Printed house as a model for future housing

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Abstract. The printed house is one of the latest and most important global attempts to solve the housing crisis, based on its speed of delivery and reasonable cost; new versions of such houses are also generally able to meet the requirements of individual families far better than previous standard models, allowing them to be adopted as a model for future housing. The research problem for the current work was thus the existence of a knowledge gap with regard to the applications of printed houses in terms of such adoption, and the research objective was to build a theoretical framework around current and potential applications of printed houses in such a way as to allow this to be adopted as a model for future housing. The hypothesis was the importance of printed house applications depends on the types of future houses supported by market forces. The study found that printed houses offer a solution for temporary housing needs due to their small footprints that correspond to the demographic nature of many modern families. Other positive features, such as affordability, flexibility, eco-friendliness, style, and support of healthy lifestyles mean that they also represent the future of housing by meeting the requirements of individual families more effectively, allowing better customisation and a move away from mass production.

Introduction
Finding the solution to the housing problems of the twenty-first century, which include, but are not limited to, continuous urbanisation, overpopulation, pollution, energy and land shortages, and a lack of affordable housing, is not possible by applying the ideas of the twentieth century. A shift in models, based on the technological development of the Fourth Industrial Revolution, must instead provide an alternative to traditional understandings of house design and production processes, fundamentally changing the way people live and work. The use of advanced 3D printing techniques provides new possibilities for designing, manufacturing and building house, yet there has been, so far, a knowledge gap with regard to the role of printed houses as a model for future housing. The goal of this research is thus to build a theoretical framework that demonstrates and supports the role of printed houses as a model for future housing. The research hypothesis is thus the primacy of the importance of developing printed house applications based on the types of future house supported by market forces. The research methodology followed thus included the following steps:

- Defining the printed house,
- Studying the transformation in the housing model in light of Fourth Industrial Revolution and the attitudes towards and drivers of change for future housing models,
• Studying the housing market in light of the determined future housing model, including supply and demand forces and possible types of future house,
• Determining printed house applications,
• Achieving a theoretical framework for the printed house as a model for future housing,
• A questionnaire process among a specialised sample to clarify the relationship between types of future houses and market forces, based on analysis of examples, and
• Developing findings and conclusions.

Printed house definition
A printed house is any dwelling with a modern structure in which materials are distributed in layers according to digital layouts to create a three-dimensional model of actual size; often, a printed house is produced using the Contour Crafting technique, which applies the principles of 3D printing to housing construction and thus uses automated additives applied to the building, such as single layers of concrete, which are repeatedly extruded using a three-dimensional bridge system. Building concrete layers on each other in sequence allows the structure of the wall to be completed using technology that applies modern principles of automation to building principles [1], and it is these houses resulting from 3D printing building technology are most likely to revolutionise the construction industry. Their most important advantages are reduced costs and build time, reduced environmental pollution, and the possibility of increased energy efficiency from the application of better designs for isolated structures [2].

Motives and reasons for change to future housing models

3.1 Motives for change
The motives for changing the traditional housing model to meet future needs were identified by examining the increasing polarisation or fragmentation by region and the development of digital technology at the design and implementation levels, as well as the scarcity of resources at both individual and governmental levels[3]. Many of these factors are determined by population growth, population aging, slowing economic growth, and persistent levels of poverty; however, perhaps the most important motivation is the maturity of the digital technology sector and the shifting and diversification of values that now supports adopting this technology in housing production [4]. To achieve the evolution of housing development as a product of a planning process derived from a population’s need [5], the most important things to consider, which affect the forms and distribution of all future development, are the demographic, economic, social, and cultural factors, including politics, planning, and environmental impacts, that constitute the region under development. These control the main results of any future housing model, affecting both production and distribution related to the housing market, as well as the resulting houses types [5].

3.2. Drivers of Change
The most important drivers for changing the housing model from the traditional mode have been identified as follows:

3.2.1. Demographic drivers. These are represented by the needs of two main groups, tenants and small and newly formed families, to obtain small private housing units [6]. The need for availability of small units has thus increased dramatically, making this the most important demographic driver for the new housing model.
3.2.2. Economic drivers. Economic drivers are represented by development costs. Developers currently struggle to meet the need for affordable housing due to increasing costs, which can be much higher than the market price in some regions [6]. A related economic motive is the changing relationship between the future location of jobs and housing, with some houses and work markets shifting and definitions blurring so that the future picture is mixed [5].

3.2.3. Policy and Funding drivers. Development programmes and policy shifts at all levels of government increase the complexity of the issue of cost containment, which impedes effective development process, thus negatively affecting national housing programmes [6].

3.2.4. Socio-cultural drivers. These are responsible for the distribution and forms of housing development, based on the fact that the situation in the twenty-first century differs from that of the twentieth century.

The housing market in light of future housing models

Future forces in the housing market are affected by both demand for new forms of housing and the methods of construction affecting placement, people's desire to live in specific areas, and how they want to live, and by supply forces that affect the types of housing that can be built and how these may be built. This diversity of forces confirms the importance of adopting a model for future housing that meets multiple requirements as follows:

Demand side

4.1.1. Urbanisation. People are continuing to migrate to cities, increasing urban density and putting pressure on existing places to live.

4.1.2. Demographic changes. Family sizes are shrinking, and the world population is aging, increasing interest in smaller living spaces and increasing demand for these.

4.1.3. Sustainability. Tighter regulations related to energy consumption and green development have stimulated the production of more environmentally friendly housing, especially smaller units. In 2018, 88 countries had mandatory or voluntary guidelines for building energy consumption or greenhouse gas emissions, as compared to just 38 countries in 1994. These developments have been strengthened by global agreements, including the 2015 Paris Agreement on Climate Change adopted by 195 countries in early 2019.

4.1.4. Facilitation. There is a shortage of affordable housing around the world, and to solve this problem, many cities have emplaced measures such as zoning, allocating part of all new residential buildings in each area to affordable housing, and ensuring sufficient small properties, generally approximately 30% [7]. This emphasis on changes in interest and increasing the provision of houses with small areas may be the most important force affecting the market at present.

4.2. Supply side

The housing crisis has been worsened by the high price of real estate in the supply market. The use 3D printing technology is an alternative means of construction addresses this directly, however, as it saves up to about 35% of the total housebuilding cost where 3D printing of the walls and foundations is calculated in terms of the cost savings in materials and labour [1]. This has been facilitated by
4.2.1. **Construction Technology.** The Construction Technology revolution (the Fourth Industrial Revolution) has overturned the construction industry by means of the use of robots and drones on sites and building information models in construction development. In the United States, this boom attracted more than $1 billion in investment capital in the first half of 2018, an increase of 30% over the previous year’s total.

4.2.2. **Construction Methods.** The use of pre-casting for housing construction has increased, with sections of structures being constructed in factories and then assembled on-site to improve productivity and reduce costs. Modular units are a subset of ready-made constructions, and their structural parts are constructed in box-like form that give builders opportunities for customisation. In India, contracting companies have started using these processes to overcome the rising costs of building materials, which are now three times higher than they were in 2005.

4.2.3. **Building Technology.** Using smart and flexible systems helps make buildings smart and energy-efficient, while intelligent-based automated storage systems triple available living space by storing elements of units on the ceiling when they are not needed [7]. Printed houses achieve a further impact on the market through effects on both supply and demand as follows:

The impact of printed houses on the forces of demand: Printed housing represents a solution to the problems associated with continuous urbanisation and demographic changes by providing suitable and liveable units that take into account sustainability requirements in the materials and technologies used, facilitating a reduction of costs to 30%, and by facilitating the full use of areas designated for affordable housing.

The impact of printed houses on the forces of supply: The use of robots in the construction of printed houses, in addition to construction methods that manufacture some parts in a factory and then achieve site integration with the role of locational robots, may be the greatest achievements of printed houses. The use of flexible and smart systems inside such houses to suit the specific needs of each family is also important, however.

**Types of Future House**

Studies have identified several types of future house to meet the requirements of modern trends:

**Affordable**

Affordable housing considers purchasers’ budgets and thus tends to consist of small to medium structures with relatively small units built with moderate materials to constrain prices as well as using techniques that make construction fast and cost-effective. These factors reduce prices while still creating suitable living spaces, often by using ready-made materials and components [8]. Affordability supports current demographic changes affecting the forces of demand and is fully consistent with the development of printed houses and their application to produce small units to meet the demographic and economic requirements of small families.

5.2. **Eco-friendly**

Any model for future projects should consider the use of recycled materials along with the use of solar or other renewable energy sources, as these provide multiple possibilities to achieve engineering complexity and to revolutionise the construction industry [8]. Designing zero waste projects, reducing carbon emissions, and using innovative and recycled materials with new technology to enhance sustainability can achieve a type of future housing consistent with trends towards sustainability within the forces of demand.
5.3. Flexible
Flexible housing is designed to change with people, offering designs and functions that can be adapted, added to or improved as needed without the need for excess investment. For some types of housing, builders sell properties in an incomplete state, allowing the owners to design or redesign the interior spaces as required; this is often done using pre-cast concrete units and modern construction techniques that enable the transfer of manufactured parts to site. Such house designs are adjustable based on function, with units of different shapes and sizes created in a ready-made building with little pre-existing interior design; this increases the allocation of space, in addition to offering the possibility of moving a residence by dismantling it and shifting it in parts to another place. This is compatible with the forces of supply in terms of new construction methods such as prefabrication, off-site manufacturing and building technology based on flexible systems.

5.4. Stylish
This can be reflected by original features created using 3D printing or other modern technologies. Such futuristic aesthetic design offers unique features created using modern construction methods at the level of both the front and interior facades. Future residential styles can thus take into account aesthetic considerations.

5.5. Healthy
Future housing should be designed to improve residents’ health and well-being, incorporating the latest air filtration and lighting systems that simulate natural light to improve biological systems and community spaces [7].

The most important features of future housing were thus identified as affordability, Eco friendliness, flexibility, stylishness, and health-promoting, which are consistent with printed houses.

**Printed house applications**
The most important applications of printed house were identified based on previous studies:

6.1. Temporary housing
Disasters leave victims homeless and exposed to external conditions; however, printed houses can be widely applied to construction in disaster-affected areas where needed and at much faster pace than normal construction practices and processes [9]. A portable printer that can be used in humanitarian crises due to its low cost and availability of designs [10] already exists, and 3D printing has proven its ability to build concrete structures such as printed walls easily and quickly, and at lower cost than traditional building methods, as well as reducing construction waste due to using only the materials needed for the structure. It is thus possible to build a complete structure within three days, allowing a full neighbourhood to be completed within months with a project cost reduced by half; in addition, using local materials for construction is also possible. In contrast, traditional neighbourhoods require from 2 to 6 years to build [11]. This technology is economical in terms of reducing costs, materials, and labour achieving strong affordability in addition to its adoption of environmentally friendly local materials, which makes it achieves health aspects with quick achievement and efficiency in producing small units.

Benefits are also achieved from it in other aspects. In the short term, temporary house can be produced using 3D printing technology in the design, production and assembly of small parts in large numbers to speed up production [10]. In the medium term, it can be used to increase the quantity of production and improve various parts of large units to achieve higher quality, while in the long term, the application of computer control aspects to the entire construction offers greater advantages. The applications for
construction, especially in disaster-affected areas, provide many positive advantages in terms of addressing risk factor concerns, such as temperature control with a minimum of air conditioning, achieving comprehensive flexibility in social and economic terms while preserving resources. Community residents can thus focus better on improving their quality of life, allowing the population will become more productive, and thus improving the socio-economic status of the whole community [9].

6.2. Improving the aesthetics of a structure
Due to increases in the number of residents and their differing requirements, standards of living and houses prices are constantly increasing; in particular, residents want to buy good units at low cost. Printed houses achieve aesthetic results for internal and external façades, and the technique can also be used in creating complex architectural structures where a mainframe is designed for the structure and supported with architectural details based on printing blocks with three-dimensional architectural details [11]. This technology can thus achieve aesthetics on par with traditional techniques as well as more efficiently creating units of various styles.

6.3. Increasing the durability and flexibility of the structure
Reinforced concrete uses plastic and steel fibres in floors and walls, offering the necessary tensile strength while reducing the shearing stress in the rubber joints between the printed elements, which enhances flexibility [11]. The insulation of buildings with hollow columns assembled on-site offers high flexibility, as well as enabling all parts to be separated where they need to be moved to another place.

Practical study
The practical study consisted of two phases. The first was a questionnaire distributed to a specialised sample of 20 respondents, used to examine the implementation of the relationship between market forces and types of future house (Table 1), while the second phase was an analysis two international case studies. The first of these is a residential neighbourhood for low-income residents, while the second is a residential villa; both of these projects were implemented using 3D printing and have achieved significant value (Table 2). The measurement mechanisms applied aimed to determine the percentage of verification of each indicator among the item indicators of the theoretical framework and to compare these between samples to ensure the validity of the research hypothesis, the importance of applications of printed houses based on types of future house supported by market forces.

The questionnaire
A questionnaire was distributed to a specialised sample of 20 respondents to demonstrate the implementation of the relationship between market forces and types of future house. The instrument was distributed to a sample of experts and specialists in housing affairs, including professors in Iraqi universities’ architecture departments. A Likert scale of three degrees was adopted for the questions (agree, neutral, disagree). (Table 1)

Table 1. The questionnaire.

| No. | Item                                                                 | Agree | Neutral | Disagree |
|-----|----------------------------------------------------------------------|-------|---------|----------|
| 1   | Printed house applications are suitable for:                         |       |         |          |
| 1.1 | Temporary house                                                     |       |         |          |
| 1.2 | Improving the aesthetics of the structure                           |       |         |          |
| 1.3 | Increase the durability and flexibility of the structure            |       |         |          |
| 2   | The following types represent the types of future house:            |       |         |          |
| 2.1 | Affordable has suitable spaces and low-cost materials               |       |         |          |
| 2.2 | Eco-friendly with zero-waste design, reduced carbon                 |       |         |          |
emissions, and innovative and recycled materials

2.3 Flexible with adjustable design, pre-made construction, semi-raw interior with the possibility of disassembling

2.4 Stylish by taking care of the front and interior facades

2.5 Healthy by taking care of air filtration systems with sensors to track air, water and lighting

3. If the pattern is appropriate, it has an impact on the housing market through:

3.1 Effect on urbanization as it fills the need for places to live

3.2 It takes into account the demographic changes by providing small living spaces

3.3 Sustainability

3.4 Affordable by allocating part of the new residential buildings

3.5 Construction technology using robots and drones

3.6 Construction methods using prefabrication for housing construction

3.7 Building technology using smart and flexible systems

Case studies

7.2.1. “Tabasco”, Mexico. The first project examined, a residential complex was printed base on a master plan for the neighbourhood that included 50 homes; this was intended to provide a future model for the production of high-quality housing for the poorest communities in the country as part of a larger effort to reduce global displacement, as shown in Figure 1. Each single-story house was built at a faster rate than traditional building methods allowed, with an area of 500 square feet. The general design consisted of a living room, kitchen, bathroom, and two bedrooms. The families who were to live in them were also asked to provide notes about what they needed within the neighbourhood, which were considered in the design process alongside the demands of the difficult climatic conditions, such as seismic activity and floods.

The design team worked with future residents on both land selection and community planning, and the printed models were modified to allow adaptation to a range of different needs. Each house occupies an area of 120 m$^2$ with an internal space of 55 m$^2$, at a cost of $6,000 per residence. The concrete walls were left exposed inside and outside, allowing residents to choose their own finishes to achieve the required aesthetic aspects. The use of printed interiors allowed the creation of built-in items such as kitchen and bathroom appliances, seats, shelves and edges in the walls to facilitate additional storage. Windows and doors openings were placed to allow improved airflow, and the printing technology also allowed the creation curved walls with compact details without additional cost, as well as customisation to allow the personalisation of homes, encouraging families’ sense of ownership and creating variety among the buildings within the community, as shown in Figure 1.

The residences were characterised by large curved rooftes that extended at the front and back to act as a buffer against heavy rain, and the bases of structures and walls were strengthened against seismic activity to increase durability. Perforated concrete blocks along the top of the walls are used for natural ventilation, while the interior space is open plan, for increased airflow, with interior walls curved for easy cleaning. The wall and building elements were produced using a large portable printer designed for waste-
free production, which has limited impact in terms of water and energy use and labour infrastructure [11], as shown in Figure 2.

7.2.2. Winson villa, Taiwan
This 1,100 m$^2$ show villa was created at a cost of C$200,000 in cooperation with WinSun, a company providing affordable housing for low-income families in Africa and the Middle East. The intent is to provide cheap and effective units for low-income families in 20 countries including Morocco, Tunisia, Saudi Arabia, Qatar and the United Arab Emirates, and the Egyptian government pre-ordered 20,000 one-story houses. The interior of the printed villa has beautiful modern fixtures, and all building units, such as walls and columns, were prefabricated offsite utilising printing technology capable of producing hollow structures to accommodate pipes, wires, and insulation. The finished wall parts were transported to the site and installed on traditional foundations as well as being reinforced with traditional steel structures or cement for durability. The walls were supplemented with different fittings and finishes according to residents' preferences. This technology reduced waste in the actual construction process and saved between 30 to 60% of the materials that would have been used in traditional construction. Parts such as frames and walls were separately printed, creating a new type of printed structure that is environmentally friendly and cost-effective, as all materials used were generated from recycled construction waste and industrial waste [12], as shown in Figure 3.

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**Figure 1.** Tabasco project in Mexico.  
**Figure 2.** Tabasco neighbourhood.  
**Figure 3.** Winson villa in Taiwan.
| Applications of printed house | Main item | Secondar y item | The possible values | Evaluation | First example | Second example |
|-------------------------------|-----------|----------------|---------------------|------------|---------------|---------------|
| The application              | The measure | Verifi ed | Not verifi ed |                       | Hig h | Mi d | Wea k | Hig h | Mi d | Wea k |
| The first example            |            |           |                  | Urbanization by providing places to live | *    | *   |
| Temporary house              | Demand forces | *       |                   | Take into account demographic changes by providing small living spaces | *    | *   |
| Improving aesthetics         | Market forces | *       |                   | Sustainability | *    |
| Increase the durability and flexibility of the structure | Supply forces | *       |                   | Affordability by allocating part of the new residential buildings | *    | *   |
| The measure                  | The measure | Verifi ed | Not verifi ed | Building technology using smart and flexible systems | *    | *   |
| The second example           | Affordabl e | *       |                   | Suitable spaces and low-cost materials | *    | *   |
| Temporary house              | Eco friendly | *       |                   | Zero waste design, reduced carbon emissions, and innovative and recycled materials | *    | *   |
| Improving aesthetics         | Types of future house | *       |                   | Adjustable design, pre-made construction, semi-raw interior with the possibility of disassembling | *    | *   |
| Increase the durability and flexibility of the structure | Stylish | *       |                   | The front or inner facades | *    | *   |
|                               | Healthy    | *       |                   | Air filtration systems with sensors to track air, water and lighting | *    | *   |
8. Results

8.1. Questionnaire

The results from the questionnaire showed general agreement among specialists of the importance of housing market factors, especially affordability, within the forces of demand; this achieved the highest agreement at 100%, followed by urbanisation and demographic changes at 90%, then sustainability at 80%. In terms of supply forces, construction methods achieved the highest agreement at 85% and building technology scored 75% agreement, followed by construction technology at 60%. With regard to types of future house, affordability and flexibility achieved the highest agreement at 90% and 85%, respectively, with 65% acknowledging the importance of future housing being eco-friendly, and 60% supporting it being stylish and healthy. This shows the importance of future types of housing being supportive of market forces represented by the forces of supply and demand, as well as indicating widespread agreement on the importance of printed house applications, especially with regard to temporary housing and increases in the durability and flexibility of structures, which achieved 75% and 70% agreement, respectively; improving aesthetics received 60% support. All of these results confirm the importance of printed house applications in the future, as seen in Figure 4.

8.2. Case study analysis

The first example, a completely residential neighbourhood for low-income people, achieved 9 indicators out of a total of 15, a high rating of 60%. The second example, a single residential villa with high-end specifications, achieved 10 indicators, again giving a high rating of 66.67%. These results further confirm the importance of the proposed types of houses and their effects on a wide range of income level demands, strongly supporting the research hypothesis.

9. Conclusions

1. There is an increasing need for units that respond to the needs of the market, the most important of which is housing those made homeless due to natural disasters or wars and those with limited incomes. Temporary or permanent housing with small footprints is most consistent with the demographic nature of current and future families, and providing this at reasonable cost may be
the most important achievement of printed house applications; however, the techniques may also be used in producing middle and upper-class houses with high specifications at reduced prices.

2. The importance of printed house applications is highlighted by the reductions in costs and materials that allow a move towards achieving affordability for many different groups while achieving the requirements of each family. This can be done by moving towards mass customisation as opposed to mass-production, which is an important feature of printed housing, allowing it to support future trends and opening the way for investment and the employment of skilled workers and programmers on-site or in the manufacture of building blocks in the factory.

3. Time is an important factor in the spread of printed houses; however, this technique is unlikely to replace traditional construction in the next few years. It is more likely that both technologies will be present, with printing development occurring alongside traditional technologies and offering support to them, especially for advanced projects.

4. Printed houses create opportunities to personalise units at all levels, according to the practical study, by removing the restrictions imposed with regard to shape caused by traditional methods of construction. The growing number of medium and small families, in addition to the desire to help families with lower incomes build homes utilising their own designs at lower cost and in an environmentally friendly manner are indications of the maturity of this market.

5. Printed house types (affordable, flexible, eco-friendly, stylish, and healthy) represent future types of houses by taking into account market requirements and families' needs; whether such housing is temporary or permanent, it can achieve strong and flexible structures as well as offering portability when needed.

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