying	Bricklaying CDPR robotic system with a gripper attached to a frame by cables	Masonry walls
In-situ fabrication systems	An articulated robotic system with a fabricator to produce building components on-site	Concrete structures, masonry walls
Automatic concrete spraying	An articulated robotic system with a spray cannon that allows construction elements to be sprayed with concrete, or "shotcrete" directly on-site	Concrete structures
Autonomous spraying	A mobile 3-DoF platform equipped with an articulated robot with a painting head system for autonomous spraying	Interior finishes with a painting head system for autonomous spraying
Distributed robotic construction	**A set of articulated robots with a gripper on movable platforms to assemble building elements using distributed equal-mass partitioning**	**Steel structures**
Fused filament fabrication (FFF)	An articulated robotic system with a fused filament fabrication equipment to print thermoplastic filament materials based on the shell formation process in snails	Concrete structures
Printing Technology for foam concrete	A robotic idea for applying foam concrete automatically using a foam concrete generator	Exterior envelope
Unevenness recognition	An articulated robotic system based on artificial neural networks that detect unevenness is used, to apply materials to the building surface.	Interior finishes

Source: Gharbia et al. (2020)

For use on building sites, several attempts have been made to create mobile bricklaying and construction robots (Helm et al., 2014). Among the first efforts to create semi-mobile and autonomous robotic technologies for construction sites were the EU Robot Assembly System for Computer Integrated Construction (ROCCO) and the Bricklaying Robot for Use on the Construction Site (BRONCO) (Dörfler, 2018). A building site, unlike a normal prefabrication facility, is a spatially complex and diverse environment in which a robotic unit would be exposed to constantly changing conditions, unpredictable events, impediments, and the activities and movements of people working on-site (Helm et al., 2014). Building sites are generally regarded as unstructured because, in contrast to steady conditions that are typically present in industrial manufacturing, they gradually evolve and continuously change shape during construction, floors are not always flat, and there is no guarantee of regular structures in the surrounding (Helm et al., 2012). Various attempts to develop mobile robots for on-site robotic construction have already been made. When visiting a normal construction site today, one may likely notice a wide range of machinery of various sizes and functions (Agustí-Juan et al., 2017). We are likely to see a similarly diverse range of robots performing specialized duties in the construction industry (Agustí-Juan et al., 2017).

Because both geometrical complexity and variety often resulted in exponential cost consequences, building components created throughout the twentieth century were for the most part geometrically simple and limited in terms of kind (Architectural Design, 2014). This situation has been changed thanks to digital fabrication processes, in which the number and complexity of design parts has no bearing on manufacturing costs or efficiencies (Architectural Design, 2014). Regarding, robotic in situ fabrication, a number of external factors and uncertainties in the immediate environment pose a challenge to the robotic operations (Dörfler, 2018). There are a variety of factors that contribute to such uncertainty. Building site surroundings, for example, frequently exhibit variations and dimensional tolerances when compared to their digital blueprint (Dörfler, 2018). The physical domain's capacity for unpredictability conflicts with the predetermination of a digital building plan. However, it is precisely this dilemma that motivates architectural research in this field (Dörfler, 2018).

Two main groups of robotic systems for in-situ construction are distinguished, irrespective of the robotic of the robotic system's customisation for tasks-specific operations, or the material system used, namely: stationary robotic systems and mobile robotic systems.

1.4.1 Stationary robotics systems

Stationary robotic systems are usually comprised of a gantry system (Keating et al., 2017). The advantage of a gantry system is that it has fixed mechanical links throughout. This enables absolute positioning of the end effector inside the work space as well as simple control operation. Contour Crafting, an additive fabrication process, has been embraced by a variety of forms in recent years and integrated into stationary robotic set-ups for in situ building (Dörfler, 2018). For non-standard wall structures, the technology promises a waste-free, low-cost, and quick automated construction process (Dörfler, 2018).

Fig. 1.3: Wall fabrication by utilizing a large-scale gantry system set up on the building. (Dörfler, 2018)

Fig. 1.4: A stationary rotational robotic system for constructing buildings using concrete extrusion. (Dörfler, 2018)

1.4.2 Mobile Robotic Systems

Mobile robots may manufacture structures larger than their own static workspace, as opposed to the constrained workspace of stationary robotic systems (Dörfler, 2018). Their mobility is classified as either ground-based or aerial. They can fulfil the dexterity, agility and heavy payload requirements of construction tasks. Mobile robotic systems, on the other hand, lack a mechanical referential point, unlike stationary robotic systems that have fixed mechanical links throughout their setup. To attain global location precision, mobile robots rely on advanced sensing and control solutions (Dörfler, 2018).

1.4.2.1 Wide-range semi-mobile robotic systems

An extended manipulator and a movable base make up a wide-range semi-mobile robotic system. These robots can drive to the construction site thanks to the movable base (Dörfler, 2018). They are eventually utilized as stationary and fixed base robots due to their wide-range static workspace that can cover the area of a building (Dörfler, 2018). Hadrian 105, as well as its successor Hadrian X, the brainchild of Australian enterprise Fastbrick Robotics are being developed since 2015 (Berger, 2016). The robot has the potential to deliver a completely automated brick deposition system for the construction of structurally sound walls (Berger, 2016). A similar approach is demonstrated by the MIT Media Lab's Digital Construction Platform (DCP). A 6m long hydraulic boom with an industrial-type arm is coupled to the large-range robotic equipment (Keating et al., 2017). Additionally, solar panels put on the back side demonstrate the goal of achieving energy (Keating et al., 2017). This autonomy would allow mobile robotic systems to operate in areas where there is no access to electricity, such as uncharted terrestrial or extraterrestrial region (Dörfler, 2018).

Fig. 1.4: The DCP (Digital Construction Platform) (left). In 2017, the system fabricated a stay-in-place formwork for an open dome-like structure. (Dörfler, 2018)

Fig. 1.5: Hadrian 105 prototype (left) and successor version - Hadrian X (right) by Fastbrick Robotics: a one-armed robot for the construction of structurally sound brick walls on site. (Dörfler, 2018)

1.4.2.2 Mid-range Model Robotic Systems.

The use of an arm-based manipulator installed on a mobile platform distinguishes mid-range mobile robotic systems. They are used to fabricate constructions that are larger than their own static workspace by relocating them. DimRob, a pioneering arm-based mobile robot developed by the Gramazio Kohler Research group in 2012, was one of the first of its kind. The device was created to test robotic brick assembling procedures that had previously been designed for on-site prefabrication.

CyBe Construction, formed in 2013 and based in the Netherlands is another company that has pioneered robotic 3D printing. It has created the "R 3Dp," a modular system built on a six-axis robot capable of printing concrete at 200 mm/s (Bogue, 2018). The CyBe RC 3Dp is built out of a tracked movable base with a liftable undercarriage that can reach a working height of up to 4:5 meters. With a layer height of roughly 20mm and a printing speed of 200mm per second, the integrated concrete extrusion system allows for a layer height of around 20mm (Bogue, 2018). They demonstrated the mobile robot's first use in 2017 by fabricating a drone laboratory in Dubai, and a second application in 2018 by fabricating the walls for a 100m2 house during the Milan Design Week (Dörfler, 2018).

Fig. 1.6: DimRob, the first mobile construction robot prototype of Gramazio Kohler Research presented in 2012. (Dörfler, 2018)

Fig. 1.7: The mobile construction robot CyBe RC 3Dp fabricating a drone laboratory by applying a concrete extrusion process on a job site in Dubai in 2017. (Bogue, 2018)

1.4.2.3 Short-range Mobile Robotic Systems

This category encompasses mobile robotic fabrication technologies that are exceptionally small. These short-range robots can independently climb a structure as it is being built, despite their minimal payload capability (Dörfler, 2018). An innovative method of fabricating large-scale digital architecture that draws inspiration from biological systems could result in structures with integrated and continuous functionality (Architectural Design, 2014). As a result, production would be able to exceed the limitations of conventional construction on an architectural scale (Architectural Design, 2014).

Robotic Swarm Printing (RSP), a robotically driven multi-nodal additive fabrication platform being investigated by the Mediated Matter group, has the potential to revolutionize the field of digital overcoming the current limitations of additive manufacturing (Architectural Design, 2014). By leveraging the potential to move with the expansion of the fabricated structure, these robots can reach elevated heights without the need for an extra scaffolding aside (Dörfler, 2018)

Fig. 1.8: Harvard's TERMES swarm robots project, presented in 2014. (Dörfler, 2018)

2. Method and Materials

The study will use a pragmatic worldview that drives the mixed-method approach. Mixed method approach is a type of inquiry that integrates or associates qualitative and quantitative forms of research Creswell(2009). Additionally, it involves integrating the two approaches so that a study's overall strength is greater than that of either qualitative research or quantitative research Creswell(2009). This study used snowballing sample approach – a non-probability sampling technique – as the optimal sampling approach.

According to Polit & Beck (2004). snowball sampling is a variant of convenience sampling. Snowball sampling is a non-random sampling strategy that leverages a few cases to urge others to participate in the study, resulting in a larger size Taherdoost(2016). Snowballing starts with a convenience sample of initial subjects - a few competent study participants - and expands from there, relying on referrals from those participants to reach the target sample size polit et. Al(2004) and Etikan et. Al(2016).

A fraction of the data for the research objectives was obtained in part through the literature review through data collected from reviewed journals, books, articles, and other sources. These data were collected concerning the theories of robotic construction and its evolution over the years. Questionnaires were distributed to key stakeholders to gain insight into the many factors that influence robotic fabrication incorporation into construction and academia. Semi-structured interviews were carried out with some industry and academia stakeholders to further investigate the stated objectives of the study.

Participants in the field of architectural design in academia and practice were the basis to determine to sample size for this study. The sample size for the study will be limited to students in the third and fourth-year undergraduate levels of Architecture at the Kwame Nkrumah University of Science and Technology and practising architects. This was chosen to represent a varied population to obtain a perspective on the topic under study based on their level of education and experience in architecture. A population size of 240 was determined for the study. Hence the sample size was 69 participants using the indicated sample size parameters indicated as follows: a confidence level of 95% and a confidence

3. Results and Discussion

The data acquired was explained based on the core trend indices above and the significance of the study was explained in the subsequent chapter. Sixty-four (64) questionnaire responses were retrieved out of sixty-nine (69) questionnaires distributed and twenty-one (21) of industry persons were interviewed. A total number of eighty-five (85) responses from interviews and questionnaires distributed were analyzed and discussed. A diverse group of participants was selected across the sample population as shown in Tables 1 and 2; the goal was to attain a sample that reflected the majority of the traits of the target population. This provided a wide array of unique viewpoints

Table 1:Category of respondents	Frequency	**Percent**	Cumulative Percent
Undergraduate Student	54	**84.4**	84.4
Probationer Architect	8	**12.5**	96.9
Registered Architect	2	**3.1**	100.0
Total	64	**100.0**	

Source: *Author's Construct, 2022*

Table 2: Year of Students

	Frequency	Percent	Cumulative Percent
3rd year	14	21.9	25.9
4th year	40	62.5	100.0
Total	54	84.4	

***Source:** Author's Construct, 2022*

3.1 Factors Influencing the Adoption of Robotic Fabrication

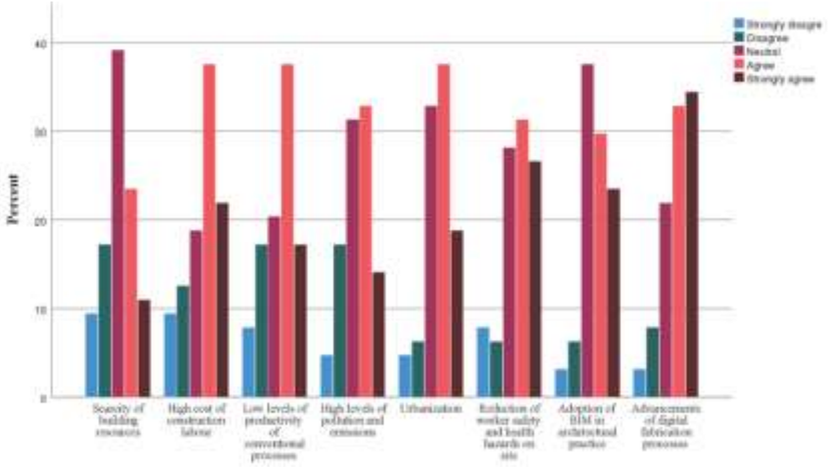

Fig. 3.1: Comparison of factors influencing adoption of Robotic Fabrication (Author's Construct, 2022)

Advancements in digital fabrication processes are observed as a major influence in the drive for the integration of robotic fabrication in in-situ construction. The urbanization of cities and the need to reduce threats to workers' safety and health and site, in a bid to reduce construction labour costs, are all driving factors pushing for the incorporation of robotic elements into the on-site construction workflow. However, the inconsistencies in the views of the respondents may be influenced by a more theoretical appreciation than practical realizations of the use of robotic machinery on site.

3.2 Barriers to adopting In-situ Robotic Fabrication

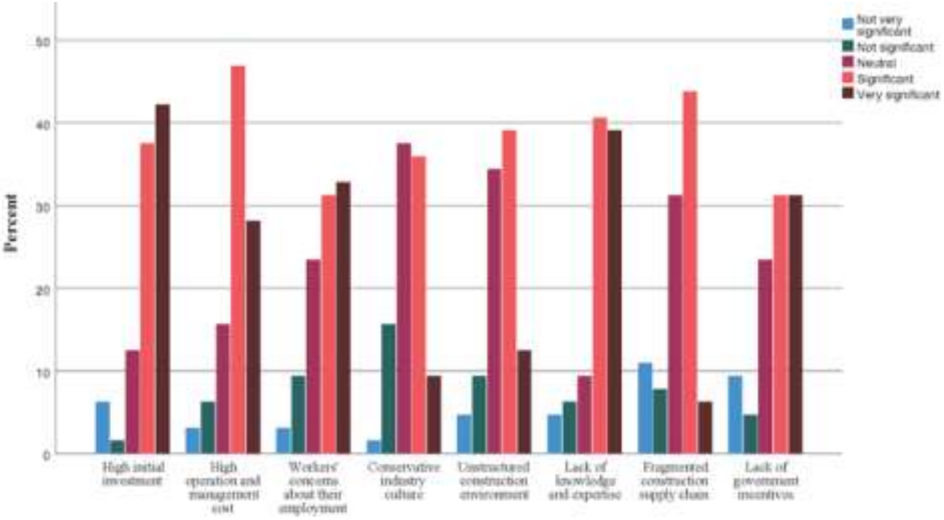

Fig. 3.2: Comparisons of barriers to adopting robotic fabrication (Author's Construct, 2022)

The high initial investment and high operational costs of running robotic machinery on construction sites pose the biggest hindrances to the implementation of in-situ robotic fabrication. The conservative nature of the construction industry and the unstructured construction site environment also are major bottlenecks to the realization of the application of robotic elements directly on site.

3.3 Level of Familiarity with Robotic Fabrication Application

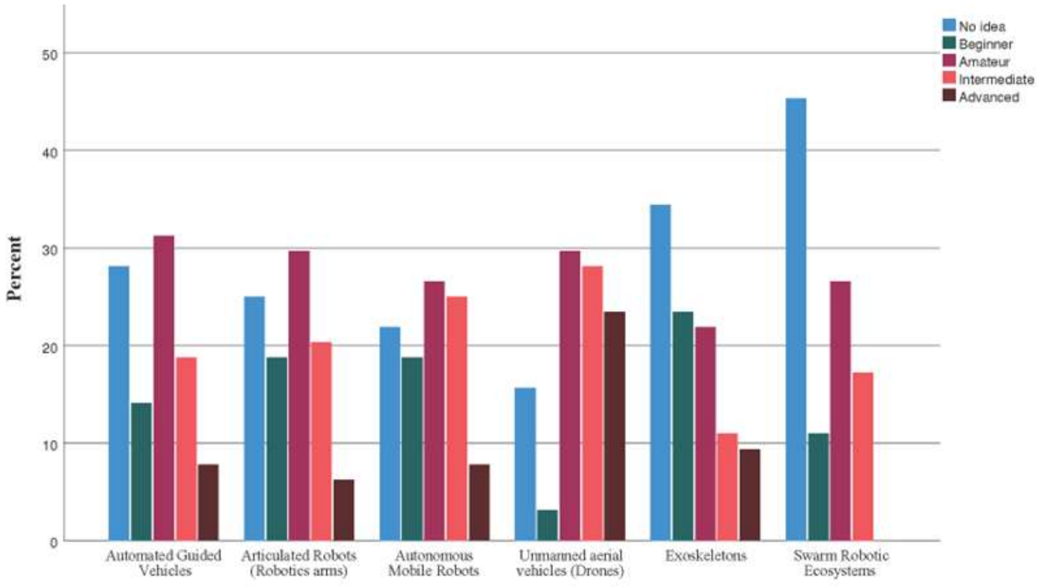

Fig. 3.3: Comparisons of level of familiarity with the application of robotic fabrication (Author's Construct, 2022)

With the development of in-situ construction robotics tools still in the early stages, there was a general average appreciation of the application of various robotic machinery on site. Unmanned aerial vehicles are the most applied robotic elements in construction because of major advances in surveying, mapping and supervisory roles with the construction workflow.

3.4 Timeframes for Construction site evolutions

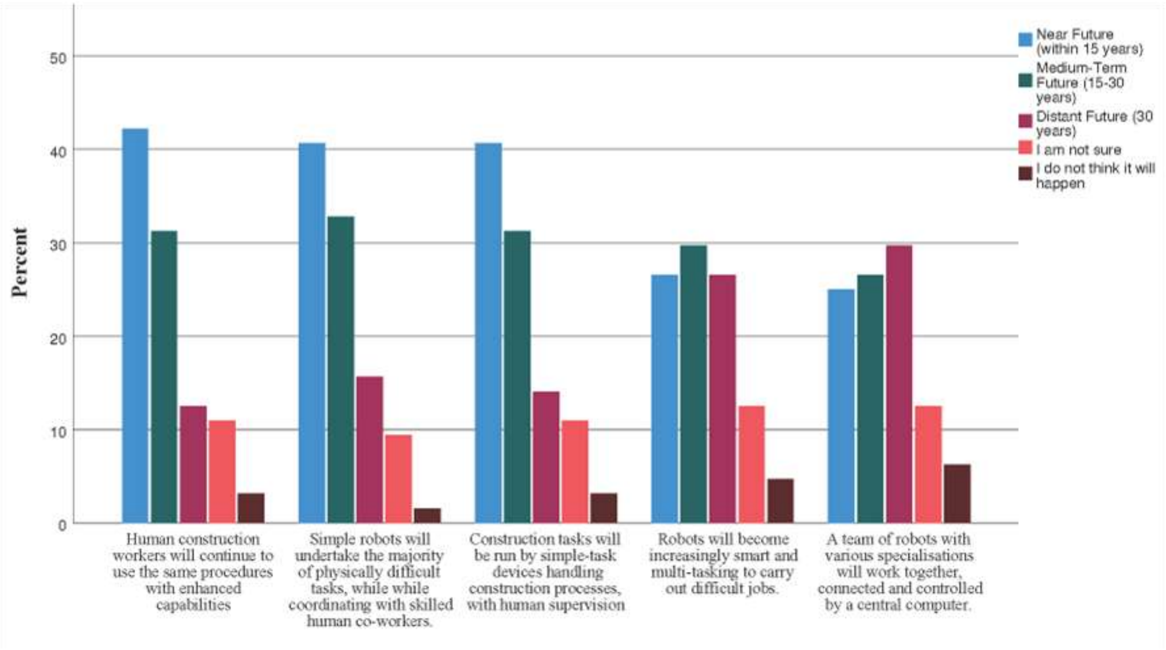

Fig 3.4 Comparison of timeframes for construction site evolution with the adoption of robotic fabrication (Author's Construct, 2022

Tasking robotic machinery with physically difficult tasks, whiles being coordinated by human co-workers is deemed as the most immediate and feasible application of robotics in construction. The need to reduce the safety hazards on site is a leading factor in the development of robotic machinery with the optimal loading capability to ease the pressures of human construction labour. Concerns of workers are addressed with the improvements in wearable exoskeletons to aid in the regular construction works but with enhanced capabilities.

3.5 Strategies to implement Robotic Fabrication in Architecture education.

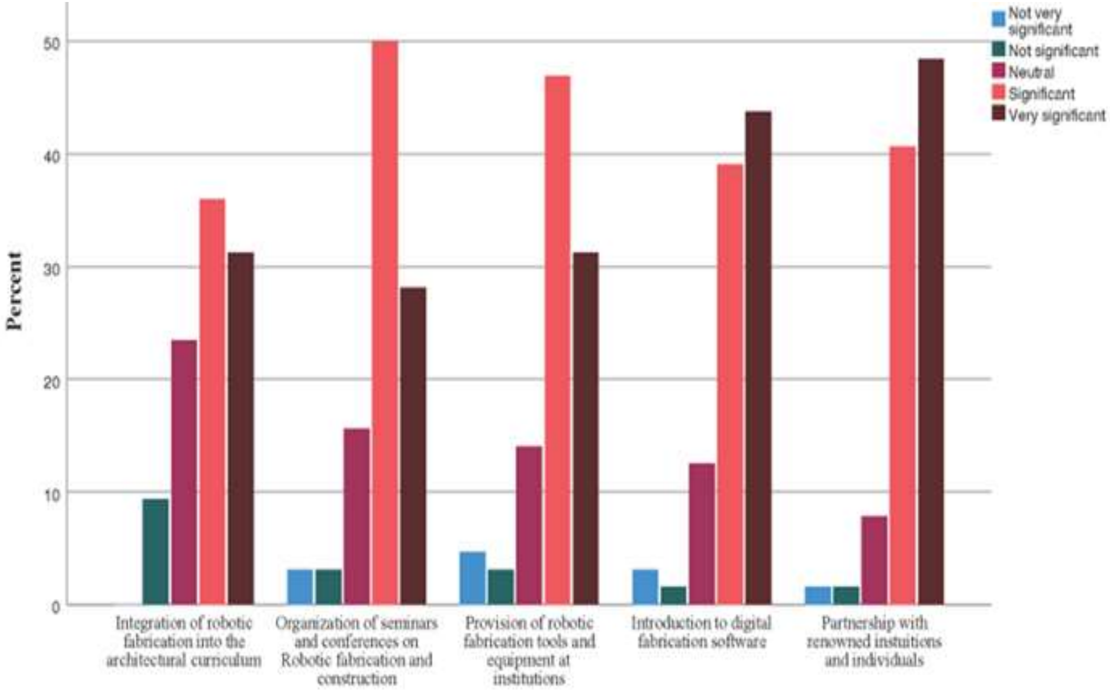

Fig 3.5 Strategies to implement Robotic Fabrication in Architecture education

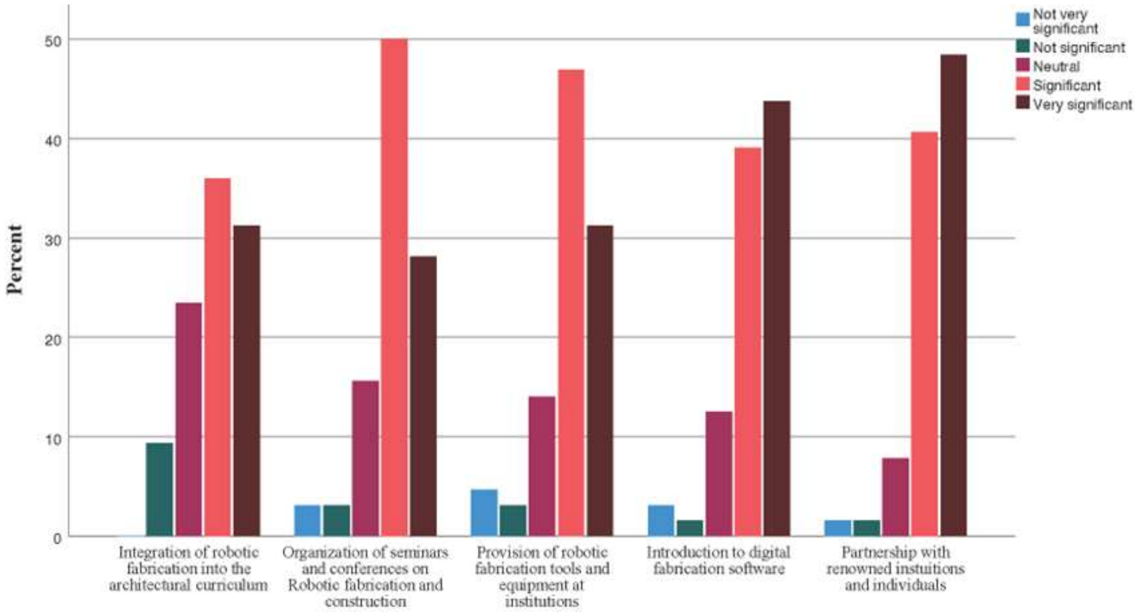

Fig 3.6 Comparison of the significance of the various strategies to implement Robotic Fabrication in Architecture Pedagogy (Author's Construct, 2022)

All respondents assented that the introduction and integration of robotic technology into conventional building methods is practical. The feasibility of this integration is being influenced by the advanced use and investment in robotics in many other fields of production and also, increasing levels of complications in construction detailing. The respondents further explained that to adopt robotic fabrication measures to in-situ construction, all construction stakeholders are to be included in decision-making, to identify potential work areas for effective and efficient implementation. According to Figure 11, the speed and cost of construction and the precision of construction to design specifications were the most influential issues driving the evolution of on-site construction works. The effects of construction on climate, increasing level of unemployment, the emergence of the internet and technological advancements are also among the significant issues, defining the shift in traditional construction

Fig 3.7 Issues influencing the shift in Conventional construction processes (Author's Construct, 2022

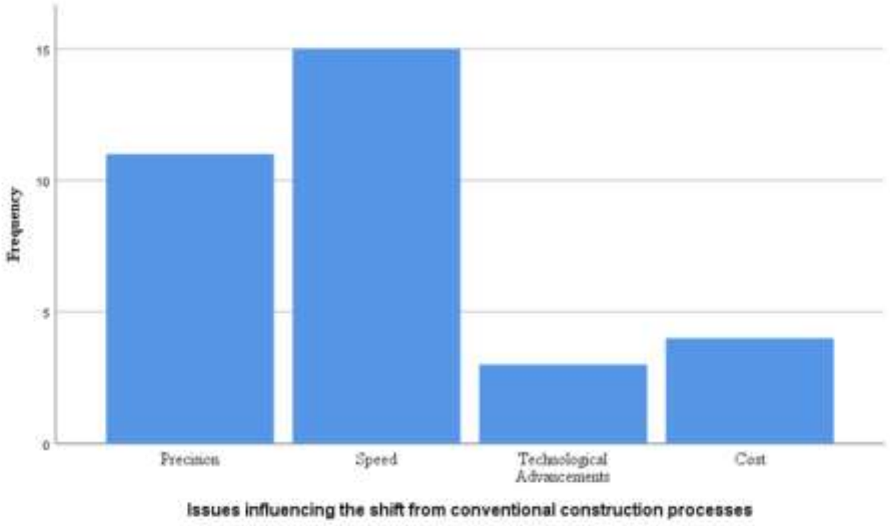

Fig 3.7 Issues influencing the shift in Conventional construction processes (Author's Construct, 2022

The adoption of robotics is viewed to greatly reduce the cost of construction and increase efficiency on site. Additionally, the accuracy and quality of works are expected to improve with the involvement of robotic fabrication in the fine detailing and construction designs, shown in Figure 3.7

Fig 3.8 : Merits of adopting Robotic Fabrication (Author's Construct, 2022

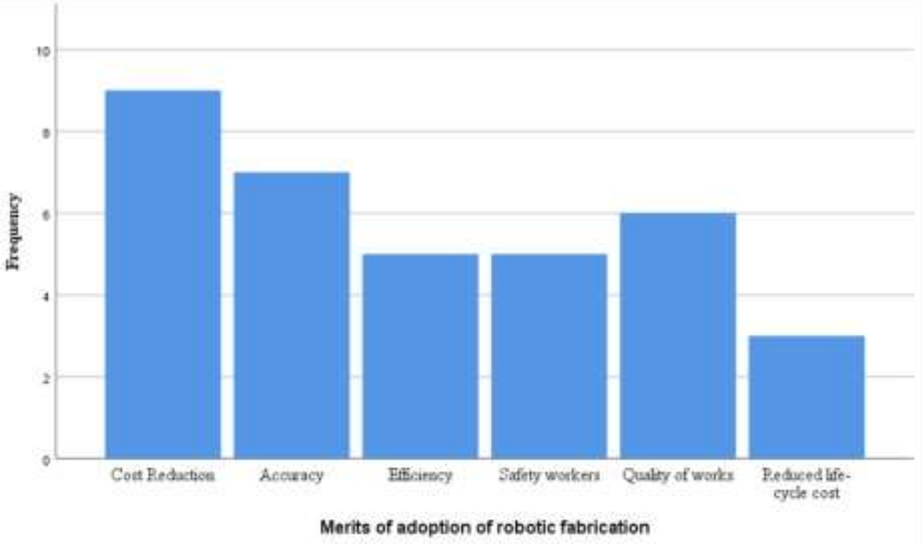

Fig 3.8 : Merits of adopting Robotic Fabrication (Author's Construct, 2022)

Remote handling of dangerous and tedious tasks by robotic elements is also expected to increase the safety of construction workers on site. The respondent further claimed that robotic fabrication will be critical to the reduction of the life-cycle cost of building construction. Other merits mentioned were the standardization of building elements, enhanced aesthetics of a project and potential job creation and sustenance within the construction industry. Three of the respondents stated their firms were not willing to invest, mainly because of the high initial cost of investment and lack of the logistics to facilitate the shift from conventional processes. The remainder of the respondents stated that they were willing to make some investments in the technology. However, their willingness to invest was dependent on certain factors that we mentioned. These factors include; cost-effectiveness and return on investments, logistical capacity of the firms, partial application in selected job areas and the type of projects handled by the firm.

With the high initial cost of investment as a major barrier to its implementation, the majority of respondents see the introduction of a tax relief facility on imports of robotic fabrication machinery as the most critical incentive for industry players and construction stakeholders to integrate robotic fabrication in the works. Furthermore, the introduction of awards and certification of buildings and firms implementing robotic fabrication components within their workflow would incentivize firms to begin to include such methods. In the bidding / competitive tendering stages of a project, advantages can also be given to companies that involve robotic fabrication as a part of a sustainable procurement method. Introduction of government legislature, access to loans and subsidizing the training cost of construction personnel are also measures assessed as potential incentives for the industry.

(1)

4. Conclusion and Recommendation

The various developments in robotic fabrication technology for in-situ construction include stationary robotic systems, mobile robotic systems (Hadrian X by Fastbrick, MIT Media Lab's DCP, In-Situ Fabricator by ETH Zurich) and short-range mobile robotic systems such as the Harvard TERMES project. From the findings of the survey, it was realized that the majority of participants were willing to invest. However, the level of willingness was mainly based on the logistical and economic capacities of the firms and the types of construction works undertaken.

To facilitate the effortless adoption and integration of robotic fabrication into in-situ construction processes, the following recommendations were from interactions and brainstorming with the study participants.

Firstly, there is a need to introduce robotic fabrication into the architectural curriculum at an early stage. This includes the integration of introductory courses in construction technology and architectural sciences programmes and the facilitation of digital fabrication practices with the creation of fabrication labs in educational institutions.

Moreover, there should be establishments of partnerships between renowned institutions, industry professionals and educational facilities. This will promote the retraining and retooling of design and construction workers, as well as students.

Lastly, there is a need for awareness creation and sensitization of construction stakeholders. The facilitation of tax reliefs on imports of robotic fabrication machinery, and the introduction of awards and certification of firms and buildings implementing robotic fabrication are significant measures that can promote the adoption of robotic fabrication in in-situ construction.

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