ASSESSING THE EFFECTIVITY OF ADDITIVE MANUFACTURING TECHNIQUES FOR THE PRODUCTION OF BUILDING COMPONENTS

Implementing innovation for housing construction in Saudi Arabia

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Abstract. This paper examines the suitability of existing robotic technologies and large-scale 3D printing techniques for the fabrication of three-dimensional printed building components to be applied in the Saudi housing construction industry. The paper assesses a series of cases based on the applications for 3D-printing cement-based materials in construction. In particular, we investigate five different additive manufacturing techniques and evaluate their performance in terms of their flexibility/mechanism, control/navigation, calibration/operation system, fabrication suitability (in-situ or off-site), size of printed components, printing speed. The findings include in a matrix chart, where the advantages and disadvantages of each technique become evident. The paper further evaluates the suitability of each technique in relation to the particular climatical and sociopolitical context of Saudi Arabia, applicable to other construction industries with similar conditions.

Keywords: *Building Technologies; Additive Manufacturing of Concrete; Housing Construction; 3D Printing*.

ملخص. هذه الورقة تبحث مدى ملاءمة تقنيات الطباعة الثلاثية الأبعاد للمباني لاستخدامها في إنشاء المباني السكنية بالمملكة العربية السعودية. تم إجراء الدراسة بناء على تقييم وتحليل لأفضل ممارسات الطباعة ثلاثية الأبعاد التي تستخدم مادة الخرسانة بشكل أساسي في عملية الطباعة. تحديداً، قمنا بتحليل خمس تقنيات طباعة ثلاثية أبعاد وتقييم أداءها بناء على هذه المعايير: المدى الحركي لأداة الطباعة، وكيفية التحكم، و معايرة نظام التشغيل، وسهولة الاستخدام في موقع البناء، و حجم العنصر المطبوع، وسرعة الطباعة. تم تلخيص مخرجات الورقة في جدول يقارن أهم المميزات والتحديات لكل تقنية على حداً. بالإضافة إلى ما تم

ذكره، المخرج النهائي من هذه الورقة سيساهم في تقديم نظرة شاملة لمدى إمكانية استخدام تقنيات الطباعة الثلاثية الأبعاد في المملكة العربية السعودية، مع الأخذ في الاعتبار الأجواء المناخية الحارة والجهود الحكومية لتطوير قطاع الاسكان ضمن رؤية المملكة 2030، علماً أنه من الممكن الاستفادة من مخرجات هذه الورقة في أسواق بناء أخرى مماثلة للملكة من حيث الدعم الحكومي والأجواء المناخية.

الكلمات المفتاحية: *الطباعة الثلاثية الأبعاد للمباني- صناعة البناء- الإسكان- تقنيات البناء.*

1. Introduction

The discovery of oil in 1938 was a significant catalyst for transforming the Kingdom of Saudi Arabia. In the 1970s, the massive profits from selling oil enabled the government to subsidise the development of infrastructure throughout several industries, including electricity, transportation, telecommunication and water. Later, the subsidisation expanded towards other essential sectors in the country such as education, health and wellness, military, and the creation of petroleum-based industry. Accordingly, the construction industry started to play a vital role in contributing to the country’s rapid development and is currently the second biggest industry, aside from the oil.

In 2016, Saudi Arabia launched an economic and socio-political restructuring plan in 2016 under the title ‘Vision 2030’ (Government of Saudi Arabia, 2016). The future vision aims to diversify the Saudi economy and society by modernising the country and ending its long-term dependency on oil. The distinct socio-economic challenges include the rapid population growth of 2%, unemployed citizens, and the decrease of global demand on oil (Roll, 2019). The Ministry of Housing has stated that there is an urgent need to build millions of residential units within five years aiming to match the Vision 2030 target of an increase in homeownership from 24% to 52% by 2030 (Saudi Ministry of Housing, 2016).

Besides, governmental decision-makers have started exploring a new strategic plan to meet high housing demand. Part of this plan is focusing on novel construction technologies. Hence, the Ministry of Housing has started an initiative called ‘Building Technology Stimulus Initiative (BTSI)’. BTSI aims to transform the construction market by utilising a feasible, intelligent, and sustainable building system. It also seeks to cope with the Fourth Industrial Revolution by attracting the best practice of additive manufacturing and robotic technologies in the market through a subsidisation programme. Thus, it is essential to explore the best practice of existing construction technologies and then assess their suitability to be implemented within the Kingdom’s current construction standards. To the best of our knowledge, the results of implementing these technologies in the

Saudi construction market has not been evaluated to be implemented based on the Saudi Building Code.

Furthermore, after studying the different factors of which the Saudi housing crisis is composed of, it became evident that the construction sector lacks productivity, is short of labour, and the average construction quality is relatively low. This indicates that the current construction typology and method of load-bearing, in situ, reinforced concrete frame, is inefficient to meet the aim of the Saudi Vision 2030 (Theodore Karasik, 2017). It is linked to high material waste, is very time-consuming, and requires intensive labour.

Another vital issue is the deficiency of industrial standardisation for housing construction. Precast construction is applied for commercial projects mostly. Most of the existing precast facilities are dedicated to the construction of megaprojects. Besides, precast components are lacking customisation, which makes them being disregarded by the local citizens. Besides, the cost of creating precast moulds, for mass customisation propose, in addition to the high transportation cost, makes prefabricated houses unaffordable. The average Saudi home buyers prefer to live in a customised house, based on their individual needs.

Finally, the labour force shortage is another significant impact factor to the country's construction industry, causing construction delays, a challenge identified by different Saudi researchers (Alqahtany and Mohanna, 2019). Indeed, foreign construction workers represent the majority in the housing construction industry. In 2017, about 796,000 ex-pat workers left the Saudi labour market, 221,000 of them left during the first quarter (Bridge, 2018).

Consequently, we are looking for additive manufacturing techniques able to operate with reinforced concrete as specified by the Saudi Code of Construction (SBC 304), are easy to transport, can operate in small construction sites, can be protected by the harsh weather conditions, e.g. by being contained indoors and are reliable in their performance, quality and fabrication speed.

We believe that construction time, cost, and quality can be improved by integrating robotic fabrication in the construction process. Our research focuses on the use of robotics and additive manufacturing technologies in comparison to conventional methods using formwork to cast the reinforced concrete. We aim to highlight potential solutions for Saudi Arabia's housing construction industry by conducting comparative analysis and assessing the suitability of currently available methods and techniques of 3D printing and additive manufacturing technologies for the Saudi construction market. Thus, the following research questions will be addressed:

• What large-scale additive manufacturing technologies are available, and how can they be used in housing construction?

• What is the most effective way of implementing additive manufacturing technology in housing construction?

• What construction materials and restrictions must be taken into account to achieve an appropriate design within the Saudi climatic/socio-political context?

2. Methodology

To answer our research questions, we will analyse seven distinctive case studies to provide a comprehensive overview of existing additive manufacturing/3D printing processes in the construction industry and examine their suitability for the Saudi context. All case studies explore different tools and techniques. However, they all share the same principle of implementing additive manufacturing to fabricate large-scale building components. The selection of the following additive manufacturing techniques is based on cementation-based extrusion.

In particular, we have categorised the selected case studies based on their additive manufacturing technique and applied technology in the following categories: (1) mobile robotic arm 3D printing; (2) static robotic arm 3D printing system; (3) gantry-based 3D printing system; (4) customised robotic printing (5); and swarm robotic 3D printing.

We will then conduct a comparative analysis of this case studies focusing on the following evaluation criteria: (a) flexibility/ mechanism, (b) control/ navigation, (c) calibration/operation system, (d) fabrication suitability (in-situ or off-site), (e) size of printed components, (f) printing speed.

Indicating the key challenges influencing each type of classified techniques is one of the key findings in this paper. An insightful discussion of the presented case studies will be provided through exploring issues affecting the practical use of 3D printing in-situ and in-factory.

We aim to provide a guideline for the possible challenges when it comes to practice by presenting the advantages/disadvantages of each 3D printing technique examined here. These critical findings are summarised in a matrix, offered to help future research by providing essential criteria to evaluate each technology. The paper concludes with the effectiveness of concrete 3D printing technology and the role it could play in the Saudi Housing Vision 2030 as well as to inspire future research in this field.

3. Case Studies

3.1. CASE STUDY 1: 3D STUDIO 2030 BY CYBE IN SAUDI ARABIA

This case study demonstrates the process of in-situ 3D printed concrete components using a mobile robotic arm, which was installed on a caterpillar. The fabrication was performed in a controlled environment. The 48 printed components consist of 27 walls and 21 parapets. Steel reinforcement grouted manually to the printed elements (***Figure 1***). The construction of the project was completed within one week, which became a showcase for several 3D printed houses as set by the Saudi Ministry of Housing.

Figure 1. Showcase for Studio 2030 by CyBe in Saudi Arabia

3.2. CASE STUDY 2: DUBAI MUNICIPALITY BUILDING BY APIS COR

This case study verifies the applicability of implementing in-situ concrete 3D printing using a developed 3D concrete printing robot. However, the steel reinforcement has been embedded conventionally (***Figure 2***). This is building considered to be the largest 3D printed building in the world. The building contains two floors, the area of which is 640 square meters, with a total height of 9.5 meters (Block, 2019). This case study has proved the productivity of additive manufacturing technology to be implemented in an arid climate without any insulation for the printing robot.

Figure 2. One can see reinforcement embedded conventionally in Dubai Municipality Building

3.3. CASE STUDY 3: APARTMENTS BUILDING IN SHANGHAI WINSUN COMPANY

This case study presents a 6-story building, which was 3D printed using a gantry-based system. It is considered to be the tallest 3D printed concrete building. The Chinese based company used recycled construction waste as a filament, which was extruded by a 150 meters long printer (***Figure 3***) (Perry, 2015). The utilisation of the gantry-based system is like a production line in a factory. The gantry printer can move in three-axis.

Figure 3. Winsun 6-Story tall 3D printed building

3.4. CASE STUDY 4: THE BOD BY COBOD IN COPENHAGEN

This case study presents the first 3D-printed building in Europe. The name BOD refers to "Building on Demand". This building is a small office unit, built on 50 square meters in Copenhagen (***Figure 4***) (3Dprinthuset.dk, 2017). The aim of constructing this building is to prove that 3D printing technology can be applied in line with the Danish Construction Code. The size of the gantry printer used in this experiment is 8 m × 8 m × 6 m, it can print a component with a thickness 20mm and width of 50-70 mm for each layer, with a speed of 2.5 meters/minute. The used concrete was made out of recycled tiles and sand.

Figure 4. First 3D concrete printed building in Europe by COBOD

3.5. CASE STUDY 5: CONPRINT3D BY TU DRESDEN

This case study presents a novel approach of using a mobile concrete pump as a 3D concrete printer for in-situ construction (***Figure 5***). Researchers in this project have explored a similar concrete 3D printing approach exploring both for in-site and off-site fabrication. They distinguished their unique method from others by developing the CONPrint3D printing nozzle for conventional construction with leaner walls and sharp corners. This approach is making the most of the available equipment by upgrading mobile concrete pumps to 3D printers, which means the cost of the concrete 3D printer could be decreased. The upgraded machinery can work with the existing, standard concrete composition, with a maximum aggregate size of 8mm, that can be used with the developed printing-head without affecting the concrete flow. The CONPrint3D printing nozzle can make surfaces with precise quality and tolerances (Mechtcherine et al., 2019). The printer was tested in a controlled environment to fabricate a floor of approximately 130 square meters, with a printing speed of 150 mm/s, and the height of the printed layer is 5 mm.

Figure 5. A mobile concrete pump used as a concrete 3D printer

3.6. CASE STUDY 6: LARGE-SCALE 3D PRINTING BY A TEAM OF MOBILE ROBOTS BY THE SINGAPORE CENTRE FOR 3D PRINTING

This case study describes a 3D printed wall by two mobile robots, which were programmed to work collaboratively (***Figure 6***). This was made possible through Simultaneous Localisation and Mapping (SLAM) and motion planning (Zhang et al., 2018). The advantage of SLAM-based navigation and motion planning is the robots can configure their surrounding environment, by moving around with an attached camera and sensor. They can draw a map for the site as well as avoid any site collision between them (Cadena et al., 2016).

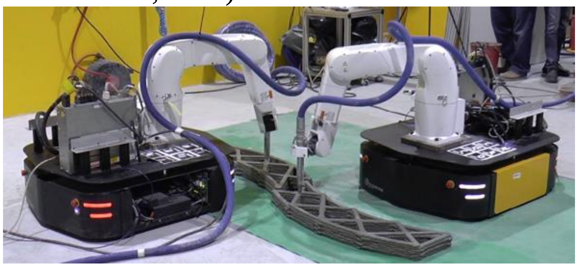

Figure 6. Swarm robotic experiment by the Singapore Centre for 3D Printing

3.7. CASE STUDY 7: MINIBUILDERS BY IAAC

The MiniBuilders project offers another method of concrete 3D printing with the use of three miniature robots with a different degree of mobility within the system (***Figure 7***). The robots were programmed via a multi-agent system. Each robot has a specific functionality. Following a pre-designed path, the first robot prints a concrete foundation with the use of a sensor (IAAC, 2013). By positioning itself on the foundation, the second robot securely holds onto the foundation with rollers and can print the walls by layers of concrete. The final robot prints the finishing vertically onto the structure with the use of suction cups and pressured air, adding reinforcement to the printed structure.

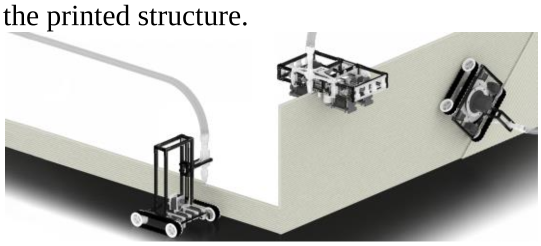

Figure 7. MiniBuilders developed by IAAC

4. Findings

After analysing the case studies mentioned above, we will now proceed to the comparison based on the following criteria: (a) flexibility/ mechanism, (b) control/ navigation, (c) calibration/operation system, (d) fabrication suitability (in-situ or off-site), (e) size of printed components, and (f) printing speed.

Studio 2030’s case study 1 is not just demonstrating the ability to implement concrete 3D printing for in-situ construction but contains other knowhow on the installation of other building components such as the floor tiles, a prefabricated roof, the windows, the mechanical and electrical system, the plumping as well as about providing thermal comfort with good indoor air quality. The operation of the printing process requires advance training for the operators.

The implementation of the Dubai Municipality building mentioned in case study 2 has proved its suitability for in-situ 3D printing in an arid climate without providing a controlled environment for the robotic-printer. However, the printing was performed during the winter season. It is vital to conduct further investigation, especially during the summer, to validate its suitability for a warmer climate.

Overall, mobile and static robotic arms are similar in terms of extruding material, calibration and printing time. Both of which are capable of printing in 3-axis, 4-axis, 5-axis, 6-axis, and 7-axis. They can 3D print various materials, such as concrete, plastic, or steel. However, when it comes to flexible mobility and the size/length of printed components, mobile robotic systems are clearly in the advantage.

Three-dimensional printing has proved its efficiency to construct multi-story buildings as presented in the apartment building in Shanghai by the Winsun compony in case study 3. Winsun has successfully developed the refinement of vernacular building construction. However, studying the building’s life cycle is vital, as there is no sufficient consideration for the long-term assessment.

Furthermore, the experiment conducted by the Danish company COBOD demonstrated in case study 4 has proven its capability to 3D printing curved buildings. It also proved its efficiency to construct buildings in a shorter time, with less workforce, with the use of environmentally friendly materials as well as its ability to minimise construction waste, which represents approximately 2 million tons annually in Denmark (3Dprinthuset.dk, 2017). Correspondingly, the showcase fulfils EU Construction Standards for 3D printing and automation in construction. The experiment does not address the obstacles of 3D printing concrete in-situ, nor a benchmark for the cost-efficiency of printing conventional walls versus curvature walls.

Without a doubt, the gantry-based system has the advantage of printing the whole building in one go. Nevertheless, the limitations of the printer size have a significant effect on architectural design. In other words, the floor area and the height of the building should fit with the printer size. However, the calibration of the gantry-based system is easier than the mobile or static robot due to the limitations of movement in just 3-axis XYZ.

Transforming an existing mobile concrete pump into a 3D printer for in-situ construction will increase the future utilisation of additive manufacturing technologies in construction. The digital chain demonstrated in case study 5 by CONPrint has a promising future for the design-to-fabrication approach. Although the innovative CONPrint3D nozzle was tested to 3D print a floor of a house, the experiment conducted in a lab environment, it will be a challenge to migrate the proposed technology to a construction site without considering climatic, architectural, and engineering factors. It is essential to examine the entire proposed system, transformed mobile concrete pump and the nozzle, in a construction site. The site experiments should include structural analysis of the proposed construction system.

The combination of different disruptive technologies such as artificial intelligence, mechatronics, and architecture will significantly transform the construction industry in the near future. In case study 6 and 7, the concept of utilising swarm robotics opens new opportunities for the construction industry by implementing new, multidisciplinary technologies. Although the swarm robotics technology in case study 6 has proven its ability to print a component in a short time, further investigation regarding the component's structural performance is needed. As shown in Figure 6, the two robots successfully printed a concrete structure, but a clear segregation line appeared. The joints between the printed components need to be examined. Furthermore, the calibration and implementation of swarm robotics require advanced programming skills.

The findings of our comparative analysis have been summarised in the chart illustrated in ***Figure 8.*** **Categorisation and analysis of different existing additive manufacturing techniques**, which highlights the different robotic/additive manufacturing technologies and their properties/possibilities.

Parameters	1. Mobile Robotic Arm	2. Static Robotic Arm	3. Gantry-Based System		4. Customised Robotic	5. Swarm Robotic	
System illustration							
Project	case study 1	case study 2	case study 3	case study 4	case study 5	case study 6	case study 7
	3D STUDIO 2030	DUBAI MUNICIPALITY	APARTMENTS BUILDING IN SHANGHAI	THE BOD	CONPRINT3D	LARGE-SCALE 3D PRINTING BY A TEAM OF MOBILE ROBOTS	MINIBUILDERS
Research Lab/ Company	CyBe construction company	Apis Cor	Winsun Company	COBOD company	TU Dresden	Singapore Centre for 3D Printing	IAAC
Flexibility/ Mechanism	6 axis robotic arm positioned on a caterpillar	3-axis (Apis Cor), and can be 4-5-6 or 7-axis	4 axis		Mobile concrete pump	Two medium-size mobile robotic arms	Three small-size swarm robots developed by IAAC
Control/ Navigation	Manipulator and motion sensor	Manipulator and motion sensor	Toolpath based on a slicer software		(N/A)	Sensor and camera using machine learning	1st robot has a sensor follows a designated path on the ground; 2nd robot climbs and rolls on the printed foundation; 3rd robot has a vacuum generator
Calibration/ Operation system	Firmware used to control robotic arms; the robotic arm has a motion sensor or a camera to perform an accurate movement for a dedicated task given through G-code		The gantry-based system is similar to a production line based-system, the instructions is given through G-code generated from a slicing software		Digital process chain starts with a BIM geometry model	Simultaneous Localization and Mapping (SLAM) and motion planning	Multi-agent system
Fabrication suitability (in-situ or off-site)	in-situ fabrication	in-situ fabrication	off-situ and in-situ fabrication	in-situ	In-situ, but the experiment for printing a floor plan was conducted in lab	In-lab fabrication	In-situ fabrication using three mini-robots collaboratively
Size of printed components	Layer height is 30 mm; printing rang up to 2.75 m; and a maximum height of 4.5 m	(N/A)	(N/A)	The largest gantry size is (L 40 x W 10 x H 6.6 m)	130 m^2 within one day; layer height 5mm	Medium-scale 3D printed concrete pattern (1.86 x 0.46 x 0.13 m)	1.5m high at the Design Museum of Barcelona (Dhub)
Printing speed	200 mm/s	(N/A)	(N/A)	Max 100 cm/sec ; Average 40-50 cm/sec	150 mm/s	7 min 50 s for (1.86 x 0.46 x 0.13 m) in	(N/A)

Figure 8. Categorisation and analysis of different existing additive manufacturing techniques

5. Conclusion

Based on the comparative analysis matrix shown in ***Figure 8***, it becomes evident that mobile and static robotic arm technology can become an ultimate game-changer for the construction industry in Saudi Arabia. Overall, printing building components with robotics-based printers will not only increase the production efficiency of construction, but it will also attempt to overcome the customisation challenge necessitated for individuals in Saudi Arabia, which the centralised precast manufacturing failed to achieve. Admittedly, there are several challenges related to implementing robotic printing in the construction sector. In this paper, the most obvious challenge is operating robotics for in-situ fabrication. It would be difficult to manage the printing of the housing components during summer season without working in a controlled environment due to the high temperature and dust, which are very typical in Saudi Arabia. Moreover, the properties of the printing materials will significantly affect the architectural design. However, these challenges will pave the way for a novel construction system which could be embedded within the current Saudi Building Code.

In that context, we are proposing a mobile mini-factory fabrication unit which will be developed further in the next phases of our research (***Figure 9***). The inspiration of the mobile printing unit came from the R-O-B unit developed by Gramazio and Kohler in 2008 for bricks laying (Gramazio Kohler Research, 2008). Our system will be utilised in a shipping container as a mini-factory unit for in-situ fabrication. This mobile unit aims to solve the issues mentioned at the beginning of this paper by mitigating the transportation cost, reducing labour in the construction site, and increasing the production quality and efficiency. The proposed file to factory workflow is based on algorithm-aided design, allowing users to adjust the required parameters based on their individual needs. The final design can be converted into Gcode as a tool path for the robotic arm, starting with the building layout. This approach offers the integration of design and fabrication into one single process.

Figure 9. Mobile mini factory unit in a shipping container

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