Evaluating the Potential of High Performance Concrete 3D-Printing for Zero Energy Homes

Paola Sanguinetti, Khaled Almazam, Omar Humaidan, Joe Colistra
University of Kansas, Lawrence, USA

Abstract
This simulation-based case study explores the potential of concrete 3D printing for a Net Zero Energy housing unit. Three building envelope scenarios will be compared to analyze the insulating capacity of concrete 3D printed walls and the predicted energy consumption. The expected utility costs are calculated based on the energy value in the Midwest region of the United States. This paper discusses the potential energy savings with the implementation of renewable energy systems. The analysis is limited to the predicted monthly utility bills to determine which of the scenarios is economically viable within the U.S. Department of Housing and Urban Development's standards for affordability.

Keywords
Net Zero Energy Building, 3D printing, Additive Manufacturing, Affordability

Introduction
Additive manufacturing (3D printing) has the potential to transform the Architecture, Engineering, and Construction (AEC) Industry by automating construction and bringing efficiency to the building delivery process. Current research in 3D printing technologies for AEC has focused on the use of high performance concrete as a material that can be adapted to this construction approach. This paper reviews the research in concrete 3D printing and aspects to consider in order to achieve economic and environmental benefits. A case study, focused on the construction of affordable homes, proposes an integrated approach to evaluate the performance of 3D printing. The study links two simulation models for an integrated performance analysis. The potential to meet the Net Zero Energy standard and achieve energy savings with the implementation of renewable energy systems is discussed. The analysis is limited to predicted monthly utility bills to determine which of the scenarios is economically viable within the U.S. Department of Housing and Urban Development's standards for affordability. The results suggest further considerations to evaluate the economic feasibility of this construction method.

Developments in 3D Concrete Construction and Net Zero Energy Buildings
The development of 3D printing in the construction industry launched a new stage of large scale construction components, which caused improvement in 3D-printing of complex walls, facades, and other large elements. Cement-based materials are the most studied option for widespread use in additive construction. 3D printed concrete homes are being built as a cost effective solution to high demand (Bos, Wolfs, Ahmed, & Salet, 2016). In terms of construction time, 3D printers that use concrete can print a house in 24 hours due to advances in curing time and construction automation (Nadarajah, 2018). However, research is limited to other performative aspects of this type of construction (Hager, Golonka & Putanowicz, 2016). The thermal insulation properties of buildings with a 3D printed envelope need to be considered when evaluating energy performance. As a sustainable approach to energy efficiency, the Net Zero Energy Building standard aims to reduce the demand for energy using a) passive approaches, such as a high R-value in the building envelope, and b) renewable energy strategies to provide the energy needed for the building (Torcellini, Pless, & Leach, 2015). The next sections review the state of the art in concrete additive manufacturing and Net Zero Energy.

Performance Aspects of 3D Printed Construction
Research in additive manufacturing (AM) has focused on the relationship between two important aspects: material design formulations and the printing system. Material optimization and geometric complexity are key issues when dealing with AM using rheological materials to fabricate building components. Research has shown that cement-based materials demand fast curing and low slump, as the substance is unsupported after leaving the extrusion nozzle (Ghaffar, Corker, & Fan, 2018). The Concrete Printing method has been explored to eliminate labor-exhaustive molding, which is not possible with traditional construction procedures (Lim, Buswell, Le, Austin, Gibb, and Thorpe, 2012). A new device has been brought to the field - the sliding pipe humidity gauge, providing a more accurate prediction of pumping compressions and feeding level (Ghaffar et al., 2018). Concrete 3D printing without temporary supportive
elements, has been executed with a 6-axis robotic arm to perform an accurate cement printing layer by layer (Gosselin, Duballet, Roux, Gaudillièr, Dirrenberger, & Morel, 2016). Malaeb et al. (2015) have examined the workability and flowability of 3D printed homes.

**Performance Aspects of Net Zero Energy Buildings**

The common definition of Net Zero Energy building is that a building produces as much energy as it consumes using renewable energy sources. Researchers have identified four areas of consideration: net zero source energy, net zero site energy, net zero energy emissions, and net zero energy costs. (Torcellini, Pless, Deru, & Crawley, 2006). Research in architectural design has focused on the integration of passive and active strategies to achieve Net Zero Energy single-family homes. The US Department of Energy has also promoted research in Net Zero Energy housing units that combine architectural and engineering research (Solar Decathlon, 2019). Research to improve the building’s envelope configuration include installing proper shading elements, integrating high-efficiency heating and cooling systems, adding solar panels, and implementing a smart energy management system to monitor the building use (Kolokotsa, Rovas, Kosmatopoulos, & Kalaitzakis, 2011). Other researchers have proposed new wall assemblies using highly insulated precast panelized concrete systems, including a thin external layer of ultra-high-performance concrete and a thick layer of rigid foam insulation (Wash U., 2017). This concrete panelized system was designed to be prefabricated and assembled on-site. This area of research has produced unique design prototypes that point to the need to consider the cost implications of innovative solutions to meet energy performance in residential construction.

**Case Study: 3D Printed Single Family Home in Kansas**

The case study presented in the next sections explores the potential of a 3D printed house to be economically feasible and achieve the Net Zero Energy standard. According to the US Census Bureau, the median household income ranges from $55,000 to $59,000 in Kansas, which is considered to be a moderate annual income (Fontenot, et al. 2018). The low-income earnings per capita in Douglas County, Kansas, ranges from $14,950 to $39,800. Very low income per person is $24,850 which is the average annual income in Kansas. The average monthly income is about $2,070 for one person, and $2,366 for a family that consists of two members (HUD, 2015). The average rental housing varies depending on the building scale and room numbers. The average rent for zero bedrooms (studio apartment) is about $650 per month. A one-bedroom home has an average rent of $825 per month. The third category of rental housing is a two-bedroom home with an average rent $950 per month. The last and higher average rent is a three-bedroom home at $1,065 (HUD, 2015). The house used as a case study was designed by architecture students at the University of Kansas for a community group looking to develop affordable housing in the Kansas City metropolitan area. The single-family home depicted in Figure 1 is approximately 1,544 ft² (143.44 m²), 2-bedroom, 1-bath structure. A master bedroom, second bedroom, living room, dining room, and hall are organized around a central service core comprised of a kitchen and bathroom. The central kitchen and bathroom were centrally located and anticipated to be developed as a prefabricated unit with an HVAC system located in an accessible compartment above. The one-story structure is designed as an insulated slab on grade. Thickened slab edges at the perimeter support the weight of the 3D printed exterior walls. Window and insulation configurations are described in the various case study scenarios. High-performance windows have been used. Uniformly sized 3’ x 4’ (91.4cm x 121.9cm) casement windows are shown to meet egress requirements and to maximize natural light in the space. Sun shades or canopies would be configured to maximize the winter light while minimizing the summer heat. 3D printed concrete is left exposed as the exterior finish on all scenarios in order to allow the 3D printed concrete to be displayed as a prominent design feature. Interior partition walls are non-load bearing and are anticipated to be constructed of 2x framing lumber. A wood truss system is used for the roof with a raised-heel truss configuration to allow for maximum continuous insulation.

![Figure 1: Layout of the affordable home showing the building zone and the location of the windows and doors in the building envelope](image_url)
Analysis Process
A model of the single family home is created to evaluate the building envelope and energy performance. Figure 2 shows the proposed approach to evaluate the performance of 3D printing for an affordable housing unit. The study links two models for this integrated performance analysis: a computational fluid dynamics model of the building envelope and an energy zonal model of the housing unit.

Figure 2: Integrated modelling approach to evaluate the potential of high performance concrete 3D printing.

Base-case model
In order to provide a baseline for energy comparison, the model of the home is first analyzed with a typical residential wall construction in the United States. The wall is modelled as a 2" x 6" (5.08 x 15.24cm) lumber framing with insulation in the wall cavity, as required by the building code, with a total thickness of 8" (20.32cm) (Table 1).

Table 1: Base-case typical wall construction with insulation in the wall cavity wall construction

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Material Properties</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Finish</td>
<td>Gypsum Board</td>
<td>1/2&quot; (1.27cm)</td>
</tr>
<tr>
<td>Structural Layer</td>
<td>(2x 6) Douglas Fir lumber framing with Oriented Strand Board sheathing</td>
<td>5 1/2&quot; + 7/16&quot; (15.08cm)</td>
</tr>
<tr>
<td>Thermal Barrier</td>
<td>Fiberglass Insulation</td>
<td>5 1/2&quot; (13.97cm)</td>
</tr>
<tr>
<td>Vapor Barrier</td>
<td>ZIP system Engineered Sheathing with integrated water- and air-resistive barrier</td>
<td>7/16&quot; (1.11cm)</td>
</tr>
<tr>
<td>Exterior Cladding</td>
<td>wood siding</td>
<td>7/8&quot; (2.22 cm)</td>
</tr>
</tbody>
</table>

3D printed model
Variations of the 3D printed wall configuration were examined using THERM software (Huizenga et al., 2017) to estimate the transmittance (R-value) of the wall assembly and the solar heat gain coefficient of the windows. The R-value and SHGC for each scenario were used as input to evaluate a house using the energy simulation software e-QUEST (Hirsch, 2014) to estimate the energy consumption of the 3D printed home.

3D printed wall configurations
Three concrete 3D printed wall configurations are tested to evaluate their thermal performance. Tables 2-4 show the organization of the wall layers. In Scenario 1, the 3D printed wall is finished on the interior with no additional insulating layers. In Scenario 2, insulation is added to the 3D printed wall cavity. In Scenario 3, insulation is added to the 3D printed wall cavity, and an additional layer of insulation is added in the interior side of the wall between the interior finish and the 3D printed wall. These three scenarios are tested with high performance windows to examine the solar heat gain coefficient and its influence on the overall thermal performance of the 3D printed house.

Table 2: Scenario 1 for 3D printed wall without insulation

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Material Properties</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Layer</td>
<td>High Performance Concrete</td>
<td>2&quot; (5.08cm)</td>
</tr>
</tbody>
</table>
Table 3: Scenario 2 for 3D printed wall with insulation in the wall cavity

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Material Properties</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Layer</td>
<td>High Performance Concrete</td>
<td>2” (5.08cm)</td>
</tr>
<tr>
<td>Insulation in the</td>
<td>Spray Insulation (polyurethane foam</td>
<td>1 1/2” (3.81 cm)</td>
</tr>
<tr>
<td>cavity</td>
<td>insulation)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Scenario 3 for a 3D printed wall with insulation in the wall cavity and additional insulation in the interior side of the wall

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Material Properties</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Finish</td>
<td>Gypsum Board Adhered to Expanded Polystyrene (EPS)</td>
<td>1/2” (1.27cm)</td>
</tr>
<tr>
<td>Interior Insulation</td>
<td>EPS adhered to the 3d printed wall</td>
<td>7 1/4” (18.4 cm)</td>
</tr>
<tr>
<td>Structural Layer</td>
<td>High Performance Concrete</td>
<td>2” (5.08cm)</td>
</tr>
<tr>
<td>Insulation</td>
<td>Spray Insulation In the wall cavity</td>
<td>1 1/2” (3.81cm)</td>
</tr>
</tbody>
</table>

Results

The results are presented for the CFD simulation and the energy simulation. Figures 3 and 4 show the model visualizations in THERM and e-QUEST. First the R-value obtained for the Base Case and the three scenarios for 3D printed wall configuration. These results are used as input to evaluate the performance of the housing unit.

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>Total Wall Thickness</th>
<th>R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base-Case Typical Residential Wall Construction</td>
<td>8” (20.32 cm)</td>
<td>26.6 ft²·°F·h/BTU (150.9 m²·K/W)</td>
</tr>
<tr>
<td>Scenario 1 3D Printed Wall without Insulation</td>
<td>9” (22.86 cm)</td>
<td>7.6 ft²·°F·h/BTU (43.1 m²·K/W)</td>
</tr>
<tr>
<td>Scenario 2 3D Printed Wall with Insulation in the Wall Cavity</td>
<td>9” (22.86 cm)</td>
<td>19 ft²·°F·h/BTU (107.8 m²·K/W)</td>
</tr>
<tr>
<td>Scenario 3 3D Printed Wall with Insulation in the Wall Cavity and Interior</td>
<td>17” (43.18 cm)</td>
<td>39.3 ft²·°F·h/BTU (223 m²·K/W)</td>
</tr>
</tbody>
</table>

Energy simulation results

The results are presented for the predicted heating and cooling loads, electric consumption, electric cost, Energy Use Intensity, and annual utility bill. Figure 6 shows the annual heating and cooling loads for the Base Case and the three scenarios in the case study. For the Base Case, the annual cooling load is 2440 kWh, and the annual heating load is 480 kWh. For Scenario 1, the annual cooling load is 2930 kWh and the annual heating load is 1350 kWh. For Scenario 2, the annual cooling load is 1900 kWh and the annual heating load is 710 kWh. A comparison of these...
results shows that the Base Case has the lowest demand among the predicted results, and Scenario 1 has the highest annual cooling load. Among the three 3D printed wall scenarios, Scenario 3 has the highest energy-efficient consumption where the cooling load is 1620 kWh. Scenario 1 has the highest annual heating demand which is 2560 kWh.

Figure 7 compares the predicted annual electric consumption between the Base Case and the three scenarios for a 3D printed home. The Base Case annual electric consumption is 12,310 kWh. Scenario 1 has the highest electric consumption at 21,800 kWh, and Scenario 3 has the lowest electric consumption at 10,820 kWh.

Figures 8 shows the results for the predicted monthly utility costs for Base Case and the three scenarios. Figure 9 compares the Energy Use Intensity (EUI) between the Base-Case and the three scenarios for a 3D printed home. The Base Case EUI is 27.2 kBtu/ft².yr. (85.8 kWh/m².yr.) Scenario 1 has the highest EUI at 48.17 kBtu/ft².yr. (151.9 kWh/m².yr.), and Scenario 3 has the lowest EUI at 23.90 kBtu/ft².yr. (75.4 kWh/m².yr.).

Figures 10 and 11 show the annual utility cost for the Base Case and Scenario 3. Figure 12 compares the total annual utility cost, for the Base Case, $1,231, and Scenario 3, $1,082.
Discussion

The case study considers two performance aspects of a 3D printed home. Environmental performance is evaluated in terms of the R-value of the building envelope, and Economic performance is evaluated in terms of affordability and its impact on the cost of the predicted annual utility bill.

Compliance with Energy Standards

To evaluate the potential to meet the Net Zero Energy standard, the study first explores the thermal performance of the building envelope. Three scenarios were evaluated for increasing the insulating properties of the exterior walls. The results indicate that among the three scenarios evaluated for the 3D-printed home, the wall with an insulated cavity and an additional layer of insulation will have a better thermal performance than a home with typical residential construction.

Passivhaus Standard

Because the insulation was almost doubled for Scenario 3, the 3D printed concrete wall achieves an R-value. The increase in the thermal mass is a way to reduce thermal transfer to the interior spaces at low-cost. In this case study, meeting the Passivhaus standard could be considered an important step towards achieving a Net Zero Energy building in temperate zone (Sameni et al., 2015). The Passivhaus standard places emphasis on the building envelope, by increasing its R-value, and to reducing air-infiltration. In the 3d printed house, the wall may meet the Passivhaus standard, but thermal bridging was not evaluated at the connections between the wall and the roof or the wall and the floor slab.

This study utilizes a passive energy strategy to improve the thermal performance of the building envelope; this approach performs well in winter but does not perform efficiently to enhance the passive cooling in the climates that have high temperature degrees in the summer. Specifically, residential buildings in Kansas require active systems to guarantee optimal human comfort.

Net Zero Energy Standard

The Net Zero approach requires a balance between the energy consumption and generation using renewable generation sources. Following the passive strategy of improving thermal performance, the Energy Use Intensity (EUI) is evaluated, and on-site energy generation is considered.

The case study results indicate:

a) The EUI for the Base Case is 27.2 kBtu/ft².yr. (85.8 kWh/m².yr.). This result meets the code requirement of 2012 IECC (International Energy Conservation Code) which ranges between 35 to 45 kBtu/ft².yr. (110.4 to 151.9 kWh/m².yr.). For a typical single-family home in U.S., the EU is about 55.4 kBtu/ft².yr. (174.7 kWh/m².yr.)

b) Among the three scenarios evaluated for the 3D-printed home, the EUI for Scenario 3 is the lowest, at 23.9 kBtu/ft².yr. (75.4 kWh/m².yr.). This result does not meet the code requirement of 2012 IECC, but it meets the High-performance building standard, which requires that a building’s EUI does not exceed 35 kBtu/ft².yr. (110.4 kWh/m².yr.).

c) To meet the Net Zero Energy House standard for a single-family home, the EUI for Scenario 3 should range between 5 and 20 kBtu/ft².yr. (63.1 kWh/m².yr.) (Maclay, 2014). Therefore, Scenario 3 will require on-site energy generation to cover the additional annual energy demand.
Based on the results for the Predicted Electric Consumption (Figure 6), the annual energy demand for Scenario 3 is estimated to be 10,820 Kwh. This level of energy demand can be covered with 6 PV panels, installed in the roof of the house. The size of the PV system can range between 8.10 KWh and 9.32 KWh, depending on hours of daily sun that Kansas receives. This PV system can produce 1296 KWh per month as an average on-site energy production, and 300 watts per hour with $0.72 per watt (Feldman et al., 2018).

Future studies

- Consumption of the building. More insulation strategies
- Heating and cooling strategies to reduce the energy storage by the concrete walls as one of the best passive simulation study should evaluate the impact of thermal facades to minimize external heat gain. In addition, the glazing area could also be revised on the east and west
- Improving thermal properties

Compliance with Affordability Standards

To evaluate the affordability of a 3D printed home, the monthly and annual utility costs need to be considered. The utility bills weigh heavily on moderate- and low-income families because of the high tariff rates of electricity. According to HUD (2015), the average monthly rent for a two-bedroom single-family house in Kansas is $950. This monthly rent constitutes 40% of the total income for a low-income family.

In the case study presented in this paper, the results indicate the following:

- The estimated annual electric bill obtained from eQUEST is $1,231, for the Base-Case, and $1,082, for Scenario 3.
- When these values for the annual electric bill are normalized using the house gross area, which is 1,544 ft² (143.4 m²), the calculated cost is $0.79 per ft² ($8.5 per m²) for the Base-Case, and $0.70 per ft² ($7.5 per m²) for Scenario 3.
- The average monthly electric bill for the Base-Case is $102.58, which comprises 4% to 5% of the median income of low-income households. The estimated average monthly electric bill for Scenario 3 is $90.16. This result constitutes a reduction of 12.1%, which meets the standard for affordability.

Future studies

Based on the findings in this case study, passive strategies are needed to improve heating and cooling performance. More study is needed on the potential passive strategies for 3D printed residential construction:

Reducing Cooling Demand

Adding shading elements could be incorporated into the south facade of the building to reduce the cooling demand and compliment the Passivhaus approach to a well-insulated building envelope.

Model Calibration

One of the steps in this case study will be to produce full scale 3D printed wall prototypes to evaluate their thermal performance. The data collected will be used to calibrate the simulation models.

Improving thermal properties

The glazing area could also be revised on the east and west facades to minimize external heat gain. In addition, the simulation study should evaluate the impact of thermal storage by the concrete walls as one of the best passive heating and cooling strategies to reduce the energy consumption of the building. More insulation strategies will need to be evaluated in conjunction with 3D printed wall configurations. The effect of thermal insulation included in the cement mixture could be quite impactful to the overall energy performance of the building, such as phase-changing materials or other innovations such as micro particles of ceramic insulation (Muth, Dixon, Woish, Gibson, & Lewis, 2017).

Conclusion

This case study proposes an integrated approach to evaluate the performance of 3D printing, by evaluating both energy and financial performance for this innovative construction approach. The study compares a typical constructed single-family home with three scenarios for 3D printed construction. The scenarios explore increasing the insulation in the building envelope by filling the concrete wall cavity and adding insulation in the interior side of the building. The energy use is quantified by linking a CFD model of the wall with and Energy model of the house, to analyze the wall thermal performance and its impact on the overall energy performance of the single-family home. The findings of this research paper show that the placement of thermal insulation in a 3D printed wall can significantly reduce energy consumption, and the potential reduction in utility bills can achieve a net zero energy house with supplemental on-site generated energy strategies. The use of solar photovoltaic (PV) systems is discussed for Scenario 3 as an affordable and efficient approach for on-site energy generation. When compared to a typical constructed home, this case study shows the potential of 3D printing as a construction method to meet one aspect of affordability, with reduced utility bills for the inhabitants of the home. More research is needed into this construction type to incorporate thermal insulation installation within the additive manufacturing construction process.

Acknowledgement

The case study home design was provided by Ben Marquardt and Jacob Peterson, Master of Architecture students at the University of Kansas.

Nomenclature

ACEEE: American Council for an Energy-Efficient Economy
EUI: Energy Use Intensity
KWh: Kilowatt per hour
BTU: British thermal unit
eQUEST: Quick Energy Simulation Tool, U.S. Department of Energy
S1: Scenario 1
S2: Scenario 2
S3: Scenario 3

References


