Applying 3D Printing as a New Building Technology: Potentials and Challenges in the Egyptian Context

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1 ABSTRACT

In the context of the Fourth Industrial Revolution, the world of architecture and construction is being changed by new technologies with opportunities and limitations. Large-scale 3D printing (3DP) technology has recently been introduced as a new building technology to improve productivity and quality. Recently, worldwide stakeholders started experimenting with the technology substitute of traditional. This is due to achieve potentials benefits, such as increased accuracy, customisation, and design flexibility. Additionally, it reduces wasted material, costs, manpower, and printing time. However, these initial investigations are very fragmented at the time of the study. There are different views on where technology can be directed and a large gap between ideas and their applications. 3D printers will be used primarily to print buildings for low-income housing and emergency housing in developing countries such as Egypt, while most of the buildings that have been built were executed in developed countries. Therefore, it is necessary to understand the international applications and challenges of 3D printing. This paper was set out to give insight into applying 3D printing as a new building technology on an international scale and assessing the applicability potentials and challenges in the Egyptian context; through 1. gathering and analysis of documents and references of opportunities and limitations of 3D printing factors(design, environmental, social, and economical); 2. qualitative data analysis.The descriptive study of international examples outlines the factors used to assess the international examples with anassessment matrix and analysethem within the Egyptian context. It shows that projects divide internationally into projects which invest in optimising the performance and others which are optimising the production according to different characterisations. There are greatpotentials of using 3D printing in Egypt, but it needs to be adapted to numerous challenges in achievingits maximum potential.

Keywords: 3D Printing, Building technology, Architecture, construction, Egyptian context.

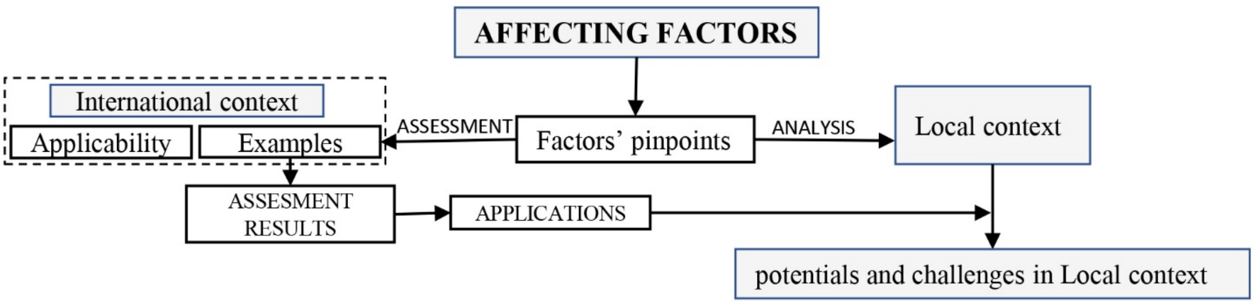

Fig 1The research flowchart

2 INTRODUCTION

The world is confronted with many challenges that have the potential to impact the well-being of societies severely. Climate change, rapid urbanisation, and the digital revolution are among the most pressing of these challenges(Renz et al., 2016). The creation of sustainable, cheap, durable, customisable, recyclable, and even environmentally reparable houses is a critical focus of recent research.The new wave of marketneedsduring the current crisis requiresasustainable economic approach to saving energy which will reduce the cost of housing and improve the quality of continuous production(Wu & Wang, 2016). Regarding the many social issues that must be considered. Fear of job loss is the main problem (De Schutter et al., 2018).

The construction sector plays a key role in any country's economy. According to a report published by the World Economic Forum, the construction industry currently accountsfor 6.2% of Egypt's GDP,and a 1 % increase in productivity around the world could save a lot in construction costs (Forum, 2018). "The promise of large-scale 3D printing (3DP) is that it can collapse these limitations, which is a fundamental shift in the relationship between architecture, construction, and manufacturing"(Hager, Golonka, & Putanowicz, 2016).

In Egypt, the traditional and most common way of building is witha load-bearing structure and a skeleton framework which requires transport of heavy materials (bricks, cement, sand, and aggregate) to the construction site where on-site wall construction is done with mixed concrete components and manual bricklaying. This approach results in the use of a large number of workers, a lengthy procedure, a high percentage of errors, waste of materials, unnecessary expense, and CO2 emissions resulting from long-distance transportation.

3 AFFECTING FACTORS IN APPLYING 3D PRINTING

3DP technology offers many opportunities for architecture and the construction sector, but also has limitations which determine its actual implementation in many aspects, concerning design, environmental, social and economic factors (Ma, Wang, & Ju, 2018; SKÖLD & VIDARSSON, 2015; Yeh & Chen, 2018).

	Opportunities	Limitations
Design-Related Factors	Production of specialised moulds (Camacho et al., 2018).	Conventional design approaches are not suitable for printing.
	3D printing technology will push design to change(SKÖLD & VIDARSSON, 2015).	The size of the built object is limited by a gantry or cable-suspended approaches
	It can also help build "smart structures" which include various properties(Camacho et al., 2018).	The building elements, doors windows, pipe systems, wires, and horizontal components were prefabricated and considered to reduce the absolute free flexibility in mass customisation.
	Complex geometries without a tool and less waste material(Camacho et al., 2018).	
	Improving the quality and reliability of elements by eliminating human errors.	Buildings today are limited to producing concrete-based load-bearing components.
Environmental-Related Factors	Some benefits of this technology can helpin adapt and mitigate climate change (Ding, 2008).	Limitation in material flexibility means that only specific material can move through a machine and can still be used in the desired manner without damaging or deforming the specific machine (Perkins & Skitmore, 2015).
	3D printing uses a significantly smaller amount of building materials than conventional buildings.	
	Reducing formwork, and waste material, (Camacho et al., 2018).	
	Decreasing the use of raw materials and removal and recycling from sites(De Schutter et al., 2018).	
	Using reused or recycled or rapidly renewable materials (De Laubier, Wunder, Witthöft, & Rothballer, 2018).	
	Decreases the emission rate of CO2 (De Schutter et al., 2018).	
	3D printing works on electricity and saving large quantities of fuel (Perkins & Skitmore, 2015).	
Social-Related Factors	Reduce the demand for professional craft while opening up new possibilities for the workforce with various skills (Camacho et al., 2018).	One great fear of a rise in the concept of automation is that workers will lose their jobs (De Schutter et al., 2018).
	Reducing exposure to harsh environments, reducing accident rates (Camacho et al., 2018).	Deal with many organisational and managerial obstacles (Yeh & Chen, 2018).
	Add more specialised suppliers (changing in the supply chain) (SKÖLD & VIDARSSON, 2015).	Directly influence already existing customers and suppliers (SKÖLD & VIDARSSON, 2015).
	For customers, 3DP. Allows end-users to adapt their house design to their own needs.	The adoption of 3DP. Was hampered by bureaucratic factors (De Laubier et al., 2018).
	For a new generation, completely new jobs that do not currently exist when they enter employment in the future.	The construction sector is one of the most conservative fields which is slowly changing and adapting with a new technology
Economics-Related Factors	Over the years, the cost of 3DP has decreased considerably (Perkins & Skitmore, 2015).	Economic unattractiveness of expensive automated equipment.
	3DP is cost-effective when it comes to a custom product with a complex form (De Schutter et al., 2018).	The unsuitability of the available automated fabrication technologies for large-scale products.
	3SP can manufacture complex geometries without additional cost (De Schutter et al., 2018).	Requires significant start-up costs and specially trained operators (Perkins & Skitmore, 2015).
	3DP decreases service staff costs (transport, accommodation, taxes, etc.)(Camacho et al., 2018)	The costs of machines arebased on print speed as well as material (Yeh & Chen, 2018).
	There is no waste or waste requiring removal and recycling from building sites (Camacho et al., 2018).	High initial costs for equipment and ongoing maintenance costs (Perkins & Skitmore, 2015).
	Reducing formwork labour costs, temporary moulding, and material costs from 35-60% of the total cost (Camacho et al., 2018).	The building elements, doors, pipe systems, and horizontal components which were prefabricated to fit custom products will increase the cost.
	The system as a whole will be capable of reducing construction costs by close to 30 % (Perkins & Skitmore, 2015).	The software packages would increase the cost (Perkins & Skitmore, 2015).
	Adding additional value (e.g., flexibility and scalability, mass customisation, thermal insulation, materials reduction, and time reduction) at no additional cost. (Camacho et al., 2018; Lim et al., 2012; Perkins & Skitmore, 2015).	In addition, automated systems operating on dirty worksites outdoors would need frequent cleaning and maintenance downtime (Perkins & Skitmore, 2015).

Table 1 Opportunities and limitations of affecting factors.(sources are cited for each point)

4 METHODS

Firstly, analysis and overview of documents for international applicability to determine the spread worldwide; secondly,descriptive study of international examples.

Fig 2 The world map showing international 3DP examples: countries which developed and export technology countries which import technology, develop and adopt it, countries which import technology (Compiled by the authors, sources are cited for each example)

TECLA habitat, Italy	YHNOVA H., France	Winsun projects, China	Residential H., Russia
On-site –2019 WASP	On-site - 2017 Batiprint3d	Off-site - 2014 Winsuns 3DP.	On-Site -2016 3DP.: Apis Cor
Clay (mould) + bio-materials	Polyurethane (mould) + concrete	Concrete with glass fibre	Concrete material
The circular housing model, created using entirely local reusable, recyclable materials moving towards eco-housing, designed to be resilient to any climate and energy-efficient (Chiusoli, 2019).	It improved the energy performance of construction, and with its zero waste, raw materials, and decreased transport, the project's ecological footprint was lowered (Furet, Poullain, & Garnier, 2019).	The highest 3DP building was prefabricated elements and assembled on a site. 10 houses in Shanghai, Winsun reduces the overall construction time by 50% to 70%, labour by 50% to 80%, and materials by 30% to 60% (Hager et al., 2016).	Ease of transporting systems, Only two people are required for operation and material supply, less time just 24 hours minimise human errors, It consumes only 8 kW of power, and The cost of the building is $10,000 (Craveiroa et al., 2019).

1. AMIE, USA	2. DFAB H., Switzerland	3. Grotesque – Switzerland	4. Fluid Morphology, Germany
Off-site -2015 Ornl'sBaam	Off-site 2019 3D Sand P.	From 2013 3D sandstone	Off-site - 2020 3DP Delta Tower
Steel rods + glazed materials	Concrete material	Sandstone material	Polycarbonate material
Many functions of a conventional wall system structure, insulation, moisture barriers, and cladding. This could lead to zero-waste construction, reduced material (Craveiroa et al., 2019).	An 80 m² lightweight concrete floor slab as part of the House, its highly complex structures are as easy to create as a solid block. In addition, time on site was reduced (Redaktion, 2018).	The computer was a partner in design who proposed an endless number of permutations. This highly ornamental structure is designed entirely by algorithms (Dillenburger, 2017).	The facade is divided into panels, each measuring 1 m². While textural waves and bulges create shadows. Thin integrated tubes allow air circulation from one side to the other, ensuring the best ventilation (barandy, 2019).
5. Future Office,UAE	6. Multi-use B., UAE	7. 3DP. Village, Mexico	8. 3DP. House, Saudi Arabia
Off-site 2016 Winsun3DP. (china)	On-site-2019 Apis Cor (USA)	On-site -2017 ICON's 3DP. USA	On-site2018 Cybe (Netherlands)
(SRC), (FRP), and (GRG)	Concrete and gypsum	Cement mixture	Cement mixture
Fully functional building featuring electricity, water, and systems. It took 17 days in China and was shipped and installed in 2 days. It reduced labour costs by 50 % to 80% and construction waste by 30% to 60% (Craveiroa et al., 2019).	Apis Cor developed a gypsum-based material to run through the printer, which was sourced for a local producer. Reduction in labour and, therefore, reduction in cost (Molitch-Hou, 2020).	In a remote area in Mexico, The printer has been created as a solution to minimise homelessness that caters to the ever-changing social housing sector and housing crisis (Grace, 2019).	Invest in advantages in construction sites from Cost and standardisation of quality, waste minimisation, speed of implementation, reduction of work accidents, and the possibility of implementing forms (MinistryofHousing, 2018).

Table 2: selected International Examples (Project name, on-site or off-site, 3d printer name, material, description, and source)

4.1 International Applicability Overview

The analysis of the international spread of 3DP indicates that there are three categories of countries (as shown in figure 1) that deal with 3DP. Firstly, Countries that developed the machine concept, process, and materialsand are exporting 3D, such as the USA,Netherlands,UK, Italy, Switzerland, Russia, Germany, Slovenia, China, France, Denmark, Australia, Spain, and Belgium (barandy, 2019; Camacho et al., 2018; cobod, 2019; Craveiroa, Duartec, Bartoloa, & Bartolod, 2019; De Laubier et al., 2018; Valdivieso, 2019).Secondly, countries which import technology, are adapting it andseeking to invest in other experiences with local requirements such as the Philippines from the USA, Thailand from Italy, UAE from USA(Camacho et al., 2018; Craveiroa et al., 2019; De Laubier et al., 2018).Thirdly, countries which import technology, such as Saudi Arabia from China, Morocco from Spain, Mexico, and El Salvador from the USA, and Malawi from Denmark(3dprint, 2020; De Laubier et al., 2018; Valdivieso, 2019; worldeconomicforum, 2019).

Previous cases show that many countries were involved in developing 3DP technology and materials usedfor it. 3DP technology is capturing increasing international attention in the building technology field. As shown in fig 2, the technology is distributed all over the world, in developed and developing countries.

4.2 InternationalExamples

To date, there have been many experiments in the field of architecture and construction spread across the world, as shown in Fig 2 regarding mainly the construction of whole (small) buildings with materials such as concrete, bioplastic, and clay, also, manufacturing Elements and Details. 12 international Examples were selected to study aspects based on differences in the project approach.

Fig 3 Selected international Examples (Compiled by the Researcher, Sources are cited for each Examples)

5 RESULTS

The results are divided into three sections. Firstly, outlining the key factors based on the analysis of the opportunities and limitations of affecting factors. Secondly, assessing the strength of the factors of each example with an assessment matrix and thirdly, analysing the characteristics of the affecting factors in the Egyptian context.

5.1 Key affecting factors

Outline of the keyfactors derived from the opportunities and limitations of affecting factors in part 3.

Design Related Factors	Environmental Related Factors	Social Related Factors	EconomicsRelated Factors
Design flexibility	Climate change adaptation	Reducing workforce	Initial cost
Structure functionality	Lower resources	Jobs shifting paradigm	Reducing materials cost
Design optimisation	Materials	Safety in extreme environments	Reducing labour cost
Quality issues	Reduced materials	Fewer accidents rate	Cost reducing
	Raw materials	New job opportunities	Unique architecture
	Reused or recycled		Mass customisation
	Decreasing the emission of CO_2		Time-saving
	Less total energy		

Table 3: Affecting factors' pinpoints(by authors derived from part 3)

5.2 Assessment Matrix of Selected Examples

Assessment of the strong points of each example measured by achieving factors at three levels: fully present, partially present, and does not exist as shown in fig 4.

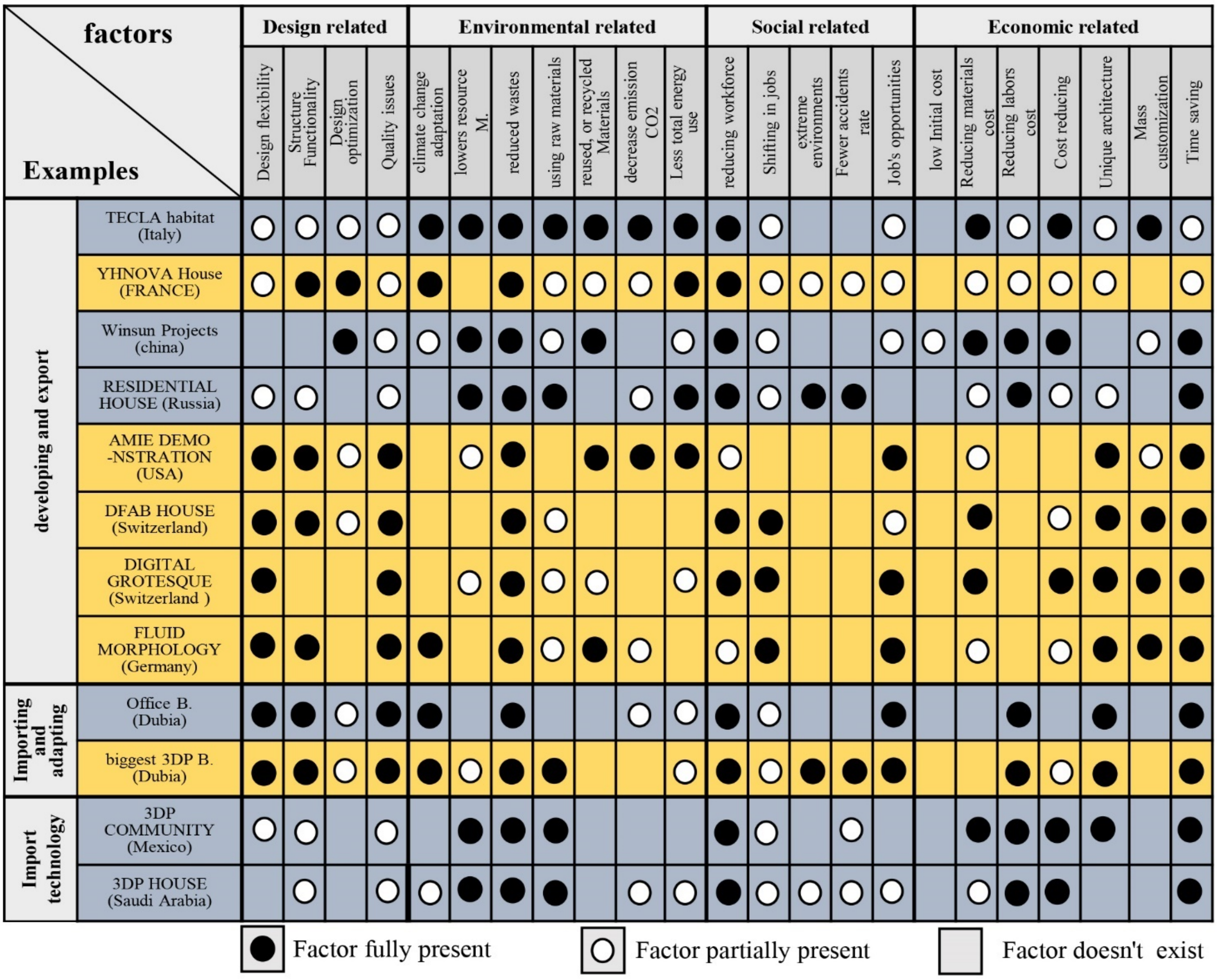

Fig. 4: Assessment matrix for selected international Examples(by authors)

5.3 Analysis of Assessment Matrix

Regarding the strategy of using 3DP, there are two main approaches in the studiedexamples. Optimising the performance, and optimising the production. The former aims to develophigh-performance by analysing the design-related factors and environmental-related factors of printable materials, methods to print unique architecture with structurally optimised shapes; overall,it aimsto achievethe highest possible quality,full customisability both of shape and printed material, and structure functionality. The latter aims at optimising the production, developing technology by considering mainly the economic and environmental-related factors, such as low cost, fast but customised alternativesof traditional construction itwould aim at using local, cheap materials and optimising the construction method in terms of cost and speed. Printing would occur locally (either on- or off-site). Based on the above analysis, the selected examples can be divided into two groups, as shown in table 4.

Examples of Optimising the Performance		Examples of Optimising the Production,	
YHNOVA H., France	Grotesque – Switzerland	TECLA habitat, Italy	Multi-use B., UAE
AMIE, USA	Fluid Morphology, Germany	Winsun projects, China	3DP. Village, Mexico
DFAB H., Switzerland	Future Office, UAE	Residential H., Russia	3DP. House, Saudi Arabia

Table 4: classification of the selected examples(by authors).

The assessment matrix is converted into a visual percentage chart divided into performance and production groups (each group has 6 examples). according to the three levels of assessment: does not exist = 0 X, partially present = 1 X, and fully present = 2 X (whereas X is a fixed number). therefore, every criterionis assessed in 12 X for each group; i.e., the first criterion is the design flexibility in the performance group from the matrix (5 fully present + 1 partially present = 10 X + 1 X = 11 X) therefore, 11 X * 100 / 12 X = 91.7 %, and so on.

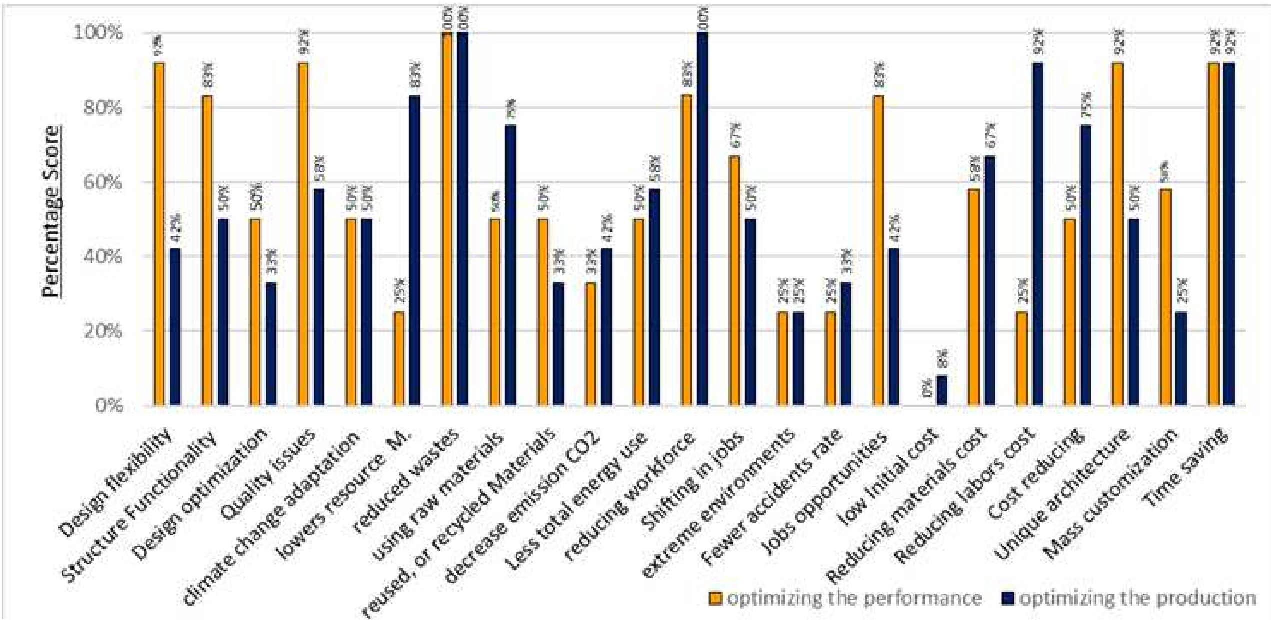

Fig 5: percentage score of assessment criteria in selected examples based on optimizing the performance or the production(by authors).

Although there are still only a few examples around the world, it could be concluded that significant strengthsare found in most of the examples, whether optimising the performance or the production (fig 4): reducing waste in resources and materials, saving time, and reducing the workforce.

The examples of optimising the performance are characterised by:

- Novel forms of design flexibility, a range of customisations and complexity,
- Optimised typology and functionality with high accuracy and quality,
- Developing new applications with new job opportunities,
- Developing a variety of materials, machine layouts, and properties.

On the other hand, the examples of optimising the production are characterised by:

- Mass production buildings by reducing cost and construction time,
- Using in situ resources, reducing material transportation costs and sustainable design solutions,
- Increased accessibility,reduced risks in remote sites and extreme environments.

5.4 Analysis of affecting factors characteristics within the Egyptiancontext

The analysis of the characteristics of the affecting factors within the Egyptian context aimed to determine the potentials and challenges in applying 3D printing in Egypt.

In addition, the construction sector is one of the most conservative fields in Egypt, where building technology development depends on the shareholders who are involved in the current value chain and are avoiding change. Also, regulatory policies have strong technological influences on regulations and building codes. Hampered by bureaucratic factors, integrating new technology into the construction process,which is considered very conservative in changing or development, is very slow. Besides that, there are mainly technological limitations, such as the size of the built object, limited by gantry which determines the options of applicability in Egypt regarding low-rise buildings (ground to ground and two levels), and to the fact that only specific material can move through a 3D printing machine.

		Characteristics of 3DP factors	The case of Egypt
Design-related F.		Design flexibility Pushing design to change and restrictingregular designs.	As a result of the rapid urbanisation in Egypt, architectural design tends to be more practical and economical. While the architectural flexibility of 3DP technology may push designers to pay attention to environmental considerations and heritage styles.
		Structurefunctionality Building "smart structures".	Opportunity for materials technology. Research &development of printable materials developed locally. Such as desert sand, to add new features suitable for this process.
		Design optimisation Producing specialised molds.	Opportunity to provide flexibility in architectural design, which does not require a standardisation of production elements, saving materials and time.
		Quality issues Increase the execution accuracy.	Egypt is at a medium level of quality due to the size and quality of the workforce, but mistakes are increasing the cost due tothe need for corrections.
Environmental-		Climatechange adaptionand mitigation	The new technology supports thermal mitigation such as wall thickness, the amount of air in the wall section
		Fewerresources.	Positive effects to save the natural resources which are the primary source for buildings.
		Reducing material waste.	Material waste of timber frameworks averages 13%, and waste of sand is as high as 9% (Garas, Anis, & El Gammal).
		Using raw, reused materials	Egypt has many local raw materials suitable for construction, such as sand and clay
		Decreases the emission rate of CO2 remarkable.	Egypt produced 310 m tonnes of CO2 greenhouse gas emissions in 2016. Thus any reduction in fuel use will be a positive impact (Hannah Ritchie, 2020).
		Fewerfossil fuel energyto produce electricity.	This is consistent with Egypt's Vision 2030 to use clean energy instead of fossil fuels.
		Characteristics of 3DP factors	The case of Egypt
Social-related F.		Reducing workforce Workers will lose their jobs	This is a threat in Egypt. The construction sector is providing around 3.7 million jobs, representing 20 percent of total workers in the domestic market(according to Planning Minister Hala al-Saeed), although it does not create sustainable or stable jobs, as it is linked to project time (EgyptToday, 2018).
	Jobsshifting	Add more value to the construction phase	It will affect the construction industry, technically, economically, and socially, resulting in the entry of new producers, processors, suppliers, and exporters.
		Changing roles and organisational processes.	Using 3D printing In Egypt shortensmany building processes (e.g., design, coding details, training, manufacturing,and marketing).
		Impact on supply chain	Using new technology will negatively affect the traditional suppliers in Egypt.
		Reducing exposure to harsh environments.	May be useful in difficult worksite conditions in Egypt, such as the extremely hot desert climate.
		Loweraccident rate Safety in the construction sector, fewer accidents	Alarming statistics indicate that the construction industry accounts for 55,000 fatal injuries each year in Egypt and the construction industry has the highest fatalities and death rates among all industries (ElSafty, ElSafty, & Malek, 2012).
		New job opportunities Reducing the demand for the professional craft.	The traditional labour market has a large number of untrained workers (who do not have a job and work in construction), leading to a shortage of skilled workers, but using 3DP would move technical construction jobs to new opportunities of dealing with technology.
Economics-related F.		High Initial Cost The costs of machines, Specially trained operators, The software packages, Special material types.	Printing technology, like anything new, starts expensive, but over time it is getting more affordable. A machine is a one-time investment that should pay for itself over time replacing computing and healthcare costs. However, the machine cost ranges from 80 000 $ to 500 000 $ (Cherdo, 2020), an investment which s the construction market in Egypt would have to bear.
	ls cost	Reducing materials cost (fewer materials are needed).	According to (ECBM),Egypt's exports of building materials, refractory and metallurgy industries was $1.5 billion during the first quarter of 2020, an increase of 32.8 percent, compared to $1.15 billion a year earlier.Research indicates that using printing saves between 30% to 70% in materials, which will positively impact the Egyptian economy (egypttoday, 2020).
		Reducing waste requiring removal and recycling from building sites.	
		Reducing labour cost (reduces the number and service)	Saving labour costs, transportation, insurance, and health expenses is an economic advantage, especially during a health crises.
		Reducing construction costs	TheEgyptian construction sector performed strongly during FY 2019, contributing 6.2% to Egypt's GDP. Therefore, any saving in the cost will have a good impact on the economy.
		Time-savingdue to printers' ability to operate 24/7	Avoiding delays related to deliveries and coordination caused by working requirements for installing utilities will be more cost-effective. One of the main reasons for the high construction cost is delays during the execution period in Egypt.
		Adding additional value at no additional cost Design flexibility Complex geometries Mass customisation, Thermal insulation, Time reduction.	Value relates to assessing the benefits brought by something regarding the resources needed to achieve it, whichin the case of 3D printing includes design, production, and environmental response, and reducing time without additional cost. In Egypt, using 3DP as new technology is itself consideredto add value.

Table 5: Analysis of the characteristics of the affecting factors in the Egyptian context (by authors)

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6 DISCUSSION

This section addresses several points. The international adaptability, Accordingly part 4, countries are divided into three categories. Those which develop and export 3DP technology and consider mainly developed countries are focusing on developing new materials, new applications, restoration and refurbishment, as an alternative method to solve the labour shortage problem in many developed countries, and ultimatelyon exporting3DP to developing countries as commercial technology. The second group of countries import technology andadapt it by developing machine properties and suitable materials to match the local requirements, while the third group of countries imports technology and focuses on affordability by reducing construction cost and time.

Although the selected examples studied are characterized by diversity in applied approaches and the materials used.However, the technology clearly shows that. It is still in the light of experiments and exploration, not consumer technology. Also, the printer's limitations in print just the foundations and entire building walls, but did not include printing other components and need special covering most constructive sites.

Regarding the strategy of using 3DP in international applications, the study found two main approaches among the examples: optimising performance and optimising production. It could be concluded that The application of 3D printing technology can bring many benefits, such as reducing waste of resources and materials, saving time, and reducing the workforce. The approach of optimising performance is characterised by novel forms of design flexibility, typology optimising and functionality, development of new applications, new materials, and machine layout. The approach of optimising production is characterised by mass production, using in situ resources, and increased accessibility which could mainly be used for affordable housing.

There are distinct international experiences that can be investigated in the Egyptian context, whether concern with optimizing the performance and optimizing the production. The following table determines the strength points which be Applicable in Egypt from different international Examples based on the assessment results.

	characterised points	International Examples		Applicable in Egypt
Optimising the Performance	Novel Forms and Design Flexibility	Future Office in UAE, CURVE APPEAL in the USA,	Applications	full or partial free form or luxury buildings,
		DFAB H. in Switzerland		Interiors-designed elements.
	Typology Optimising and Functionality,	Fluid Morphology in Germany		Architectural cladding Adaptable, portable units
	Develop New Application	Digital Grotesque in Switzerland		Print accurate details as Repairing or reproducing historical structure.
	Develop A Variety of Materials. Develop Machine Layout and Properties.	YHNOVA House in France (Polyurethane mold)	Materials	Salt as a raw material GFRC as Permanent formwork GFRP as a wireframe Bioplastic, Spray-foam as a mold Nylon as a light structure
Optimising the Production	Mass Production Concept	Winsun projects 3DP village, Mexico	Applications	affordability housing, prefabrication Building elements, Emergency shelters.
	Increased Accessibility, Reduced Risks in Remote Site	Residential House in Russia		Remote or hazard construction site, Rapid structure for military purposes.
	In-Situ Resources and Local Materials	TECLA habitat in Italy (Clay as a mold) + bio-materials (husks and rice straw) Multi-use Building in the UAE (concrete and gypsum).	Materials	Sand as a construction material Concrete reinforced by, fly ash, silica fume, and nano-silica. Clay is a ceramic material. Glass-fibre-reinforced gypsum (GFRG)

Table 6: Applicable of applications and materials in Egypt (by authors)

According to the available materials suitable for use with 3D printing In Egypt, there are opportunities to use local materials such as sand with admixtures, concrete with additives (such as flash ash, Silica fume, and nano-silica), clay, and salt.

Table 6 provides a synthesis of the outcome of the research; it lists the proposed applications of 3D printing in the construction sector derived from the analysis of selected international examples, it identifies the key characteristics of 3D printing in the field of construction, and it shows the impacts of 3DP as potentials and challenges in the Egyptian context.

Proposed Applications	Key factors	Potentials in Egypt context	Challenges in Egypt context
Full or partial free form or luxury buildings	Design Related Factors Design flexibility Structure functionality Design optimisation Quality issues Environmental Related Factors Climate change adaptation Lower resources materials Reduced materials Raw materials Reused, or recycled materials Decreasing CO2 emissions Less total energy use Social Related Factors Reducing workforce Shifting in jobs paradigm Safety in extreme environments Loweraccidents rates New job opportunities Economics Related Factors Initial cost Reducing materials cost Reducing labour cost Reducing overall costs Unique architecture Mass customisation Time-saving	Taking advantage of the mass customisation design, environmental benefits, and construction speed through materials development such as local sand, GFRC, GFRP, GFRG, biomaterials, and nanomaterials, in addition to the development ofa hyper-technical approach.	Supporting the private developers to afford the new technology, need of updating regulations and codes, lack of stakeholders' interest, dealing with shifting the supply chains, and construction workers'job paradigm
		Medium-term applicability–3DP could be applied projectsin the medium termfor luxury housing with limited floors, such as the future luxurious neighbourhoods in the Administrative Capital and the new al Alamein	
Interiors: designed elements Facade: cladding elements		Exploit reducing waste materials with design flexibility and accuracy without any additional cost. Materials could be used, such as GFRP, GFRC, and GFRG	Supporting small entrepreneurs and training designers to deal with the new design process and software
		High applicability inthe short term	
Adaptable portable units		3DP could be used for emergency medical shelters, to exploit mass production, andreduce constructiontime	The high initial cost and the benefit of speed must be a common application in use.
		Lowapplicability inthe long term	
Repairing or reproducing historical structures		Exploiting digital accuracy could be used to repair accurate details, reproduce a mesh with translucent materials in a historical building, live a new experience, compatibility with a 3D scanner for production of 3D model	Develop regulations and codes with new technology, develop 3D printer scale and machine layout, develop suitable materials, qualify professionals to manage it.
		High applicability in the short term	
Affordable housing		A new housing policy was being drafted to address the serious housing deficit; in the effort to provide affordable housing in a sustainable approach, so take advantages of in-site mass production, cost reduction (reduce wastes, workers costs) in long term,develop hyper technique approach, and using local materials such as desert sand, GFRC, GFRG, Clay, and concrete with fly ash, silica fume, and nano-silica. In addition, reducing the carbon footprint.	It's not suited in the Egyptian Urban context because of the limitations in the current 3DP., high cost of horizontal infrastructure, changes in the supply chain, shifting in workers Paradigm, update regulations and codes, overcome economic constraints, manage new technology risks, preparation in-site printing conditions,and the willingness of the lower and middle-income people to live in printed houses.
		Medium term applicability - It could be applied in the medium-term depending on the government and the private sector in providing affordable housing just in horizontal growth.	
Prefabricatedbuilding elements		Very similar to the construction on-site, except that it is characterised by greater accuracy, and controlling climate conditions.	Need of heavy transfer, disadvantages of fixtures and fittings, inflexible in design, need to qualify professionals to manage it.
		Lowapplicabilityinthe long term.	
Remote or hazardous construction sites		Replacing manual workforce with 3DP at remote and hazardous construction sites.thus reducing risks and labour costs and using raw materials such as sand.	Dealing with the problem of material properties at high temperatures condition
		High applicability inthe medium term	
Rapid structure for military purposes		Exploit construction speed and raw materials such as sand.	Manage new technology risks.
		Lowapplicabilityinthe medium term	

Table 7: potentials and challenges of applying proposed applications of 3DP in Egypt. (by authors)

It can be concluded that 3Dprinting is not a magical solution that can solve all the problems of traditional building techniques. Critical several challenges need to be resolved to achieve the maximum potential of the 3D printing technology, and many more potentials have to be investigated.

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potentials	challenges
Increased design flexibility Time-saving Ability to use in-situ materials Variety of raw materials Reduced resources and material waste The environmentally way is to use demolition waste Cost reduction in addition to the minimised cost of storage and transportation cost of materials Reduced workforces and their transportation costs New lob opportunities as a new supplier Reduced health and safety risk on-site. Mass customisation at no extra cost.	3DP is reducing job opportunities for qualified workers. Materials of use for 3DP are limited as they require specific properties 3DP is not suitable for larger-scale projects Specific geometrical possibilities limit the printing method Utilities (electric, plumbing, and door and window) are not yet integrated into the design process Using 3DP also requires a change in the design process It is still a limited and expensive technology. There are no set regulations for using 3DP in construction Lack of knowledge about technology among the stakeholders 3DP requires new skills (installation, operation, control, and maintenance) for workers.

Table 8: Challenges and potentials in applying 3DP. (by authors)

7 CONCLUSION

This study aimed to give insight into applying 3D printing as a new building technology on an international scale and assessing the potentials and challenges in developing and applyingit in countries like Egypt. Based on qualitative data analysis of international examples, the study analysed 3D printing factors, their characteristics, opportunities and limitations. It assessed key factors with theassessment matrix and analysed the applicability of 3DP in the Egyptian Context.

From understanding the role of applied projects and Egypt's economic, social, and scientific situation as a developing nation, Egypt belongs to the second group of countries that import technology and adapt and develop it according to their needs and resources. But there are urgent challenges that need to be dealt with, such as developing local printable materials, updating the regulations and codes, spreading awareness between the different stakeholders and, most importantly, dealing with shifting the job paradigm because 3DP will reduce the need for a significant number of construction workers. While this is considered a benefit for countries with a shortage of labour, it is a disadvantage for countries with a large workforce depending on the construction sector whose jobs are at risk.

Although the technology is still in its infancy, it has continued to gain popularity among researchers and practitioners in the architecture and construction field of some developed and developing countriesworldwide. The future of technology in Egypt is most likely to be a partially built process that allows stakeholders to take advantage of both traditional and 3D printing technologies at the same time. The efficiency of reducing time and waste of materials could be the keys of this technology in the Egyptian context. Moreover, this technology would be applied locally for very limited cases in the near future, such as repairing or reproduction of historical structures, elements designed for interiors, and facade cladding elements. In the medium-term. The construction sector may invest in the mass production potential of 3DPfor affordable housing due to its economic efficiency or invest in flexible design and environmental benefits forfull or partial free forms of luxury buildings.

8 RECOMMENDATIONS

At the level of completing this research, This research provided background and deliberated potentials and challenges of the applicability of 3DP in different cases throughout the world so that future research could match local requirements and properties with the key factors which determine the applicability of 3DP toseveral local contexts. As regardsgeneral 3DP development, further work is needed to explore ways of printing with multiple materials, develop new materials, use in situ resources, faster printing, quality assurance, and mechanical property data, and combine 3DP with other processes such as hybrid techniques to increase the potential of applying it as new building technology.

9 ABBREVIATIONS

Abbreviation	meaning	Abbreviation	meaning
(3DP)	Three-Dimensional Printing	(GFRP)	glass-fibre reinforced plastic
(GFRC)	glass-fibre reinforced concrete	(GFRG)	glass-fibre-reinforced gypsum

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