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Print Time vs. Elapsed Time

A Temporal Analysis of a Continuous Printing Operation for Additive Constructed Concrete

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Preface

This study was conducted for the U.S. Army Corps of Engineers in collaboration with the 7th Engineer Support Battalion, Marine Wing Support Squadron 372, NASA Kennedy Space Center and through a cooperative research and development agreement with Caterpillar.

The work was performed by the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication of this paper, the Acting Deputy Director of ERDC-CERL was Ms. Michelle Hanson, and the Director was Dr. Andrew Nelson.

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Print time vs. elapsed time: A temporal analysis of a continuous printing operation for additive constructed concrete

Abstract

In additive construction, ambitious goals to fabricate a concrete building in less than 24 hours are attempted. In the field, this goal relies on a metric of print time to make this conclusion, which excludes rest time and delays. The task to complete a building in 24 hours was put to the test with the first attempt at a fully continuous print of a structurally reinforced additively constructed concrete (ACC) building. A time series analysis was performed on the events during the construction of a 512 ft^2 (16'x32'x9.25') building to explore the effect of delays on the completion time. This analysis included a study of the variation in comprehensive layer print times, expected trends and forecasting for what is expected in future prints of similar types. Furthermore, the study included a determination and comparison of print time, elapsed time and construction time, as well as a look at the effect of environmental conditions on the delay events. Upon finishing, the analysis concluded that the 3D-printed building was completed in 14-hours of print time, 31.2-hours elapsed time, or a total of 5 days of construction time. This emphasizes that reports on newly 3D-printed constructions need to provide a definition of time that includes all possible duration periods to communicate realistic capabilities of this new technology.

1.1 Introduction

In construction, the controlling factor for the extent, labor and cost of a project is time. Since labor is 50% of the project costs [1], the duration of an operation and the resources will affect the acceptance of new technologies [2]. For additive construction (AC) to be considered a viable construction method, it must be viewed as a competitive method as well as complementing traditional methods. One such method is additively constructed concrete (ACC), where concrete material is extruded in a specified path in a horizontal plane and layered vertically to form a 3D object.

3D printing with cement paste and mortar materials has been studied exclusively with typical nominal maximum aggregate size (NMAS) not exceeding 4 mm [3]–[5]. The aggregate size is typically limited due to the minimum dimensions through which the material is pumped or extruded [4]. The following study utilizes a larger output printer and a large aggregate ACC material. The selection of the components of a printing mix can affect the printability of that mix. These include parameters, such as shape stability, pumpability, extrudability, print stability and open time which are defined elsewhere [3], [6], [7]. These parameters will affect the time of construction and are dependent on the rheology and curing properties of the material [5], [8]. Flowable (low viscosity) mixes increase the print time since the previous layers must set enough and be shape stable before successive layers can be printed, unless set time modifiers are incorporated. The additional time to wait has been shown to affect the layer bond strength as the next layer is placed after the previous layer has been allowed to set, this has been referred to as the time gap effect [9]. These properties set the material limits used in the design of structure geometry [9]. The mix used for this study has a minimal time gap effect due to rheological and chemical properties.

The rheology of a printable mix is defined by the plastic yield strength and the viscosity [4], [10], where printable mixes are defined by a range of values for these properties [3]. While this study uses a cementitious large aggregate concrete mix, it is feasible that mixes with alternative binder materials (e.g.

geopolymer) and smaller aggregate sizes with the proper rheological parameters could be used [11]. The rheology of cementitious materials are affected by the water-to-cement ratio, paste content, the use of admixtures and the aggregate size distribution (gradation)and aggregate shape [10], [12]. The addition of properly designed printable large aggregate concrete mixtures can reduce shrinkage, improve shape stability, improve print stability, improve durability and reduce cost [13].

Once the material prescription and construction practices are shown to be viable, ACC will be another construction method that sits next to cast-in-place concrete, precast concrete and concrete masonry unit (CMU) in the design professional's tool box. ACC's competitive edge is the reduction in labor costs and time of construction [14]. Time can be defined as the construction time, elapsed time, print time and delay time.

- Construction time: The actual time to print an object, items or structures including delays and breaks. It is defined as the recorded time from the start the end of the print.
- Elapsed time: The number of worked hours including delays each day (e.g. set-up, calibration, material preparation, test print, relocation of printer, clean up).
- Print time: The total of the times to print each layer without delays and breaks. The print time is the time that the printer is moving and extruding material.
- Delay time is the elapse time minus the print time.

The standard metric that most companies and researchers use is print time. Most of the widespread newscasts on the printing of these structures further mischaracterizes the time it takes to build a structure by not reporting the construction time or elapsed time and only including the print time. The reporting of only print time can be misleading, as construction time is typically longer and is directly related to the cost of the operation.

Concrete 3D printing is being consider a new device in the construction and architectural fields[15]. Research of 3D printing with cementitious materials at a small scale (print envelopes less than 6 ft x 6 ft x 6 ft) and/or under highly controlled environments, provides a better understanding of the materials and process [16]. In large scale additive construction, companies like Apis Cor, Xtree and CyBe explore construction possibilities through their concept 3D printing homes[17]–[19]. In this study, the gap between construction time and print time is narrow. However, printing under these conditions may not provide a proper representation of the material behavior and print operations required during the construction of civil structures (e.g. buildings and bridges). As with any construction project, this gap widens when operations are scaled to the component and construction scales as manufacturing plant and job site conditions lead to challenges resulting from the handling of logistics, materials and machines [2]. Other popular methods of printing that have been developed are print-in-place (PIP)[2] and pre-print concrete[3] [1].

PIP concrete and pre-print concrete at a scale capable of performing construction requires constant printing. This involves an uninterrupted operation of a material delivery system, concrete mixer, concrete pump and concrete printer. Long print times induce strain on the equipment which can cause unwanted delays. A necessity in performing round-the-clock operations, is to account for the delay time before the process begins. The following discusses the time series analysis of a continuous print of a 512 ft^2 barracks hut (b-hut) and categorizes the type of issues that may lead to an increased delay time.

While speed is an advantage of additive construction, it isn't the only benefit of 3D printing [20]. Cost reduction associated with labor, logistics and materials are reduced offering 12-24 continuous print time [21]. In regions of the world were climate conditions are taxing on the area, increased strength and durability are extremely important factors to end users, with 3D printed structures withstanding earthquakes and hurricanes [21]. With 3D printing's technology using layers to construct it's, the need for formworks or molds can be eliminated, which amounted for approximately 60% of the total construction cost of concrete, generating 80% of construction waste worldwide [22].

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[2] Print in place (PIP) means it stays where it has been printed.
[3] Pre-print concrete is concrete that is printed ahead of time.

Concrete 3D printing is ever-changing, with areas of growth. Architects are able to explore untraditional ideas that would not be possible in traditional methods of construction [23]. More research and development of the thermal properties and moisture mitigation, additively constructed concrete could pave the way for a more sustainable future [24]. War fighters would have buildings that could withstand blast and ballistics, as well as quality indoor air and comfort. Homes could become more affordable for families, decreasing the homeless population.

1.2 Materials and Methods

The walls of the structure used ERDC's patented printable concrete material [25], is a Portland cement based concrete that incorporated additives to control rheology and an aggregate mixture using a NMAS of 3/8 inch (9.5 mm). The additive construction system used in this analysis is described as the following:

Printer – Custom gantry "ACES Lite" - Cartesian
Build area – Approximately 9'x 34'x10'
Software – Linux CNC
Print speed – 400-600 in/min
Material – Large-aggregate concrete (Patent [6])
Extruder – Similar to Bowden-style – Stator/rotor pump (variable speed) with 2" hose.
Extrusion rate – 4/3 cubic yard per hour
Nozzle size – 1.15" x 1.15" (square)
Layer height – 1"
Numbers above are approximate due to material consistency.

A Cartesian coordinate system gantry printer (ACES Lite) is used to direct the path of the extrusion. The gantry system is fed with an extrusion system similar to a Bowden extruder by utilizing a stator-rotor concrete pump to push concrete through a 2" concrete hose to an extruder nozzle. The constituents and consistency of the materials affect the extrusion rate of the printer, which is related to the printer speed and pump speed. The print speed and pump speed are adjusted by operators to maintain a uniform extrusion rate. This feature allows for accommodation of pump wear during extended operations and has the added benefit of allowing for a wide range of concrete mix designs and consistencies to be used. The material used is a concrete material developed at the US Army Construction Engineering Research Laboratory (CERL) in Champaign, Illinois, USA. Details of the material composition can be found in the referenced patent [26]. The material is created in batches and each batch is deposited into the pump for extrusion. The concrete material incorporates large aggregate and exhibits specific rheological properties that allows for proper pumping, extrusion and shape stability [27]. Tests have been completed on past concrete rheology requirements for printable concrete [28], [29]. Because of the use of large aggregates and proper aggregate gradation, the material used is capable of high build rates and shorter print times due to improved layer shape stability.

Some researchers [30], [31] claim it would be possible to 3D print a concrete building in 24 hours. However, there is no evidence that this metric has been tested. This demonstration explores the feasibility of using a single gantry type printing system. However, a decrease in print time could be performed using multiple printing systems simultaneously, which could be multiple gantry systems or multiple robotic systems [32]. To test this, a continuous print was performed to confirm whether this is a realistic construction time for the concrete 3D printing community. This metric is dependent on building size, amount of material required, timing of material delivery, speed of printing and print delay time. Planning, mechanical and finishing processes are considered in the overall time, as these time periods are necessary in the completion of any structure.

According to the National Association of Home Builders (NAHB), the average size of a small home is 1,600 square feet, where the bedroom space accounts for 468 square feet [33]. The size of an Army Barracks

Hut (Army b-hut) used for soldier sleeping quarters is 512 square feet. Therefore, a continuous print of an Army b-hut would represent the printing of an equivalent bedroom area in a small, single-family home.

Typical buildings are designed for conventional methods of construction using straight wall geometries. These simple geometries are capable with AC, but do not exploit the benefits of the process. Based on the print stability and rheology of the material used the layer to layer overhang was limited to 1/8th of an inch overhang. This print geometry was chosen to account for the material limitations and to optimize structural performance, reinforcement locations and maintain compliance with current structural building code requirements. Therefore, the design of the walls utilizes a geometric morphology, where the base of the wall was a repeating chevron pattern (i.e. zig-zag) and the top of the walls straighten out to allow for a simplified roof connection (Figure 1). This geometry means that each layer is different and had an overhang of 1/8th of an inch. The walls consisted of a total of 111 layers, with each layer being 1 inch tall. Openings for three windows and two doors were included in the wall design. Openings for Heating, Ventilation and Air Conditioning (HVAC) ducts typical used for military b-huts are also incorporated in the building's configuration. Each opening integrated a precast lintel that was placed for structural support. The design also allowed for a reduction in reinforcement, using only vertical rebar anchored to the slab foundation. The building structure was designed in partnership with Skidmore, Owings & Merrill of Chicago, Illinois.

Due to the limited build area the building was printed as two halves, as shown in the polymer prototype (Figure 1). As depicted, the print was defined by seven separate portions as follows:

Portion 1: Layers 1-42 = Bottom wall portion
Portion 2: Layers 43-86 = HVAC component on North wall and three windows on South wall
Portion 3: Layers 87-98 = Top wall portion covering all lentils
Portion 4: Layers 99-102 = First Roof Form or First Portion
Portion 5: Layer 103-105 = Second Roof Form or Second Portion
Portion 6: Layer 106-108 = Third Roof Form or Third Portion
Portion 7: Layers 109-111 = Fourth Roof Form or Fourth Roof Portion

During the printing process, the temperature, humidity, time of day, material quality, pump conditions, hose conditions, software/computer interactions all factored into irregularities and variations in layer printing time. While printing, the time for each layer, incidents, specific delay times, time of day and weather conditions were documented. Each layer was timed from start to completion. Based on this data a time series analysis and a comparison of incidents to environmental conditions were performed.

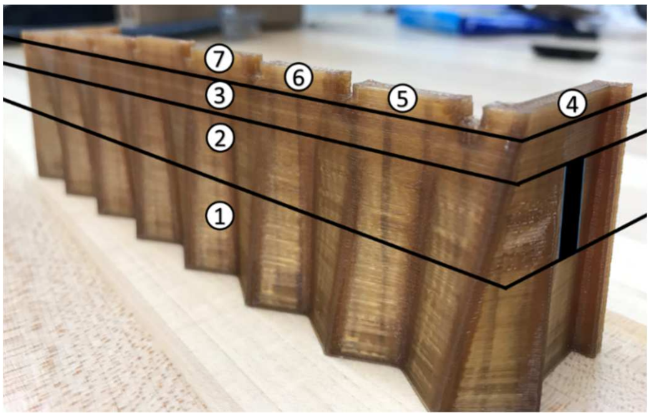

Figure 1: Half of the building prototype with portion designations

1.3 Theory/Calculation

The total times to print each layer of the building were compiled and sequenced in order of deposition to create a time series. Each layer was timed according to how long the printer took to complete one layer and then moved 1.00 into the +z direction for the next layer to begin. The total time for each layer is comprehensive and critical in understanding the downtime that could cause delay in printing procedures.

1.3.1 Various Time Situations

As mentioned, the construction time is the total number of days worked regardless of hours per day. The elapsed time and print time are used to determine the delay time. Delays are considered the irregularities and variations during the nozzle movement. The delay time is the difference between the time spent to correct these irregularities and variations and the recorded nozzle movement (1). Delays can be caused by environmental, material and mechanical issues that arise during the printing process (1.1).

$$t_d = t_e - t_p \tag{1}$$

where:

t_d is the delay time
t_e is the elapsed time
t_p is the print time

Tracking the comprehensive layer time helped discover the print time needed for the completion of the structure. By distinguishing the differences of time used to erect the building, the construction time allows for accurate planning and execution of the building in future 3D prints. For example, if claims are made to have printed a building in 24 hours, but the printing occurred 2 days a week for 2 hours, then the construction time of the object would be 6 weeks. If 10 minutes of time is required to clean the pump each day, then 100 minutes was spent on nozzle movement and 20 minutes on delays. The total elapsed time, however is 120 minutes. The illusion is that the building requires only 24 hours to print, which would be incorrect if other various time situations were not reported.

1.3.2 The Time Series Analysis

The time series data provided information about trends in future layer print times, as well as the inconsistencies that may need further research in the printing procedures. To understand the issues that occur during the construction time, the recorded time data is dissected to determine the periodic variations (i.e. seasonality), trends and irregularities. In doing this, one must understand what the time series analysis terminology is and how it is used to compute delay times.

Irregularities are situations that are totally unpredictable but, in this case, can be tracked for prevention. Some irregularities that take place while 3D-printing concrete outdoors are weather and climate, material production for printing, software and printer malfunctions, human error and other machinery malfunctions. The comprehensive layer time have some of these irregularities included. Irregularities during the print of the building directly affects the construction time and contributed to the delay time the most, increasing the elapsed time. During the process of time series analysis, the layer time is deseasonalized, removing the seasonality or the common irregularity trend and the irregularity variable. The trend allows researchers to see what the time path would follow once those components are removed, factoring in environmental affect as well. The times were manually gathered by researchers at each layer for the analysis. Using the time series analysis multiplication equation, moving average, seasonlization, irregularities, deseasonalization, trends and forecasts are calculated.

The statistical technique, time series analysis is used to analyze a sequence of events that take a particular time interval to complete and identifies patterns [34]. This time series decomposition analysis (2), is used to locate irregularities, seasonality and trends. These components describe when and where problems will occur during the print, allowing a whole system feedback, thus improving the production of the printing process.

Using the common time series analysis multipliable equation,

$$Y_t = S_t * I_t * T_t \quad (2)$$

where:

Y_t is the comprehensive layer time
S_t is the seasonality component
I_t is the irregular component
T_t is the trend component

The desired outcome of a time series analysis is to predict future value and identifying the nature of the phenomenon represented by the sequences of events. This assists in forecasting the patterns in future print layers. Once a pattern is established it can be integrated with other data. Using classical multiplicative model for forecasting time-series, basic models for forecasting using the moving average (MA) approach from Autoregressive Integrated Moving Average Model (ARIMA) [35].

The starting point forms the method of the decomposition of time [36]. To prepare the data, layers were grouped into sections per print portion of the building. The first 42 layers were divided into 6 sections with 7 layers into each one. This separation also helped identify where the issues occurred during the build. Each portion of the build varied according to where the print was located on the building, thus the sections and layers incorporated would differ. The comprehensive layer times were entered representing the time including the seasonality and irregularities. Next, the actual layer time was included as the time code. Data is listed in Table 1.

Table 1. Example of Comprehensive Layer Time in each Section.

Comprehensive Layer Time per Section							
Actual Layer Number {t}	**Section #**	**Layer in Section {n}**	**Comprehensive Layer Time in Minutes {Y_t}**	**Actual Layer Number {t}**	**Section #**	**Layer in Section {n}**	**Comprehensive Layer Time in Minutes {Y_t}**
1	Section 1	1	04:14	22	Section 4	1	04:52
2		2	04:13	23		2	05:12
3		3	04:11	24		3	05:52
4		4	04:36	25		4	04:55
5		5	05:19	26		5	04:32
6		6	04:10	27		6	04:34
7		7	04:25	28		7	04:32
8	Section 2	1	04:29	29	Section 5	1	04:21
9		2	04:28	30		2	04:21
10		3	04:04	31		3	04:30
11		4	05:54	32		4	04:52
12		5	04:15	33		5	04:52
13		6	04:26	34		6	04:28
14		7	05:12	35		7	04:31
15	Section 3	1	05:07	36	Section 6	1	04:25
16		2	05:58	37		2	04:27
17		3	05:41	38		3	04:39
18		4	05:36	39		4	04:37
19		5	05:12	40		5	04:15
20		6	04:47	41		6	04:29
21		7	04:31	42		7	04:31

The moving average (3) is the average of time over a certain amount of layers. The moving average gives a smooth curve of data to fit the seasonality of the time series data. This is completed for each section. In the instances of an even number of averages, the procedure utilized the center moving average.

$$MA(n_{total}) = [Y_t + Y_{t-1} + ... + Y_{t-n+1}] / n_{total} \quad (3)$$

where:

n is the layer the section
$MA(n_{total})$ is the average for each layer

The moving average produces a curve prediction that represents the layer times with the seasonality and irregularities removed. The seasonality and irregularities can now be extracted from the comprehensive layer time. This is completed by equation (4):

$$S_t, It = Y_t / MA(n_{total}) \quad (4)$$

Table 2. Moving Average and with Combined Seasonality and Irregularity.

Moving Average, Seasonality and Irregularity									
Actual Layer Number {t}	**Section #**	**Layer in Section {n}**	**Moving Average (7)**	**S_t and I_t**	**Actual Layer Number {t}**	**Section #**	**Layer in Section {n}**	**Moving Average (7)**	**S_t and I_t**
1	Section 1	1			22	Section 4	1	05:03	0.96
2		2			23		2	04:57	1.05
3		3			24		3	04:55	1.19
4		4	04:27	1.03	25		4	04:56	1.00
5		5	04:29	1.19	26		5	04:51	0.93
6		6	04:31	0.92	27		6	04:44	0.97
7		7	04:30	0.98	28		7	04:32	1.00
8	Section 2	1	04:41	0.96	29	Section 5	1	04:32	0.96
9		2	04:32	0.98	30		2	04:35	0.95
10		3	04:34	0.89	31		3	04:34	0.99
11		4	04:41	1.26	32		4	04:34	1.07
12		5	04:47	0.89	33		5	04:34	1.07
13		6	04:59	0.89	34		6	04:35	0.97
14		7	05:13	1.00	35		7	04:36	0.98
15	Section 3	1	05:11	0.99	36	Section 6	1	04:34	0.97
16		2	05:19	1.12	37		2	04:29	0.99
17		3	05:22	1.06	38		3	04:29	1.04
18		4	05:16	1.06	39		4	04:29	1.03
19		5	05:14	0.99	40		5		
20		6	05:07	0.93	41		6		
21		7	05:09	0.88	42		7		

The seasonality and irregularity combination are then separated to obtain the seasonality time component. By averaging the individual layers, for example, every layer 1, then every layer 2, by the seasonality and irregularity combination, it will produce only the seasonal component for those individual layers (5).

$$S_t = [S_t,I_t\,(n_1) + S_t,I_t\,(n_1) + \dots + S_t,I_t\,(n_1)] / n_{1total} \quad (5)$$

where:

S_t is the seasonalized component

Table 3. Seasonality time component.

Seasonality Time	
Layers	**S_t**
1	0.97
2	1.02
3	1.03
4	1.08

5	1.01
6	0.94
7	0.97

To deseasonalization the comprehensive layer time (6), the seasonality component is divided and removes periodic variations from the data.

$$D_t = Y_t / S_t \quad (6)$$

where:

D_t is the deseasonalized time.

To gather the trend of the print time, the deseasonalized time was used in a liner regression the coefficients of the Y-intercept and the slope for the model. The coefficients were used to calculate the trend for each layer's actual position on the building.

$$Y = a + Xb \quad (7)$$

Where:

Y is the response (in this case the Trend or T_t)
X is the variable (in this case the actual layer number, t)
a is the intercept (calculated through linear regression modeling)
b is the slope (calculated through linear regression modeling)

The trend time cannot be found by manipulating Equation 2, because the seasonality and the irregularity are components of the comprehensive layer time for each layer and varies, thus, the equation is unique for each layer. In forecasting, however, the seasonality component and trend calculations assist in the predictions of time to print the same printed object by performing the Equation (8).

$$\text{Forecast} = T_t * S_t \quad (8)$$

1.4 Results

1.4.1 Graphical Results of the Time Series Analysis

To look specifically at continuous print operations, the analysis was reviewed at the first 42 layers, however the model was completed for each portion. The time series data was divided into 6 sections to section of the first 42 layers into equal pieces to calculate the moving average. For Portion 1(1.1), the moving average was calculated over seven layers by applying Equation 3. Figure 2 shows the plot of the comprehensive layer print time and the moving average print time per layer.

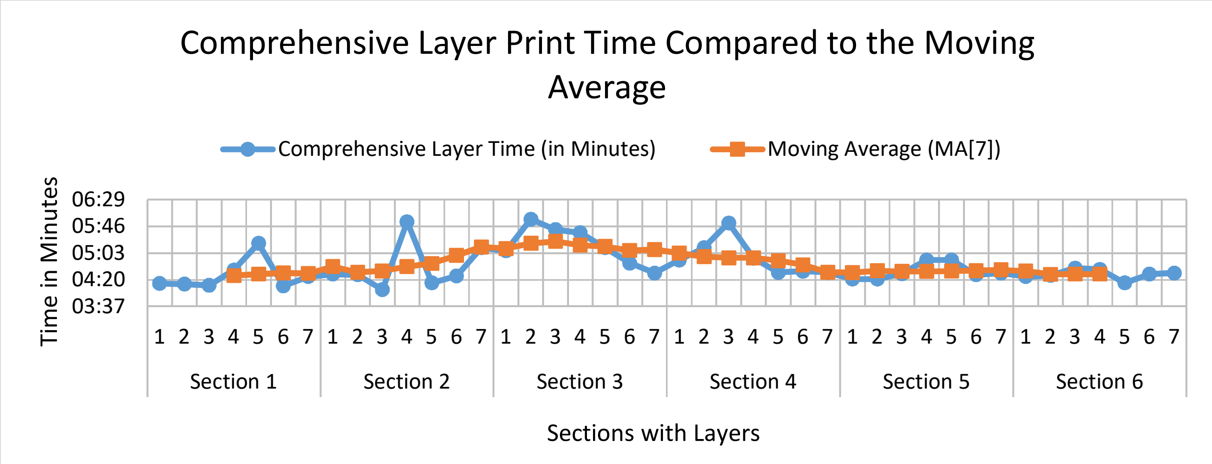

Figure 2. Comprehensive layer print time for the first 42 layers and calculated moving average.

To investigate the seasonal and irregular component of the data, the comprehensive layer time is divided by the moving average. Considering that the moving average is essentially the baseline of the time series data, finding which layers produces a positive or negative effect on the time to produce each layer would further point out the anomalies during printing. Table 4 shows the percentage of how much the seasonality and the irregularity are affecting the overall time of each layer. This examination displays when some type of failure of operational error has occurred during the printing process and where improvements were made during the printing process.

Table 4. Percent differences of seasonality and irregularity effects on layer time.

Percent Differences of Seasonality and Irregularity per Layer														
	Section 1							**Section 2**						
Component	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
S_t, I_t	-	-	-	-3%	-19%	8%	2%	4%	2%	11%	-26%	11%	11%	0%
S_t	3%	-2%	-3%	-8%	6%	4%	3%	-2%	-3%	-3%	-8%	3%	6%	4%

As mentioned before, deseasonalization of the comprehensive layer time removes periodic variations from the data by taking out these irregularities. The seasonality is removed to determine the trend of the time series data using linear regression. This is plotted in Figure *3*. The trend line of the seasonality show that there is a decrease in time spent on each layer after they were removed. For Layers 1-42, the linear regression model produces a Y-intercept of 0.0033185 and a slope of -1.08E-06.

$$T_t = 0.0033185 + t\,(-1.08E\text{-}06) \qquad (5)$$

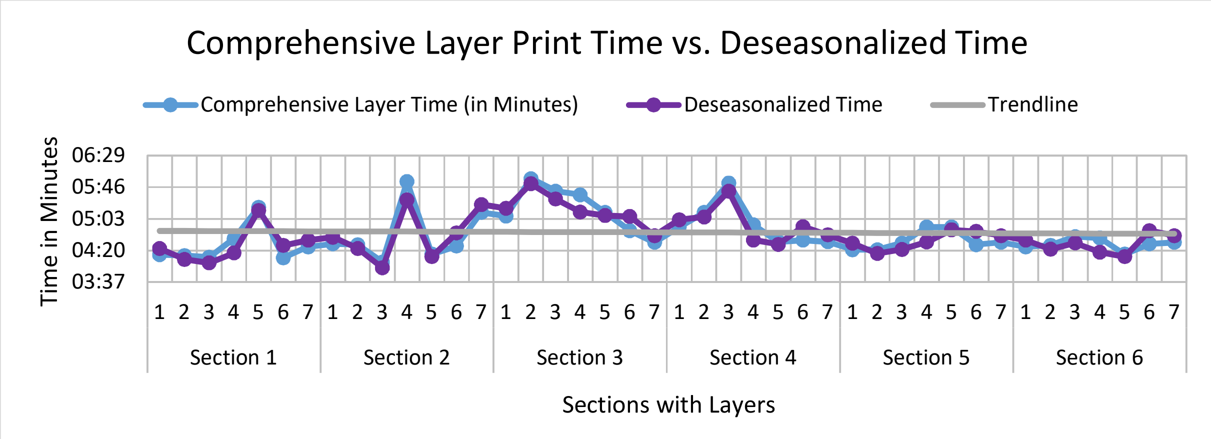

Figure 3. Comprehensive Layer Print Time compared to the Deseasonalized Layer Time.

The data collected for each layer is considered historical data and can now be used in the forecasting process. Time series forecasting uses the historical data and the patterns associated with it to predict the future's activity. This analysis can be used to summarize the next 42 layers. As with any forecast these results are merely a prediction of future events. Figure 4 displays the historical or factual data and the forecasted print time. If the irregularities and interruptions are removed from of the addition of the layer time, then forecasted time to print one layer is forecasted to be between 4:26 to 5:10 rather than the previous 4:04 to 5:58. This gives 1 minute and 10 second difference between the average times.

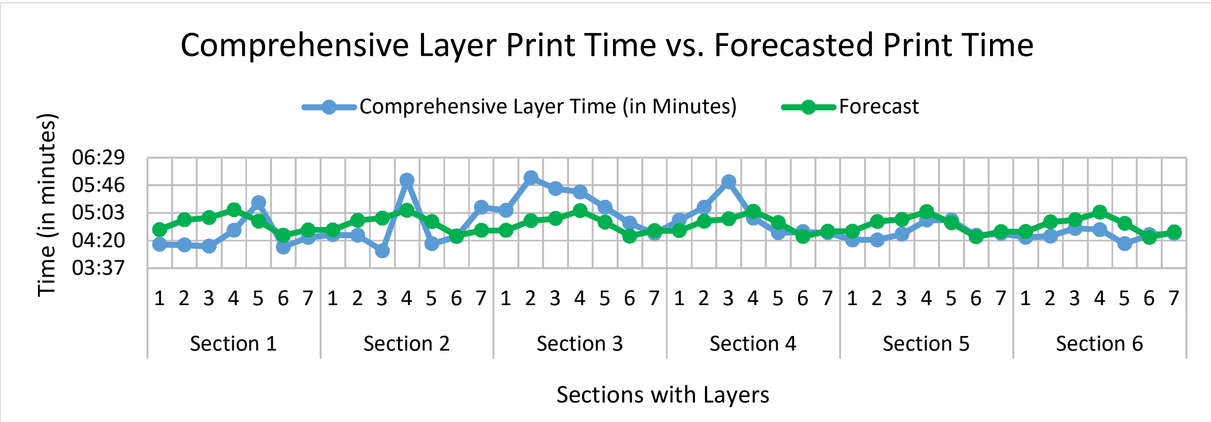

Figure 4. Comprehensive Layer Print time compared to the Forecasted Time Model.

When applying this technique to the remaining sections of the b-hut, the forecasted print time could be established including future weather conditions that would cause a change in material properties. Although future prints will be different in its own situational awareness, this analysis does provide insight on how and what occurred and the results that followed. There is no way of guaranteeing the duration of any single situation, but by using this analysis, appropriate planning can help future issues.

1.4.2 Environmental Factors

The weather and climate varied during the selected print days. Many of the days had a consistent sunny, mild heat with average humidity with instances of rain. With higher temperature and humidity, the rate of curing of the concrete will increase and the open time of the concrete will decrease (1.1). With varying temperature and heat, the concrete mix proportions require adjustments to allow for improved open time, printability and extrudability (1.1). The heat from pumping, friction in the hose, increased pressure of the system and the sun's radiance onto the hose, had researchers monitoring the concrete so that it could be pumped and extruded easily through the nozzle. These changes required either an increase or decrease in key components of the material prescription or the speed of the printer. This balance is critical for printing to run smoothly, therefore careful attention must be paid to the environmental conditions and the mix proportions. The most damaging delays come from the material curing too quickly in the hose or the material being too fluid to print for proper shape stability (1.1).

Figure 5 depicts the comparison between interruptions and the average temperature and the dew point temperature during the first 86 layers of the North wall. The red 'X' indicates where they were interruptions in the printing process. These interruptions lasted from five minutes to roughly an hour. As illustrated, there was an increased number of interruptions that occurred during the first 5 hours of printing. The early events were primarily due to startup issues, while some of the later events could have been caused by temperature changes and adjustments to the mix as the temperature decreased during night operations. When the temperature started to drop, two approaches were attempted: The first was to adjust the printing speed and/or pump speed while the second was to adjust to the consistency of the concrete. The former option is only feasible until there is no leeway in the printer speed or the material is too difficult to extrude or would not produce the proper bead formation. At this time the layer print times ranged from 4 minutes to 6 minutes. Once the concrete's consistency was adjusted to compensate for the temperature, then the printing time returned to around 4 minutes and 30 seconds. At approximately 11:00 pm on Day 1, the temperature seemed to stay consistent enough to have long successful print sessions. To reduce mechanical issues during printing, there were delays resulting from preventive maintenance on the equipment. This was done to mitigate the chance of delays due to pump overheating or hose clogs in order to maintain smooth constant print time. As the sun rose on Day 2, some minor problems occurred with the concrete's printability but was quickly adjusted to regulate printing.

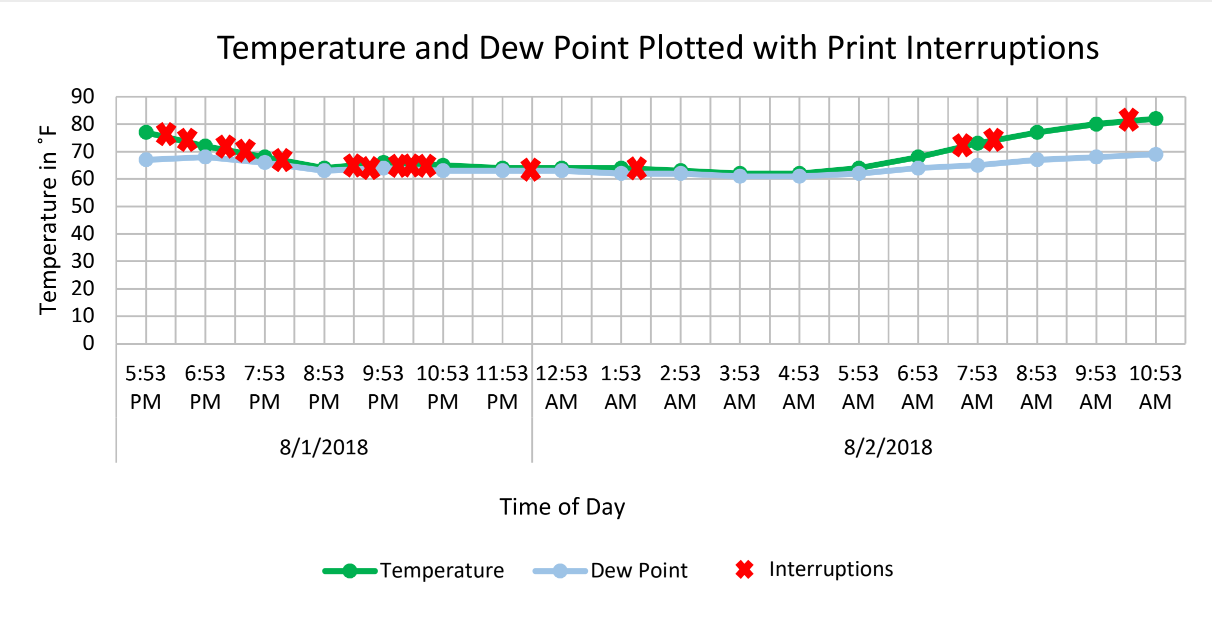

Figure 5. Comparison of Interruptions to Temperature and Dew Point.

Being able to put the data into a presentation allows researchers to physical view where and how interruptions occurred while printing. Since the environment is one of the only factors during the 3D-print that is uncontrollable, viewing comparison data will help predict issues that could ascend in future prints.

1.4.3 Print Time vs. Elapsed Time

The controller software estimated the total print time for each wall would be approximately 6 hours. With this analysis, the assessed print time to complete each wall section was roughly 7 hours to print the North Wall and the nearly 6 hours and 49 minutes to print the South Wall. The total print time was roughly 14 hours. These times are approximated as some of the layer times were not recorded due to the printer beginning to print the concrete without the start time being recorded. Since the building has a symmetrical style, the missing times were recorded when a similar section was completed. Forecasted times and minimal interpolation were used to account for those missing times. The construction print times for each portion are listed in Table 2. The projected print time from the controller software and the time series analysis predicted that the b-hut would take less than 24 hours to print.

Table 5: Total Construction Print Times

Construction Print Time Totals (From all 5 days)						
Location	**Layer**	**Description**	**Print Time**	**Gap Travel**	**Print Time**	**Wall Time**
North Wall	Layers 1-42	First layers of chevron wall	3:05:20			7:01:55
	Layers 43-86	Layer for wall section after HVAC	0:12:28	HVAC	0:00:28	
	Layers 43-86	HVAC component section near door	2:34:35			
	Layers 87-98	HVAC lintel and continuing layers	0:49:04			
	Layers 99-111	Start of roof formation, tier formation	0:20:00			
South Wall	Layers 1-42	First layers of chevron wall	3:05:20			6:49:44
	Layers 43-86	Layer for wall section with window	2:19:56	Windows	0:15:24	
	Layers 87-98	Covering lintels and continuing layers	0:49:04			
	Layers 99-111	Start of roof formation, tier formation	0:20:00			
					Total	**13:51:39**
Note: These times are approximated using interpolation and forecasted data from historical data collected.						

Delays included weather, unacceptable material quality, printer issues and manual speed adjustments. The events from a continuous portion over the dates of 08/01/2018 and 08/02/2018 of the print are listed in Table 6.

Table 6: Some of the Situations during the Continuous Print.

Date	**Situations**	**Clock Time**	**Temperature**	**Dew Point**
8/1/2018	Start Print	6:18pm	78	64
8/1/2018	Material in nozzle	6:37	74.5	67
8/1/2018	Rogue code, printer racked or out of step	7:30	74.5	68
8/1/2018	Rogue code again, adjustment of Y-axis maybe?	8:03	70	66
8/1/2018	Either rogue code or the hose management is swinging too much weight	8:28	70	63
8/1/2018	Cleanout of all machines and placed rebar, cleaned hoses, MTL has mix	9:45	66	64
8/1/2018	Start print	9:58	65	63
8/1/2018	Material too wet	10:07	65	63
8/1/2018	Material out of pump, says it separated	10:15	65	63
8/1/2018	Pause, waiting on materials	10:23	65	62
8/2/2018	Preventative Maintenance	12:07am	64.5	62
8/2/2018	Preventative Maintenance	2:25	64	61
8/2/2018	Form for HVAC placed	7:49	66	61
8/2/2018	Lintel in place	7:57	70.5	62
8/2/2018	Start print	7:58	70.5	64
8/2/2018	Finish for the day	10:45	78.5	65

It should be noted that the printing for the b-hut was performed in four printing sessions from 08/01/2018 to 08/10/2018 not including weekends (08/04/2018-08/05/2018). Therefore, using patented material [25], the total construction time would be approximately 9 days, which includes all hours on and off the job site during the range of 08/01/2018-08/10/2018. This period of time included 3 days where weather did not permit printing, as printing was performed outdoors with no cover. The total elapsed time was 31.2 hours over four sessions of printing for 5 days including set-up, materials preparation, printing, moving the printer for second half of print and cleanup. This leads to a delay time of 17.4 hours. A breakdown of those hours are listed below.

- Day 1: 5.7 hours
- Day 2: 10.75 hours
- Day 3: 8.1 hours
- Day 4: 4.67 hours
- Day 5: 2 hours

Day 1 began at 0900 in preparation for the print. The longest time period of the printing started at 1818 hours on 1 August 2018 and ended on day 2 at 1045 hours on 2 August 2018. This session printed the entire North (right) half of the building continuously (Figure 6). Printing continued on 3 August 2018 at 0215 hours and ended at 1015 hours. This 2nd session ended just below the window lintels on the South half of the building, leaving less than 3' of height to be completed on the entire print. This area can be seen as a darker horizontal portion on the left (South) half of the building (Figure 7). On 9 August 2018 at 0620 hours printing started again and continued until 1100 hours. This 3rd session was completed with approximately 1' left of the print to finish, this end area can be seen as the lighter horizontal line layer above the windows (Figure 7). The b-hut was finished on 10 August 2018 beginning at 0720 ending at 0920 hours the same day. Figure 6 and Figure 7 shows the completed walls at the end of day 5.

Figure 6. Completed North Wall.

Figure 7. Completed South Wall.

1.5 Discussion

The comprehensive layer print times in Figure 2 shows the inconsistencies and irregularities that occurred while printing the first 42 layers. Several interruptions occurred that caused this deformity such as an adjustment of the materials being delivered to the pump, altering of the speed of the print, or a hard start and stop. The speed of the print is controlled by two elements each by an operator: the printer speed (control software) and flow rate of the concrete from the pump variable frequency drive (VFD)[4]. Both speeds can be adjusted manually and can vary each layer and each concrete mix. The speed was adjusted due to:

1. Material variability (mixing and temperature variations).

[4] Variable frequency drive or VFD is used to control the speed of an electric motor.

2. The infill pattern connection with the inner portion of the wall cavity.
3. Swinging action of the hose management causing the printer to “skip” or miss steps in code.
4. Training opportunities for the Marines to learn how to control the machine.
5. The code was written in a speed to be adjusted with the printer and VFD.

During the print, the concrete is continuously mixed by batches and deposited into the pump. The pump has 2 speeds, and has a VFD to tune the flow of the concrete out of the nozzle to the consistency of the material. The pump used for this 3D printing system varies print time due to:

1. The materials being either too thick or too thin for the printing process.
2. The materials setting in the hose causing blockages.
3. Material properties.
4. Pump parts (overheating, stator, auger, etc.).
5. Climate and weather.
6. Other underlining factors (human error, other machine malfunctions, etc.).

The materials must be a specific consistency for concrete to travel through the pump, hose and nozzle. It must also cure in time for the next layer to be applied. If the materials are not correct, it will not pump through the hose correctly causing delays or curing in the hose. The material properties must be carefully reviewed for the application that it is going to be used and to ensure that it will past through the pump and nozzle. The pump’s mechanics must be checked regularly to ensure that all parts are moving smoothly and efficiently or need replacing. The climate and weather are constantly changing, affecting the composition of the materials being used. Labors should regularly rotate shifts, if a continuous print is being performed. Other machines and electrical outlets should be checked regularly as well.

The time series analysis omits some irregularities in the data, but it does not tell directly where the irregularities come from. This would come from analyzing the entire system. By looking at the entire printing processes time period and using the layer print time could pin point where the irregularities are coming from. For example, if a layer’s print time was around 5 minutes, by looking at the entire print time log, finding what happened before and after that layer’s time would show what contributed to that layer’s time. The common issues that arise are as follows:

1. Stalls with the machine’s movements
2. Waiting on materials to be made or delivered
3. Pausing for placement of vertical reinforcement
4. Weather (Rain delay)
5. Collapse in wall structure (patching required for continuation)
6. Nozzle placement adjustment
7. Blocked hose or nozzle
8. Rehoming or Rogue Code (Code off step)
9. Other (Minor issues that are not listed)

Using the times recorded and forecasted in Figure 4 also highlighted time periods of pump issues. Knowing when and where these delays happen helps identify and eliminate potential increases in time and provides a working life span of components that result in delays during continuous printing. In the case printer or pump parts, these items must be replaced to ensure that the printer and pump are in working condition.

There were times that preventative maintenance helped prevent buildup of cured concrete that would disable the continuation of printing. During this 20 min to 1-hour time period, the hoses where cleaned of all concrete material, the pumps walls were either scraped down or emptied out completely, depending on the consistency of the concrete it contained, the nozzle was cleaned out and the mixer was scraped and cleaned. These “clean-outs” also prevented large pieces of concrete from clogging the hose and nozzle.

To analyze solutions that would prevent delays and decrease elapsed time, many of the components of the printing system would have to be dissected to find the root cause of the error. Printer and software improvements could be beneficial to the printer's ability to reset during times of delays. There is also a slight difference between the prototype in Figure 1 and the finished building in Figure 6 and 7, which is mainly due the rounding corners in the code (to reduce acceleration issues) and the appearance based on layer height. An advance material delivery system would drastically reduce the amount of elapsed time. The materials aspect of the entire printing system is one of the main increases in elapsed time because the material is affected by more than one component in the printing system. Using a pumping apparatus that could handle the materials without overheating from the pressure or the wearing down of the pumps mechanical parts could also decrease the elapse time. A larger nozzle could decrease print time by allowing larger contaminant materials to pass through without clogging, increase layer height and decreasing construction time. The weather and climate aspect of printing could be resolved by printing indoors in a controlled environment but would limit the printing systems capabilities.

1.6 Conclusion

The custom gantry printing system used for this demonstration benefited from the time series analysis because it specifically points out the aspects that need improvement and forces attention to the resolution. Speculation of what could be done are not definite to the improvements of the system. By uncovering the repeated issues that increase elapsed time and construction time, researchers can improve the systems performance or eliminate some situations before they appear. This also adds a sense of integrity of the 3D-printer's abilities and dispel myths from future reported construction time all over the globe. With this printing system, the hose will need to be protected from the sun and material properties will need to be adjusted if there is a 5 to 10 degree change in temperature.

Appraising the print time, elapsed time and construction time is imperative, as each one tells the story of the build. Each indicates differences that should be evaluated individually to gain an accurate understanding of the entire process. Although others may claim to an under 24-hour print time, one must ask if the print is all inclusive and whether the timing is a reasonable goal for the associated scale of a print. The chevron-style b-hut walls took a period of 9 days to complete (including weekend and weather days) with print operations taking place on 5 of those days. The elapsed print time was 31.2 hours, which included preparations, printing and clean-up. The actual print time however was 14 hours and the delay time is 17.4. Therefore, it can be concluded that under current limitations of the technology a 512 ft^2 building structure could be completed within a 48-hour or less time period under continuous print operations with typical construction delays. This would require print operators to be on-site in shifts. Since the overall print time was only 14 hours it may be feasible to print within a 24-hour time period once the issues that lead to the lengthy delay time in the print have been addressed.

The print time, elapsed time and construction time for each structure should be reported for the purposes of clarity to avoid misleading the public and reduce the amount of hype associated with ACC. While the possibility of a building of 512 ft^2 structure in 24 hours could be done through eliminating materials issues, multiple fully trained crews and avoiding weather delays using cover or planning, the current state of the art is around 48 hours for a building with complex geometry and an infill pattern or horizontal reinforcement. Although the buildings walls have been completed, this print time does not include the time to install the roof, windows, doors and other components needed for a finished structure. Those times would also be included in the total construction time of the building.

With 3D printing, processes that are used in precast and site cast concrete making are eliminated. In construction, many sites are not under cover so exploring the capabilities of 3D printing in-situ provides information that will allow growth in field. Minimalizing infrastructure, reducing manpower and resources needed to create b-huts, peak military interest because it reduces logistics and installation time [24]. It is important to continue research in various outdoor environments to further knowledge of preparedness.

For future demonstrations, the time series analysis and environmental factors provided for assessment of the delays could mitigate issues that arise. Although the environmental factors will vary, knowing how the environmental factor relates to the delay and how it affects the construction time provides insight on how to prevent issues. Using environmental factors to stop specific delays would require prior research of the climate and weather before printing commences. Close attention must be paid to the material quality when night operations or temperature swings are present. As the temperature changes the material must be adjusted as environmental factors will affect the material behavior. The time series analysis provides further knowledge on the human factor of the construction time. The material and print quality, material delivery, pump and printer speeds are all contributing factors of the irregularities of the construction time. These factors are all based on the environmental impact on the material. Careful consideration of the time of day is imperative in the consistency of usable material for printing. Proper project scheduling and operations management will address and mitigate delays and reduce the delay time experienced in construction scale concrete 3D-printing.

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References

[1] E. Kreiger, M. Kreiger and M. Case, "An Assessment of Reinforced Additively Constructed Concrete (RACC) Structures," *Addit. Manuf.*, 2019.

[2] H. Randolph, Thomas and R. D. Ellis, *Construction Site Management and Labor Productivity Improvement: How to Improve the Bottom Line and Shorten Project Schedules*. 2017.

[3] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibband T. Thorpe, "Mix design and fresh properties for high-performance printing concrete," *Mater. Struct. Constr.*, 2012.

[4] D. Asprone, F. Auricchio, C. Mennaand V. Mercuri, "3D printing of reinforced concrete elements: Technology and design approach," *Constr. Build. Mater.*, 2018.

[5] A. S. J. Suiker, "Mechanical performance of wall structures in 3D printing processes: Theory, design tools and experiments," *Int. J. Mech. Sci.*, 2018.

[6] R. J. M. Wolfs, F. P. Bosand T. A. M. Salet, "Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing," *Cem. Concr. Res.*, 2018.

[7] A. Perrot, D. Rangeardand A. Pierre, "Structural built-up of cement-based materials used for 3D-printing extrusion techniques," *Mater. Struct. Constr.*, 2016.

[8] T. Wangler *et al.*, "Digital Concrete: Opportunities and Challenges," *RILEM Tech. Lett.*, vol. 1, pp. 67–75, Oct. 2016.

[9] Y. W. D. Tay *et al.*, "Large-scale 3D printing by a team of mobile robots," *Autom. Constr.*, vol. 95, pp. 98–106, Nov. 2018.

[10] P. Banfill, "The rheology of fresh cement and concrete-a review," *Proc. 11th Int. Cem. Chem. Congr.*, 2003.

[11] B. Panda, C. Unluerand M. J. Tan, "Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing," *Cem. Concr. Compos.*, vol. 94, pp. 307–314, Nov. 2018.

[12] C. F. Ferraris, "Measurement of the rheological properties of high performance concrete: State of the art report," *J. Res. Natl. Inst. Stand. Technol.*, 1999.

[13] S. H. Kosmatka and M. L. Wilson, *Design and Control of Concrete Mixtures*, 2016th ed. Portland Cement Association, 2016, 2016.

[14] T. S. Rushing *et al.*, "Investigation of concrete mixtures for additive construction," *Rapid Prototyp. J.*, 2017.

[15] L. Gregurić, “Concrete 3D Printing – How it Works & The Applications | All3DP,” 2018. [Online]. Available: https://all3dp.com/2/concrete-3d-printing-how-to-do-it-and-application/. [Accessed: 11-Feb-2019].

[16] R. A. Buswell, W. R. Leal de Silva, S. Z. Jonesand J. Dirrenberger, “3D printing using concrete extrusion: A roadmap for research,” *Cem. Concr. Res.*, vol. 112, no. June, pp. 37–49, 2018.

[17] A. Hoffman, “3D Printing House: Watch Apis Cor Print Tiny Home In One Day | Time,” *TIME*, 2017. [Online]. Available: http://time.com/4692376/3d-printing-house-apis-cor/. [Accessed: 06-Apr-2019].

[18] YRYS, “Site monitoring | YRYS concept by MFC,” 2017. [Online]. Available: http://www.concept-yrys.com/suivi-de-chantier/. [Accessed: 06-Apr-2019].

[19] Dome X, “Vilogia House | First 3D Printed House in the Lille Region | France,” 2018. [Online]. Available: https://cybe.eu/portfolio-item/vilogia_house/. [Accessed: 06-Apr-2019].

[20] Y. W. D. Tay, B. Panda, S. C. Paul, N. A. Noor Mohamed, M. J. Tanand K. F. Leong, “3D printing trends in building and construction industry: a review,” *Virtual Phys. Prototyp.*, vol. 12, no. 3, pp. 261–276, Jul. 2017.

[21] “The Benefits of 3D Printing from Concrete - Concrete Renovations,” *Concrete Renovations*, 2018. [Online]. Available: https://www.concreterenovations.co.uk/news/the-benefits-of-3d-printing-from-concrete/. [Accessed: 06-Apr-2019].

[22] J. Sanjayan, “3D concrete printing could free the world from boring buildings | The Independent,” *The Conversation*. [Online]. Available: https://www.independent.co.uk/life-style/design/3d-concrete-printing-could-free-the-world-from-boring-buildings-a8644986.html.

[23] L. Mirani, “Architects are starting to 3D print houses—but without a house-sized printer — Quartz,” *Quartz*, 2013. [Online]. Available: https://qz.com/68780/architects-are-starting-to-3d-print-houses-but-without-a-house-sized-printer/. [Accessed: 06-Apr-2019].

[24] B. Diggs, “Clustering Analysis: Envelope Energy Performance, Moisture Control and Thermal Bridge of Military B-HutsNo Title,” North Carolina A&T State University, 2017.

[25] G. Al-Chaar, M. Case, G. Northrup, M. Kreiger, B. MacAllisterand W. Wagner, “Printable Concrete Composition,” US20180057405, 2018.

[26] G. Al-Chaar, M. Case, G. Northrup, M. Kreiger, B. MacAllisterand W. Wagner, “US20180057405.pdf,” 2018.

[27] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibband T. Thorpe, “Mix design and fresh properties for high-performance printing concrete,” *Mater. Struct. Constr.*, vol. 45, no. 8, pp. 1221–1232, 2012.

[28] H. A. Mohamed, “Effect of fly ash and silica fume on compressive strength of self-compacting concrete under different curing conditions,” *Ain Shams Eng. J.*, 2011.

[29] N. Roussel, “Rheological requirements for printable concretes,” *Cement and Concrete Research*. 2018.

[30] S. Nicholson, “This $10,000 3D-Printed Concrete House Took Only 24 Hours to Build,” *Interesting Engineering*, 2018. .

[31] J. D., “We Interviewed Apis Cor, Creators of the 3D Printed House,” *3dnatives*, 2018. .

[32] M. Li, Y. Weng, Y. Wei, D. Tayand H. Pham, “Large-scale 3D printing by a team of mobile robots Large Scale Selective Laser Melting View project 3D Cementitious Material Printing View project.”

[33] B. P. Emrath, “Spaces in New Homes,” pp. 1–8, 2012.

[34] A. C. Harvey, *Forecasting, structural time series models and the Kalman filter*. Cambridge: Cambridge University Press, 1990.

[35] G. E. P. Box, G. M. Jenkins, G. C. Reinseland G. M. Ljung, “Time series analysis: forecasting and control,” in *J. Time Ser. Anal.*, 5th ed., vol. 37, Hoboken, New Jersey: John Wiley and Sons Inc., 2015, pp. 709–711.

[36] R. J. Hyndman and G. Athanasopoulos, *Forcasting:principles and practice*, 2nd ed. OTexts, 2018.

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14. ABSTRACT

In additive construction, ambitious goals to fabricate a concrete building in less than 24 hours are attempted. In the field, this goal relies on a metric of print time to make this conclusion, which excludes rest time and delays. The task to complete a building in 24 hours was put to the test with the first attempt at a fully continuous print of a structurally reinforced additively constructed concrete (ACC) building. A time series analysis was performed during the construction of a 512 ft2 (16'x32'x9.25') building to explore the effect of delays on the completion time. This analysis included a study of the variation in comprehensive layer print times, expected trends and forecasting for what is expected in future prints of similar types. Furthermore, the study included a determination and comparison of print time, elapsed time, and construction time, as well as a look at the effect of environmental conditions on the delay events. Upon finishing, the analysis concluded that the 3D-printed building was completed in 14-hours of print time, 31.2- hours elapsed time, a total of 5 days of construction time. This emphasizes that reports on newly 3D-printed constructions need to provide a definition of time that includes all possible duration periods to communicate realistic capabilities of this new technology.

15. SUBJECT TERMS

Concrete; construction; extrusion; 3D printing; building; time

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