THE REDUCTION OF CONSTRUCTION DURATION BY IMPLEMENTING CONTOUR CRAFTING (3D PRINTING)

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ABSTRACT

Construction methods are evolving daily due to the increasing challenges and complexity in projects which require fast, safe, and efficient methods to deliver their scope. Contour crafting (CC) is a 3D printing method developed for constructing big elements, it is based on printing the building layer by layer using special material ejection. This method promises an automated construction process that is safe, fast and reliable. 3D printing helps us make one step further towards lean principles by minimizing waste in construction duration and increasing Poka-Yoke (error-proofing) through activity automation. Furthermore, it guarantees an evolution in building textures that increases the quality of life for its residents without having a negative impact on public safety and welfare. In this paper we study the effectiveness of this technique in reducing construction duration using computer simulation and comparing the building of a house using the conventional construction method with the Contour Crafting method. Results give an overview of the potential of improvement in the construction field; and how waste can be reduced by the industrialization of the construction process which facilitates the implementation of lean philosophy. Findings suggest that contour crafting can reduce project duration by automating the construction process.

KEYWORDS

3D-Priniting, Contour Crafting, Waste in Construction, Production System Design, Industrialization, Lean construction.

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INTRODUCTION

THE CONVENTIONAL CONSTRUCTION METHOD

The construction industry is becoming extremely competitive that companies are bidding at lower prices and excluding their profit to get projects, then the problem of delivering them on time arises (Higgins et al. 2012). The concept of time is becoming more and more important, and for construction stakeholders finishing a project earlier means thousands and millions of dollars profit. Many systems and methods were developed in purpose of delivering high quality projects in a short period of time, but the conventional method of placing concrete is still the same. Whether for precast concrete or casted on site concrete, time and labor cost is still high, due to the need of assembling formwork to get the structural components shape needed. In addition to time and labor cost, pouring concrete into formworks limits the creativity of architects in various geometries to avoid high costs and to be able to reuse the same formworks. Fortunately, an innovative technique known as 3D printing promises to eliminate the restrictions imposed by the use of conventional formwork by providing a high quality and wide range of construction geometries within minimal duration.

3D PRINTING, A NEW TECHONOLOGY

3D printing is based on the technology called Stereolithography, an innovative invention based on creating a 3D object by replicating its cross section, layer by layer (Hull 1986). This technology, if implemented in the construction industry, promises less human factor related problems, just in time deliveries of customized parts, design freedom for architects, greater functionality for structures, better control of materials, and better finishing of a homogenuous structure (Fisher et al. 2013). In attempts to implement this technology in construction, 3D printing on a larger scale had to be invented, this new technique was called contour crafting (Khoshnevis 1998).

WHAT IS CONTOUR CRAFTING?

"Contour Crafting is an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling in order to create smooth and accurate planar and free form surfaces out of extruded materials." (Zhang & Khoshnevis 2013). CC constructs objects layer by layer using robotics, it is used for small scale industrial parts and also was identified as the only method capable of delivering components large enough for building structures (Fischer et al. 2013).

The contour crafting machine is a combination of a robotic extruding system with two metal rails and gantry frames (Figure 1). The machine takes its order from a 3D CAD software that can be customized even during execution, it circumnavigates the perimeter of the structure pouring concrete layers through a nozzle. Special hardeners and fibers are used in the concrete mortar mix to make each layer hard enough to carry the next one by the time the nozzle circumnavigates the whole structure. It can further install all the plumbing, electrical and air conditioning conduits in addition to the required reinforcement. All of these are installed in small segments embedded through layers of concrete that are being poured by the CC machine in order not to hinder its movement. Furthermore, the gantry frames can be altered to move along the height of the structure building one story at a time and multi-nozzle contour crafting machines can be used for faster construction of big buildings (Khoshnevis 2012).

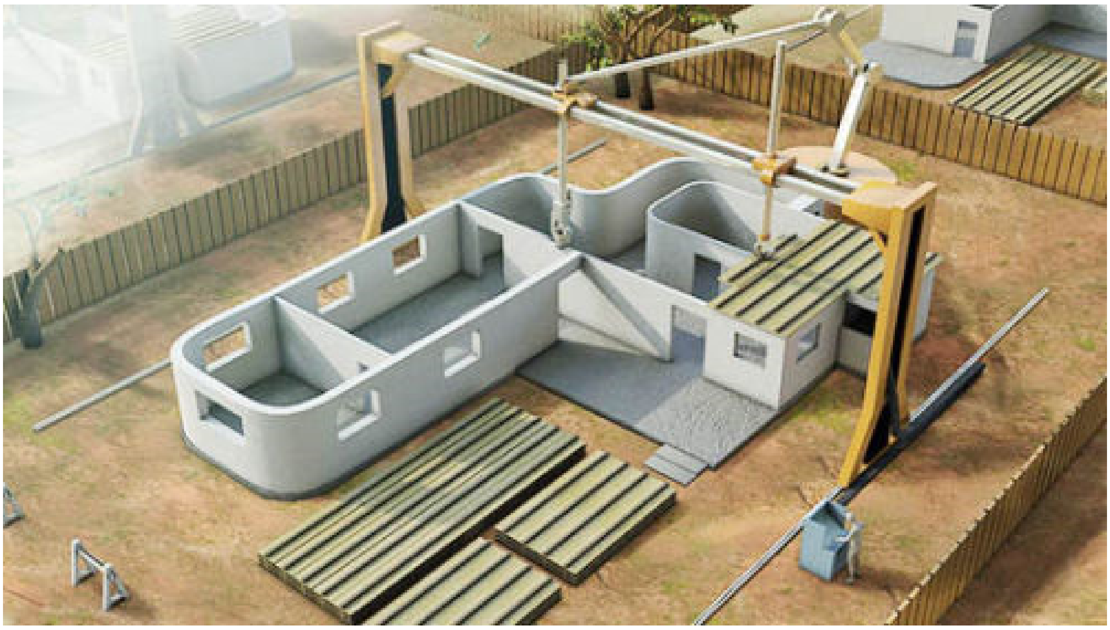

Figure 1: The Contour Crafting Machine (www.contourcrafting.org)

WHY USE CONTOUR CRAFTING?

Contour Crafting provides flexibility in building concrete shapes that was very difficult to achieve in the conventional pouring method; with that, houses can be built efficiently and environmentally friendly by adapting them to exterior conditions (Zhang & Khoshnevis 2013).

Two delicate issues were handled in contour crafting to have a significant return on safety, quality, and productivity in contrast to other fully automated construction practices. The first is rebar installation, an important aspect since concrete fails under tensile and bending loads. The second is formwork, one of the most important components of building since it affects significantly the quality of concrete. Moreover, concrete was tested and the best mix proportions for 3D printing were determined. The effects of the layering process on density, compressive strength, flexural strength, tensile bond strength, and drying shrinkage were also studied. The additive extrusion process proved that a high performance of the material is retained in the printing method (Khoshnevis et al. 2005; Le et al. 2012).

Other advantages of this method are that it can provide a wide range of surface shapes and complicated structures with few types of troweling tools unlike the conventional plaster handwork and sculpting (Khoshnevis 1999). CC is also a rapid prototyping process that gives a better surface quality that is exceptionally smooth and accurate due to the elimination of surface discontinuities. The fabrication of a component is considerably faster than other prototyping methods because the layers thickness is larger. CC is used for a wide variety of materials such as thermosets, thermoplastics, metal, cement, clay, concrete, and others. Currently at the USC (University of Southern California) rapid prototyping laboratory intensive research on

Contour Crafting is done to improve the machine design, speed and superior surface forming capabilities (Khoshnevis 2012; Khoshnevis & Hwang 2005).

With this advanced technology, a new era of construction is expected to happen where complete neighborhoods with ultimate architectural flexibility will be built with a minimal time and cost compared to the conventional method. In addition, the flexibility in designs that this method can provide were found to be resistant to lateral forces; therefore, an increase in safety is associated as well with this new technique (Khoshnevis 2012). Hence, the main focus of current studies in this domain is improving CC, due to its large benefits and its capability of being integrated with other robotics methods (Kwon 2002). Contour crafting is expected to build a 200m^2 house in 20 hours (Khoshnevis 2012). This study investigates the duration required to construct a 200 m^2 house using the conventional construction method and the contour crafting method by simulating both. Additionally, it highlights the role of contour crafting in achieving lean principles in construction.

METHODOLOGY

For this study two simulation models using EZStrobe are done; one for the conventional construction method used, and another using Contour Crafting. The construction activities considered for the above simulations are those for a 200 m^2 single unit, square shaped house, with a 3 m clear height shown in Figure 2. The house is divided into four small apartments constituted of four rooms. This layout is very useful if applied for poor regions where many families can be sheltered in the same structure.

Figure 2: Simulated House Layout Drawing using Revit

The model was subject to structural analysis using ETABS to assure its safety. For both simulations, only concrete pouring and rebar installation is considered, site preparation, foundation pouring, mechanical, electrical, plumbing and finishing activities are excluded from this research.

The conventional model consists of ten reinforced concrete walls having each a thickness of 20 cm, and an area of 42 m^2. These structural elements hold at their end a 30 cm concrete roof slab having an area of 200 m^2. As for the second model; it has the same components except for the roof; it is a composite structure made of a steel deck along with 10 cm concrete topping. In addition, the model contains 24 steel lintels to be placed above each opening.

CONVENTIONAL CONSTRUCTION METHOD SIMULATION

The simulation of this method consists of five EZStrobe models of which two are for pouring concrete; one for the roof, and the other for walls. As well, two models were done for laying the roof and wall formworks without considering lintel placement since concrete walls are reinforced. As for the final model (Figure 3), it combines the whole construction process using the outputs generated from the preceding four models.

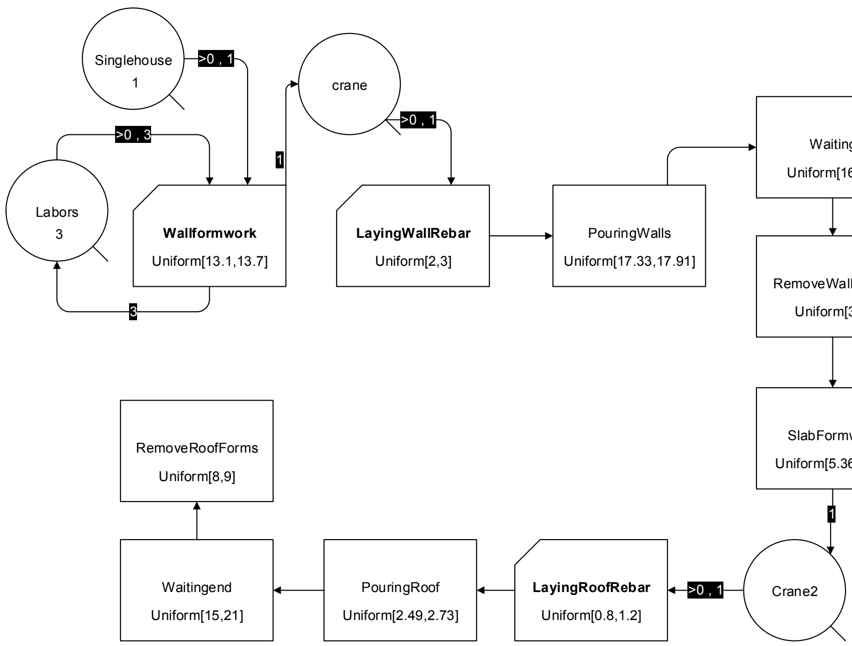

Figure 3: Combined Conventional Method Simulation Model

The main activities are described below:

- Walls formwork: Consists of placing the first face of formwork, its duration was found to be ranging between 13.1 and 13.7 hours.
- Walls reinforcement: Consists of laying preassembled rebars inside the walls formwork using a crane, this activity takes between two to three hours.
- Pouring concrete for walls: Consists of pouring a total amount of 84 m3 of concrete for walls, one truck is assumed to have a capacity of 10 m3.
- Removing walls formwork: Formwork has to be removed two to three days after pouring is completed, considering one working day made of height hours. This activity takes between three to four hours.
- Roof formwork: Consists of installing the slab formwork for the roof, it has a duration varying from 5.36 to 5.66 hours.
- Roof reinforcement: Consists of laying the preassembled rebars of the roof within a duration of 0.8 to 1.2 hours.

- Pouring concrete for roof: Consists of pouring a total amount of 60 m3 of concrete for the roof, the duration was found to be ranging between 2.49 and 2.73 hours.
- Removing roof formwork: Consists of removing the slab formwork after casting is done and concrete reaching the required strength which is after around two working days, this activity takes between 8 and 9 hours.

Results

The time assigned for the main activities was generated by modeling each one alone for 100 runs to get the uniform distribution and input it in the model of Figure 3. After 1000 iterations of the conventional method combined model we got a total average duration of 90.52±2.12 hours with a standard error of 0.067, a summary of the numerical information is presented below:

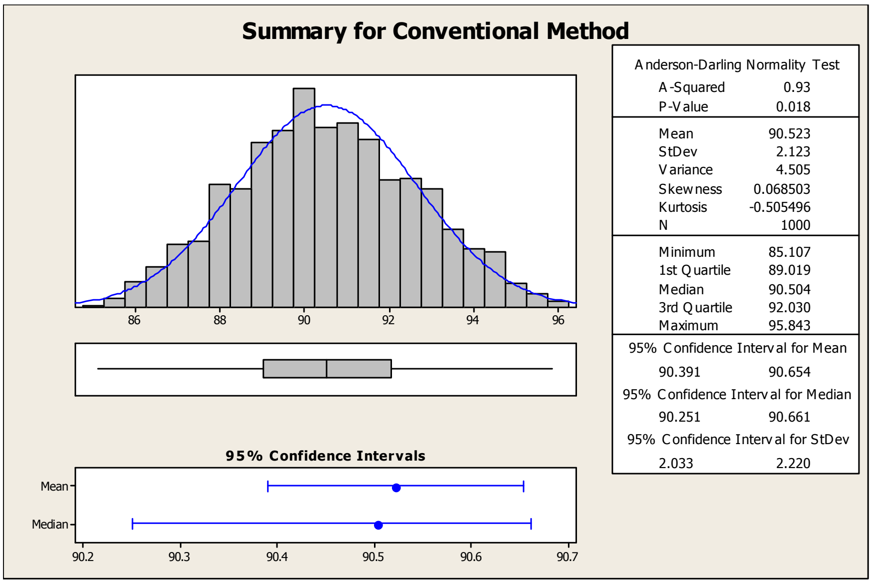

Figure 4: Convention Method Statistical Summary (Minitab)

Contour Crafting Method Simulation

The simulation model of the CC method is done using EZStrobe also, it is a simplified model to represent major activities and estimate a duration for the process. The model is divided into six entities designated in Figures 5 to 7 by the crossing lines; each entity can't start unless the loop of the preceding one has finished. The model simulates pouring and rebar installation activities working in parallel such that when the machine is pouring two layers of concrete for half the house perimeter, the robotic arm is installing the reinforcement of the other half.

The first entity is a simulation of the first 140 cm wall height for the full house (Figure 5). By the time the machine installs the reinforcements of half the house, the nozzle starts pouring above these reinforcements, while the robotic arm continues its way to install the second half. The number of vertical segments T20 at 45 cm in half the house (7,000 cm perimeter) is 156 segments. The number of horizontal segments needed, T16 at 20 cm, is 155 segments.

As for pouring concrete, the rate of the nozzle is 12.7 cm/sec (Lemley 2005) with layers of 20 cm width and 10 cm height. To pour two layers of 7,000 cm length we need about 1,102 seconds to finish. To avoid subjecting the nozzle to idle time which solidifies the concrete, we decided to decrease the rate of the nozzle to balance it with that of installing rebars. The nozzle has to pour two layers for half the house in the same duration as the robotic arm installs rebars for the other half of the house. That is, pouring two layers for half the house (7,000 x 2 cm) in 2,700 to 2,800 sec; while the robotic arm is installing all rebars for the other half of the house that is 311 rebars, in approximately 2,874 sec. This duration was calculated by assuming that the robotic arm picks up 10 segments of reinforcement together and install them one by one along the wall path. Vertical rebars has to be screwed together, others are just placed. To complete the first 140 cm wall height for all the house, we need 14 loops.

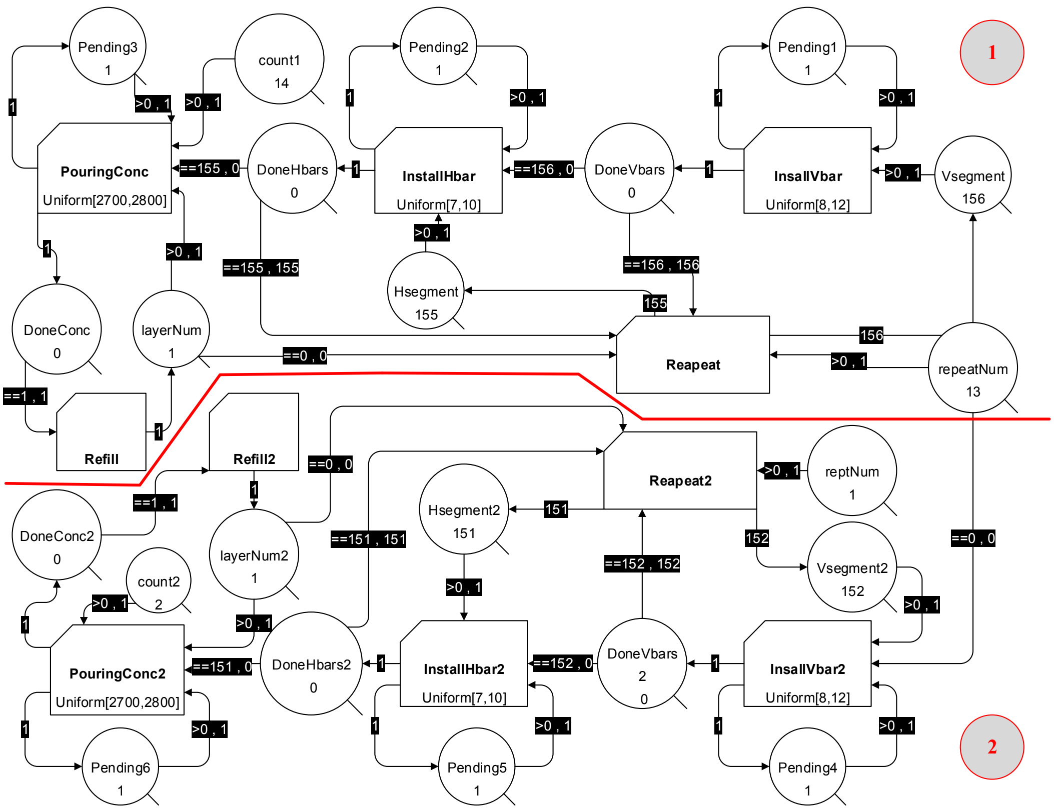

Figure 5: Entities 1 and 2 of the CC Simulation Model

The second entity is the simulation of preparing the base of eight windows having a 50 cm length. For the vertical and horizontal reinforcement we subtracted the rebars contained in the length of the windows from the total number. As for pouring we calculated the time needed to pour one full layer to reach 150 cm wall height, and then pour a layer that excludes the window lengths without reducing the duration since the machine will still pass above windows. Two loops are needed to finish one full house.

The third entity needs four loops, equivalent to two horizontal lines of rebars (40 cm height) to continue building the house above windows, from 160 cm to 200 cm height.

The fourth entity is lintels installation, 24 lintels in total are installed, eight above windows, 16 above doors. This activity takes between 1,488 sec to 5,040 sec (Figure 6).

The fifth entity is the simulation of pouring and rebar installation for the remaining 100 cm remaining height to reach the 3 m wall in 10 loops (Figure 7).

The sixth entity depicts the installation of steel deck composed of 93 pieces where each piece is 30 cm wide and 7 m long with a rate similar to that of the lintels. In addition, pouring the roof takes around 7,700 sec because it is poured at the maximum nozzle rate.

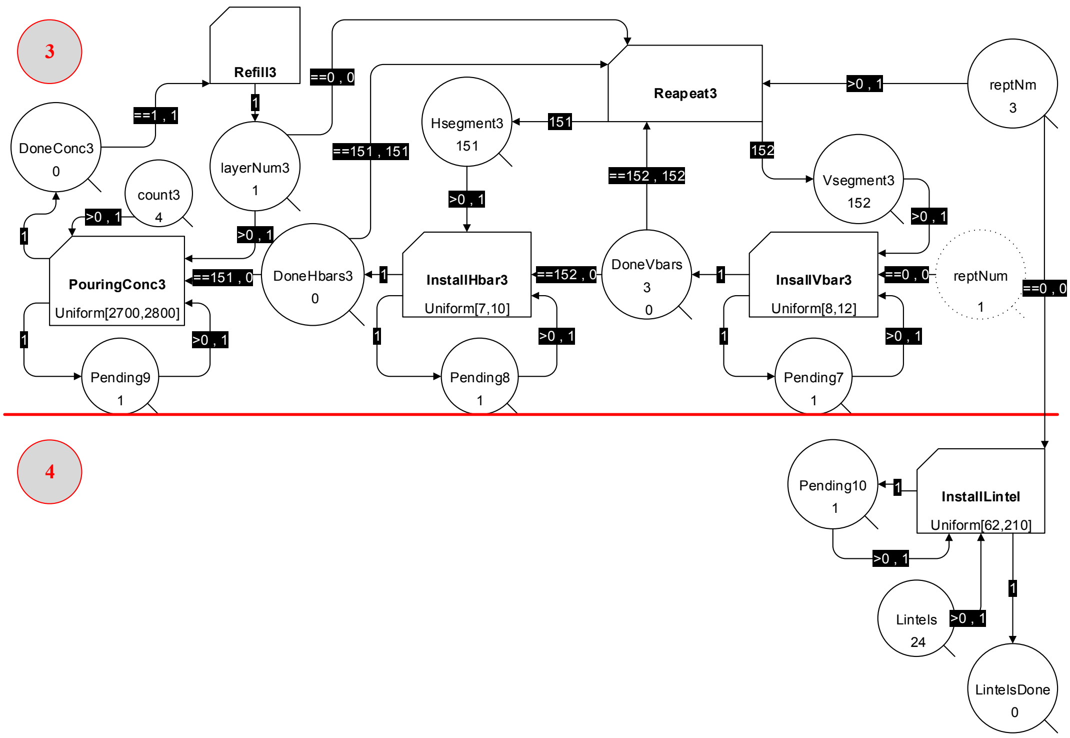

Figure 6: Entities 3 and 4 of the CC Simulation Model

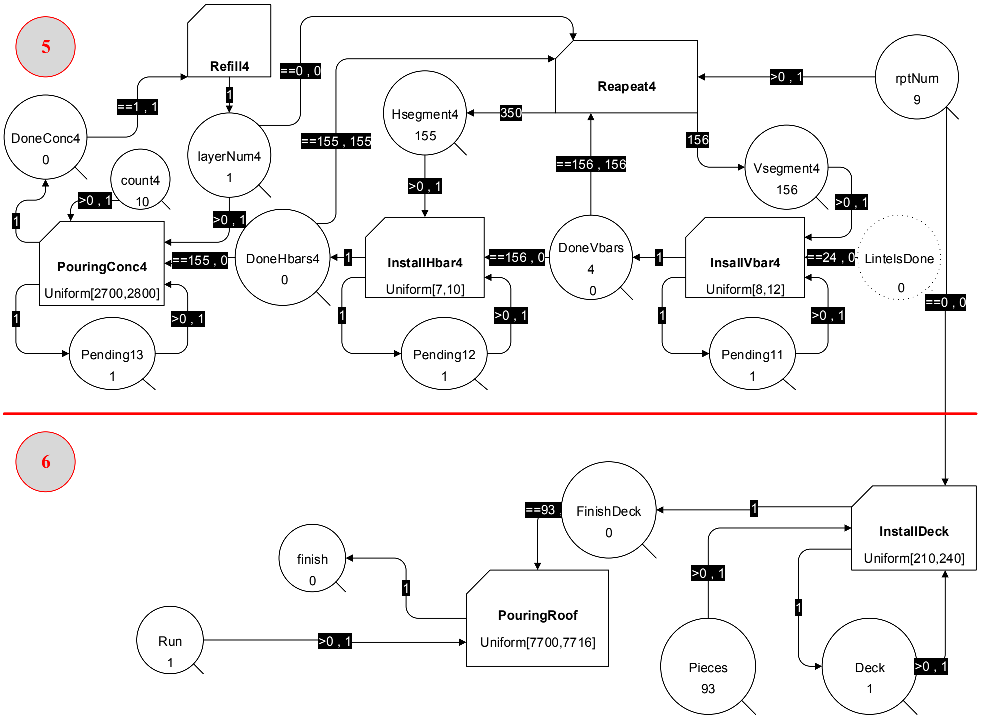

Figure 7: Entities 5 and 6 of the CC Simulation Model

Results

After 1000 runs of the model, the results of the simulation gave a total duration of 29.54±0.065 hours with a standard error of 0.002, a summary of the numerical information is presented below:

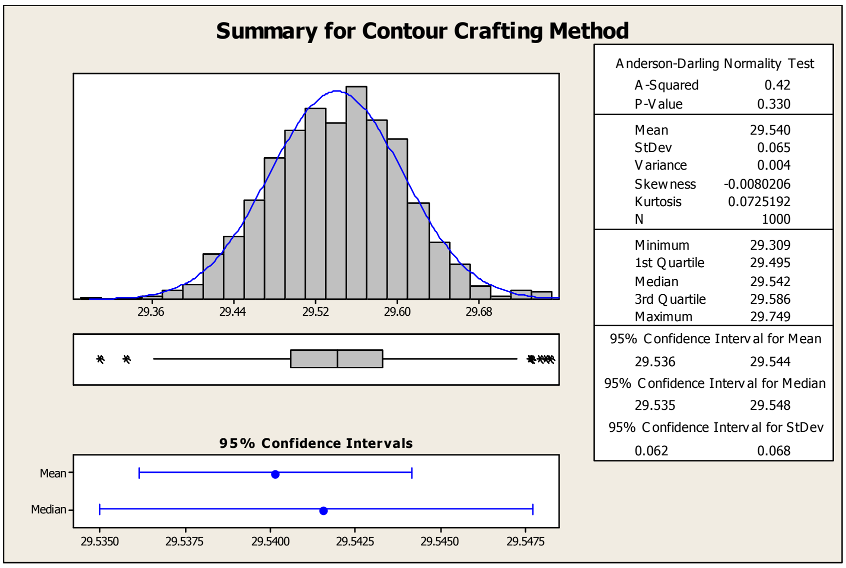

Figure 8: Contour Crafting Statistical Summary (Minitab)

DISCUSSION

After simulating the contour crafting process, we got an average duration of 29.5 hours. The structural construction of the project by the CC method is faster than the traditional. CC method is expected to build a 200m^2 house in less than 20 hours, custom designed (Khoshnevis 2012). However, reaching the target of 20 hours needs further efforts specially to design a fast robotic arm since rebars installation defined our project duration and fiber reinforcement is not enough for large spans.

The results of the model show that the conventional construction method of a 200m^2 house with reinforced concrete has a duration of almost three times more than that of contour crafting and this can be seen in Figure 9.

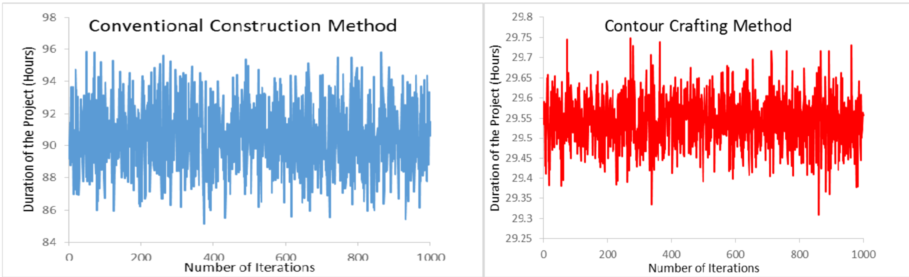

Figure 9: Project Duration of Conventional Method vs Contour Crafting

To identify the reasons for this difference, we checked the activities durations. In the conventional construction method. Installing and removing formwork takes around three working days; these durations include man hours and effort which is also costly to the project and is reduced by CC. Another necessary activity in the conventional method is waiting for concrete to set before being able to continue working, it takes about four to five working and is not needed in CC. Therefore contour crafting showed to be faster than the conventional construction method.

LEAN PRINCIPLES ACHIEVED

In contour crafting (3D printing) projects, design is carried out by consensus of all parties and is elaborated in one 3D model. In order to produce an accurate model containing the least amount of clashes, it is important to involve contractors at the early stages of design. This integrated approach improves organization's ability to apply Lean project delivery. To facilitate that, teams should not to be overloaded with work while others are idle. This is elaborated in contour crafting where the project scope is well defined in the integrated model and the workload is divided into consequent layers keeping a consistent production rate.

Quality is an important factor to consider when evaluating whether lean production has given the customer the value needed or not. In CC any quality problem will be highly visible by poke-yoke since only one machine or crew is working on site. Such problem will hinder the continuous work of the machine provoking fast problem solving.

In addition, overproduction is considered as a main source of waste that must be avoided in any Lean project (Liker 2004). The model used in contour crafting is an integrated model. The machine prints various structural elements, plumbing and electrical wires simultaneously keeping a continuous flow and just in time delivery.

The only inventories kept are those of raw materials, while inventories of work in progress are fewer and of relatively smaller sizes. For example pouring the next concrete layer is pulled by the placement of lintels.

Standardization and continuous improvement are critical in lean production and can be applied in 3D printing. For the machine to do various tasks; each task should be standardized, and the whole model continuously improved whenever standardized tasks fail to generate value. Moreover, implementing the 5S tool (sort, set in order, shine, standardize, sustain) (Liker 2004) can facilitate the machine and robotic arm work.

CC projects are expected to form a less suitable environment for several types of waste defined by Ohno (Liker 2004). Unnecessary movement of people or goods is reduced during construction since the site is run by a single crew and one operating machine. Nevertheless, unnecessary movement of the machine might occur; accordingly, a detailed study is required to find the shortest and optimal path for the nozzle to take while pouring the structure, as for multiple nozzles a collision-free path should be defined. Other constraints should be considered too, like the minimization of the nozzle idle time to avoid concrete solidification in the pipelines. An optimal operation of the machine can be achieved using a 3D simulation platform (Zhang & Khoshnevis 2013).

In regards to cost, target costing is one of the key elements towards lean project delivery (Ballard & Rybkowski 2009). Having a target budget in mind makes it essential to reduce the overall cost of the project in order to keep a safe margin of profit. CC projects have a potential to reduce cost due to the following factors: elimination of formwork costs, reduction of project duration (Fischer et al. 2013), and minimization of overhead cost during construction since less supervision is required. Other additional costs like the cost of the machine need to be studied. But it is expected that the saving would overweight the extra costs.

CONCLUSION

Contour crafting is a very powerful tool that can be used in AEC (architecture, engineering, and design) applications, since it can build small scale architectural purposes models up to real life scale engineering projects, in more efficient ways. It can also achieve very complex structures that are hard to build using conventional methods, and which are more structurally sound then the present design of buildings. CC technology improves the quality of the structure and allows building it in a duration approximately three times less than that of the conventional method according to the simulation done. This technology could be used by governments to build structures for homeless or refugees in a reduces time and labor cost (Khoshnevis 2012). Further research can be done on the difference in cost between the two methods. An economic and financial assessment for CC implementation should be done for each country because construction cost varies from country to another. Likewise, research is required to improve the concrete placement method and robotic arm rebar installation. Finally, advanced skills in robotics, building information modeling, programming, and construction engineering are required, along with high management skills to deliver automated construction projects according to lean principles.

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