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Simulating the Workflow of Industrial Robotic Steel and Concrete 3D Printers to Build Organic Shaped Structures

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Abstract

For decades, humans have designed concrete structures according to limited shapes of concrete elements that can be cast into forms and rebar shapes that can be manufactured on a mass scale. Architectural creativity has always been bound by the structural design capabilities and constructability. With generative design emerging, organic shapes of architectural elements are expected to be more emphasized in design outputs. This is accompanied by organic design of structural elements and reinforcement shapes that are generated with optimized layouts based on algorithms that explore thousands of design possibilities. Manufacturing of such steel reinforcement has never been possible before. However, with the emergent of 3D printing and advanced robotics in steel printing, engineering designs are only bound by the architect's creativity. This paper aims to propose, analyze and optimize the workflow of concrete and steel printing robots on a construction project. Data on the printing properties (concrete and steel printing speed, robot speed, robot arm, etc.) are based on the best performing robots in the industry. Then agent based modelling using Anylogic was performed to simulate the printing of retaining and shear walls for a floor in a reinforced concrete building. Results show values used for later optimization of steel printing heads to concrete printing heads ratios using the current technology. Additionally, this study shows that the proposed method can reduce both time and cost in a construction project and provide cleaner, safer, more automated and unbounded construction processes. Findings from this research call for an in-depth investigation of the capabilities of steel 3D printing and its utilization in construction. It also highlights the importance of considering the application of new construction tools that would cope with the rapid growth of computational power, and its adoption in design practices.

Keywords: 3D Printing; concrete 3D Printing;, Steel 3D printing; Generative design; Robotics in AEC industry.

1. Introduction

Construction has always been lagging manufacturing, and this is true with the 3D printing industry as it is true for other industries. Globally, the 3D printing market increased from US$1.5 billion in year 2011 (Kilger & Wienken, 2016), to US$4.2 billion in year 2015 with only US$24.5 Million for the concrete printing industry (marketsandmarkets.com, 2016). An expected growth to US$22.4 billion in year 2020 (Alto, 2016) is expected with USD$56.4 Million for the concrete industry (marketsandmarkets.com, 2016). This increase is due to the wide usage of 3D printing in different sectors of the industry including aerospace, automotive, medical, architecture and engineering sectors. If considering only architecture and construction, this development was accompanied with the ability to 3D print various most importantly concrete (Khoshnevis, 2004), and steel (MX3D/Metal, 2015). Advancements in 3D printing means and materials allow architects to implement most complex designs using genetic algorithms (Larsen, 2012), and this will lead to a wider adoption of organic shapes for load bearing structural elements. If working with a steel structure, 3D steel printing solutions have been proposed and implemented (MX3D/Metal,

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2015). Concrete 3D printing of large scale complex geometries has also been studied and applied. Organic shaped concrete elements have already been generated using algorithms, and have been printed using ultra high strength concrete (Gosselin, et al., 2016), yet if looking at a real scale fully functional structural element, concrete should be reinforced with steel to better distribute internal forces that result from external effects. Fiber reinforcement has been used with concrete mortar to serve this issue, and while fibers enhance the mechanical properties of concrete, fiber reinforced concrete is only limited in use to a certain height since discontinuous reinforcement will not provide enough tensile strength for structural elements. In addition, using standard rebar would not solve the problem for two reasons: first the complex geometry of concrete would, in some cases, make it very difficult if not impossible to place standard rebar inside concrete and second the concrete 3d printing nozzle wouldn't be able to pass through the already erected vertical rebar. In this paper, a methodology for 3D printing organic shaped rebar and concrete will be proposed and its workflow will be simulated using Anylogic to determine its optimal configuration.

2. Concrete 3D printing

In 1997, Joseph Penga conducted an experiment on solid freeform construction where he attempted to 3D print cement by depositing a thin layer of sand followed by a layer of cement bonded by a blinder. Historically, this was the first attempt to 3D print cement (Penga, 1997).

Later, other methods of 3D printing were developed to serve the construction and architecture industry. Several researches considered the different methods of 3D printing for the construction industry such as (Khoshnevis, 2004), (Lim, et al., 2012), and (Gosselin, et al., 2016).

The main three additive manufacturing methods that suit construction and architecture are: Contour Crafting (Khoshnevis, 2004), D-Shape (Dini, 2008), and Concrete Printing (Lim, et al., 2009).

2.1 Contour Crafting

This method is based on extruding concrete from a nozzle and building forms layer by layer while smoothening layers using a trowel. The path that it takes is dependent on a CAD file that is linked to the robotic arm's program. It is characterized by its applicability in-situ, high speed, automation, and ability to use the robotic arms for other uses (Steel reinforcement, MEP fixtures, Lintels…) (Khoshnevis, 2004).

Despite its many benefits, this method has some drawbacks such as extra process requirements, weak bonding between batches due to segmented backfilling batches by a considerable amount of time interval (Lim, et al., 2012), and its restriction to print only 2.5D topologies (only in vertical direction) (Gosselin, et al., 2016).

2.2 D-Shape

D-Shape printing is a method developed by Enrico Dini. It is composed of a frame that has the print head mounted into it. These nozzles depose granular materials in layers and these granules are hardened by a binding material. When done printing, sand is removed from around the printed structure for reuse.

2.3 Concrete Printing

This method is like contour crafting where a cement is extruded through a nozzle layer by layer until the intended shape is built. However, this method allows for more geometric control due to the small nozzle size. Despite its precision, this method is slower than contour crafting and it only allows for off-site construction.

A recent study by (Gosselin, et al., 2016) aimed to explore a new way of printing concrete. In this study, an industrial 6-axis robotic arm was used to trace the printing path using the tangential continuity method (TCM) which in his opinion is better for large-scale additive manufacturing and would exploit the geometric potentiality of 3D printing technologies. TCM has also proven to yield more efficient and mechanically sound construction (Gosselin, et al., 2016).

This method is much like the fused deposition modeling (FDM), first the cement mortar is prepared and then conveyed using a pump to a mixing screw located in the printing head. Meanwhile, additives are added into the mix to accelerate the hardening of concrete right after it is extruded. This method could revolutionize construction and architecture since it could print complex 3D shapes with no addition cost and at large scale. The use of robots and the use of TCM method for slicing would automate the process, minimize waste and error, and would produce structurally sound concrete elements using high performance concrete. For all these reasons, the latter will be adopted in this study.

3. Steel 3D printing

Additive manufacturing (AM) has been around from 1987. Ten years after its initial emergence, ArmoMet developed laser additive manufacturing (Wohlers & Gornet, 2014), and so did this industry grow in a fast pace and is promising low cost of highly complex metal based parts (Ding et al. 2015).

On a high level of abstraction, AM process is classified to either a powder-feed/bed process, and as the name implied, powder is laid on a bed and the part is build layer by layer, or a wire-feed process where a wire is fed throughout a nozzle and melted using one of several ways discussed below.

Powder-feed/bed approach can print parts with high accuracy and functionally graded materials. However, its powder deposition is very slow compared to its counterpart, the wire-feed system. (Ding et al., 2015).

Wire-feed AM can also be classified into different processes depending on how the metal is disposed (Karunakaran et al. 2010). It has higher material usage efficiency and faster disposal rate that the powder-feed process which means waste is eliminated from the process and the risk due to using powder metals is eliminated (Taminger & Hafley, 2006). In addition, wires are less costly than powder.

Three main systems are found which are: laser based, arc-welding base and electron-beam based. Metal arc welding is most efficient is considering energy efficiency with an efficiency up to 90% compared to laser based with (2-5%) and electron beam with (15-20%) efficiency (Rännar et al., 2007). All wire-arc AM methods have a high deposition rate. Laser based AM needs a bed to dispose materials on and electron beam requires a high vacuum environment which is more suitable for aerospace applications.

Another innovative technology used by (MX3D/Metal, 2015) to print free standing 3D organic shapes using wire-arc AM and a robotic arm. This technology was used to create some fascinating projects such as the steel bridge in Amsterdam.

Arc-welding is the most suitable method available if is to be utilized in the construction industry due to its high disposition speed, low cost of equipment and materials, high efficiency and low volume which means ease of transportation or mounting on a robotic arm. For that we will be using the wire-arc process in this study.

4. Additive manufacturing missing chain in construction

The above literature review summarized the latest development in concrete and steel 3D printing technologies. Civil and construction management researchers have been trying to optimize and enhance the concrete printing process, yet they have not taken into consideration the compounding effects of the on growing complexity in architectural practices especially after the latest advancements in genetic algorithms (GA). The latter allows the computer to generate organic shapes which are much more optimized than any human design mimicking nature's evolution in this process, based on a set of algorithms and rules set by the designer (Swenson, 2016). Steel AM has facilitated the work of manufacturers and is starting to get architects interest as well, and the technology is quite advanced, yet it has not been implemented to construction yet. That is probably because of the low levels of innovation in the construction industry. Yet with the exploration of GA, new architectural shapes will emerge with a complexity not seen before. Here rises the need to explore alternative methods to design the structural aspect of those shapes. GA will have an important role in this design process since traditional rules found in building codes will not be sufficient to determine complex shapes integrity and robustness, neither will the available steel shapes help in shaping the steel that is generated with GA. This study aims to simulate the process of 3D printing a concrete member with organic shaped steel reinforcement and optimizing the number of steel 3D printing heads needed to maintain a balanced process.

5. Methodology

To reach the research objective, a stepwise research methodology has been designed. First the author conducted a review on the latest emerging technologies available in construction. This review led to studying and analyzing the deficiencies that 3D concrete printing still has from a structural engineer's point of view. Then, an innovative approach was suggested to solve the problem of reinforcing 3D printed concrete by incorporating steel printing into the process.

Due to the lack of technology that can implement this new approach, a simulation model is built to analyze the applicability of the process and assess its benefits and drawbacks.

In an earlier study, discrete event simulation was used to simulate the contour crafting process and its impact on construction was explored (Rouhana et al., 2014). For this study, agent based modeling (ABM) is used to simulate the process of concrete and steel printing. Parameter values that are used as input to the model have been collected from literature and from the latest technology available in the market. Two agents are defined which are the concrete printing robot and the steel printing robot. Simulation is done on the basement level of a concrete structure containing retaining walls on the circumference with a total length of 232.2 meters and shear walls in the middle with a total length of 36.375 meters. The story height is 4 meters. All wall thicknesses are assumed to be 20 centimeters. A 3D view of the structure to be studied is shown in figure 1.

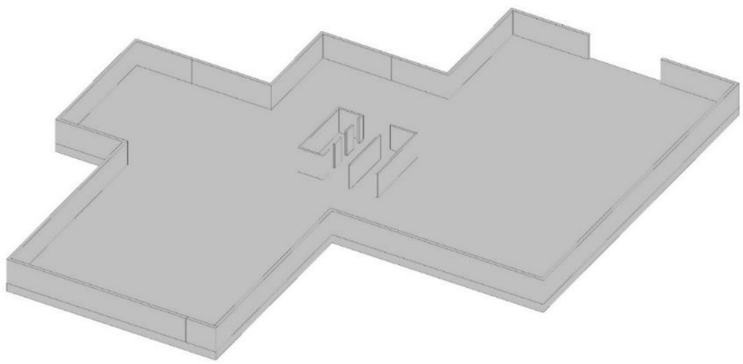

Fig. 1. 3D View of the printed walls

Steel reinforcement is assumed to be designed using generative design and optimization algorithms, hence the shape of steel reinforcement is not conventional (straight rebar can't be used). Also, no data is available on how much these algorithms will optimize our design. Alas, simulation of steel reinforcement installation is not possible. For that, steel 3D printing is used. Robotic arms enable freeform printing (moving is 6 axis) which satisfies our purposes of printing organic shaped steel. The ratio of reinforcement assumed in walls is the minimum reinforcement bound of 0.25% as per ACI 318-14.

6. Simulating the workflow of the 3D printing robots

Simulation of the workflow of both steel and concrete printing robots was done using Anylogic agent based modeling. State-charts, which describe the state of the agent and his corresponding activity, were constructed for both robots. All relationships within an agent and between the two interacting agents were defined.

For the Steel Printing Robot (figure 2 (a)), the state chart with the robot being Idle until it gets an order to start printing where it starts moving to the printing location. In its first round, steel does not need cleaning since no concrete has been poured yet, while in all other rounds steel needs cleaning from concrete so that wires are welded (printed) on a clean steel surface. Steel printing starts right after cleaning is done. The time for printing steel depends on several factors such as the area of steel inside the wall, the volume of the wall, the rate at which steel is printed and the length of the robotic arm.

When the robot finishes printing steel for a given segment, a message is sent to the concrete printing robot (figure 2 (b)) so that it would start printing in that segment. Meanwhile, the steel printing robot moves to print the next segment.

Concrete printing starts right after steel printing for a given segment is done and since the steel disposal rate is much less than the concrete disposal rate, the concrete printing robot will typically wait for the steel printing to finish. When the steel printing is done, the concrete printing starts, and when done the robot's state goes back to waiting for steel printing to finish.

The process is reiterated for each location that the robots will stop and print and when the robots finish one whole cycle for all the walls, a layer is finished and the count is added in the collections of "SteelLayerDone" and "ConcreteLayerDone". The process stops when the count in the collections reaches 40, which is the height of the wall divided by the thickness of each concrete disposal.

The aim of this study is to optimize the number of steel printing heads, so the model was run several times and each time the number of steel printing heads was increased.

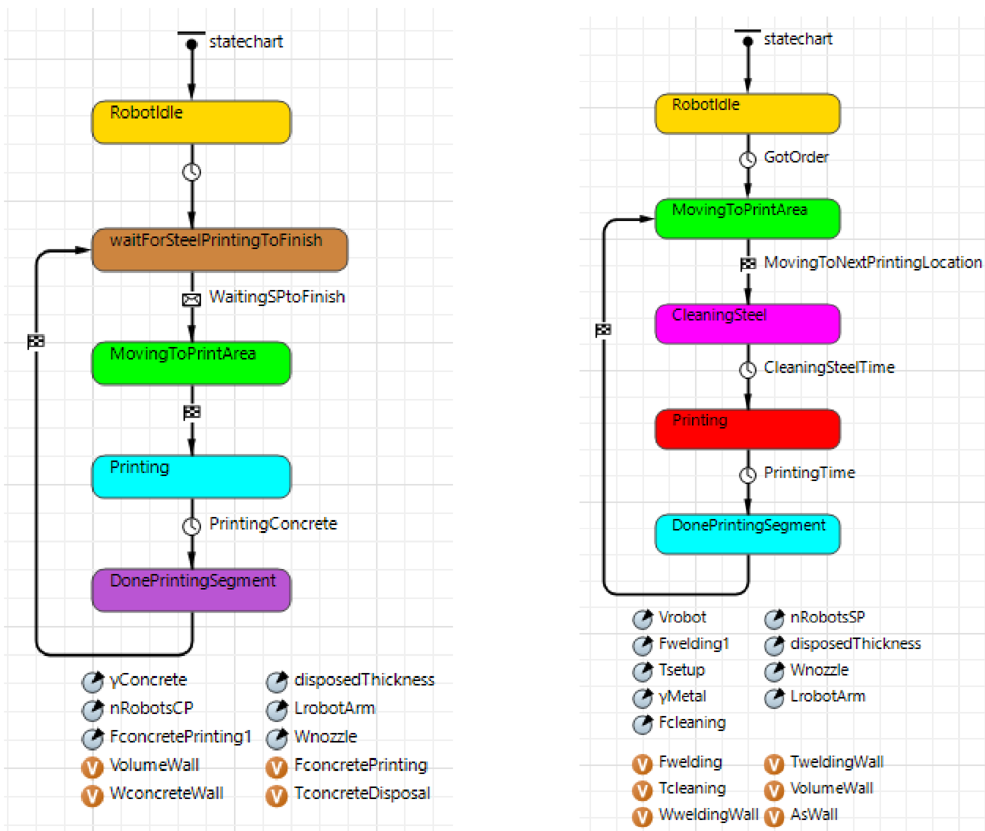

Fig. 2. (a) Statechart of the steel printing robot; (b) Statechart of the concrete printing robot

7. Model parameters and variables

Most parameters were collected from previous literature review and some parameters were assumed (such as number of steel printing robots). The parameters were then fed into the simulation model. Table 1 and table 2 below summarize all parameters assigned to both concrete and steel statecharts.

Table 1. Input parameters for the steel printing robot Statechart

Statechart: robotSP (Steel Printing Robot)		
Parameter in model	Parameter value	Parameter Definition
Vrobot	0.5 m/s	Speed of movement of an industrial robot
Fwelding	330 g/min	Rate of welding
Fcleaning	1.8 m/min	Rate of cleaning
nRobotsSP	Variable ranging from 1-10	Number of steel robots used
LrobotArm	2 m	Length of industrial robot arm
AsWall	0.0025*Wnozzle*disposedThickness	Area of steel inside the wall
VolumeWall	2*LrobotArm*AsWall	Volume to be printed per run
TweldingWall	WweldingWall/(nRobotsSP*Fwelding)	Time of welding
Tcleaning	LrobotArm/(nRobotsSP*Fcleaning)	Time of cleaning

Table 2. Input parameters for the concrete printing robot Statechart

Statechart: robotCP (Concrete Printing Robot)		
Parameter in model	Parameter value	Parameter Definition
Vrobot	0.5 m/s	Speed of movement of an industrial robot
FconcretePrinting	12.7 cm/sec	Rate of concrete disposal
disposedThickness	0.1 m	Thickness of disposed concrete filament
Wnozzle	0.2 m	Width of the nozzle
LrobotArm	2 m	Length of industrial robot arm
nRobotsCP	1	Number of concrete printing robots
TconcreteDisposal	WconcreteWall / (FconcretePrinting*nRobotsCP)	Time for concrete disposal

8. Results and discussions

Results of the simulation models were summarized below. Figure 3 shows that when there was only one printing head of each steel and concrete printers, the total time of the operation was 11.5 days. The steel printer spent 9.08 days printing steel and 2.12 days cleaning printed steel from concrete. These numbers decreased when using ten steel printing heads to 0.8 days (19.2 hours) for steel printing and 0.19 days (4.56 hours) for steel cleaning with a noticeable change in slope at three printing heads where steel printing time is 2.95 days and cleaning time is 0.69 days (16.56 hours). As for the concrete printer, the time spent printing did not change as no variation was made in the number of concrete printing robots.

However, the time wasted while waiting for the steel printers to finished varied significantly from 10.19 days and a utilization of 9% when using one steel printing head to 0.3 days and a utilization of 77% when using 10 steel printing heads with a similar change in slope at 3 steel printing heads giving 2.66 days waiting time for concrete printing robots.

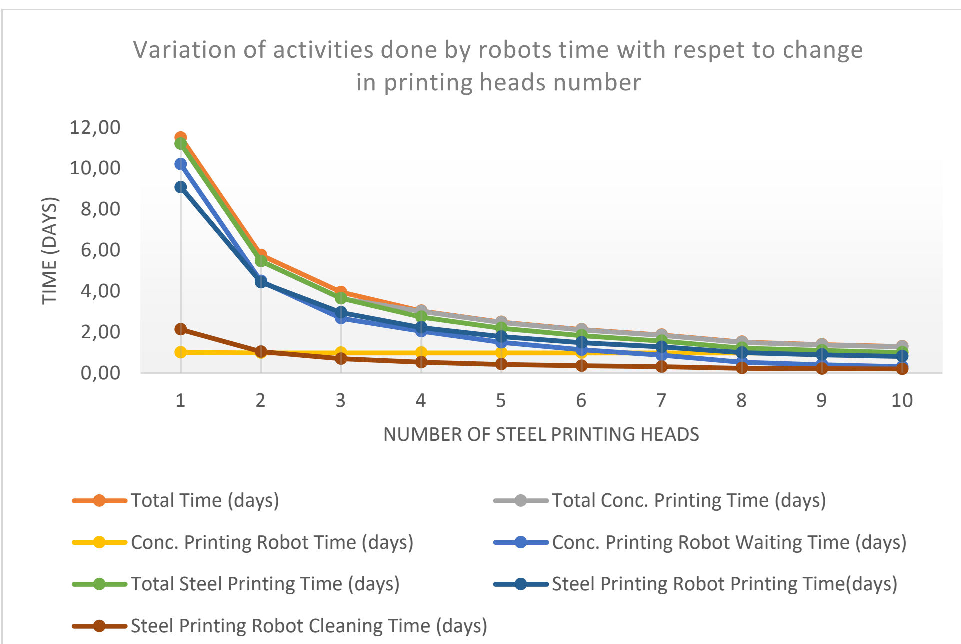

Fig. 3. Activity durations variation with the number of steel print heads used

Figure 4 shows that as the number of steel printing heads increases, the utilization of the concrete printing robot increases and the increase seems linear.

Ideally, it is best to choose the number of steel printing robots that would yield a minimum waiting time for concrete printing robot, yet each industrial robot is estimated to range between $150,000 and $220,000 (RobotWorx). However, Robot prices are declining. An online report published by "The Boston Consulting Group" shows that the price of industrial robots is decreasing and is expected to reach $103,000 in 2025. Despite the decrease in price, the performance of the robots is continually improving by an estimate of 5% per year (Sirkin et al., 2015).

A rough estimate of the time and labor cost needed to execute these walls was calculated and it was found out that the labor (4 carpenters and 2 helpers) would cost around $8500 and would take them from 8 to 10 days to complete this task. This project is a 7-story building so the total labor cost and time for execution of concrete walls would be $59,500 and 60 days respectively. This would be much cheaper than buying, for example 4 industrial robots (3 steel printing and 1 concrete printing) each at the cost of $133,000 and total cost of $532,000. However, this cost is only the capital cost and is not enduring. Figure 5 shows the variation of labor and robot initial and operation costs.

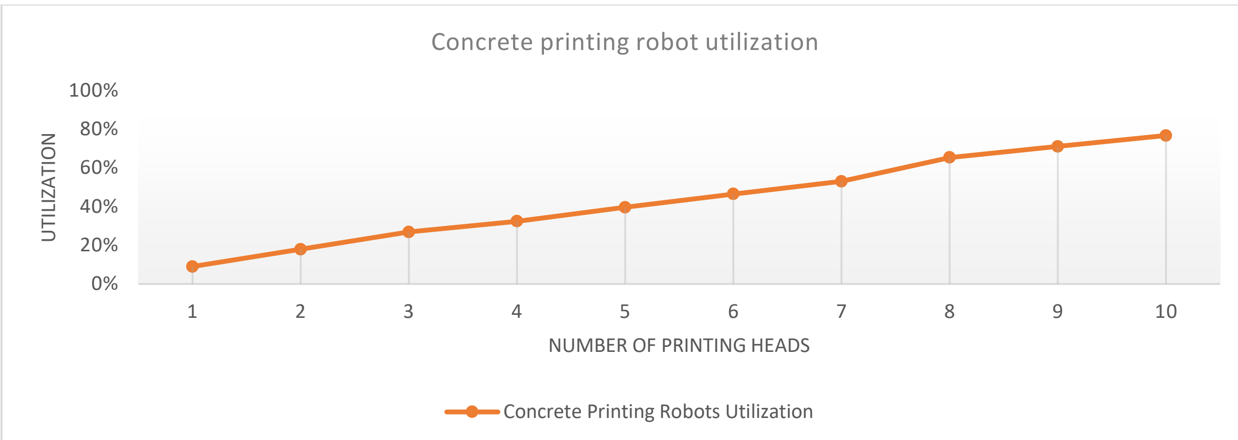

Fig. 4. Utilization of the concrete printing robot with variation of number of steel printing heads used

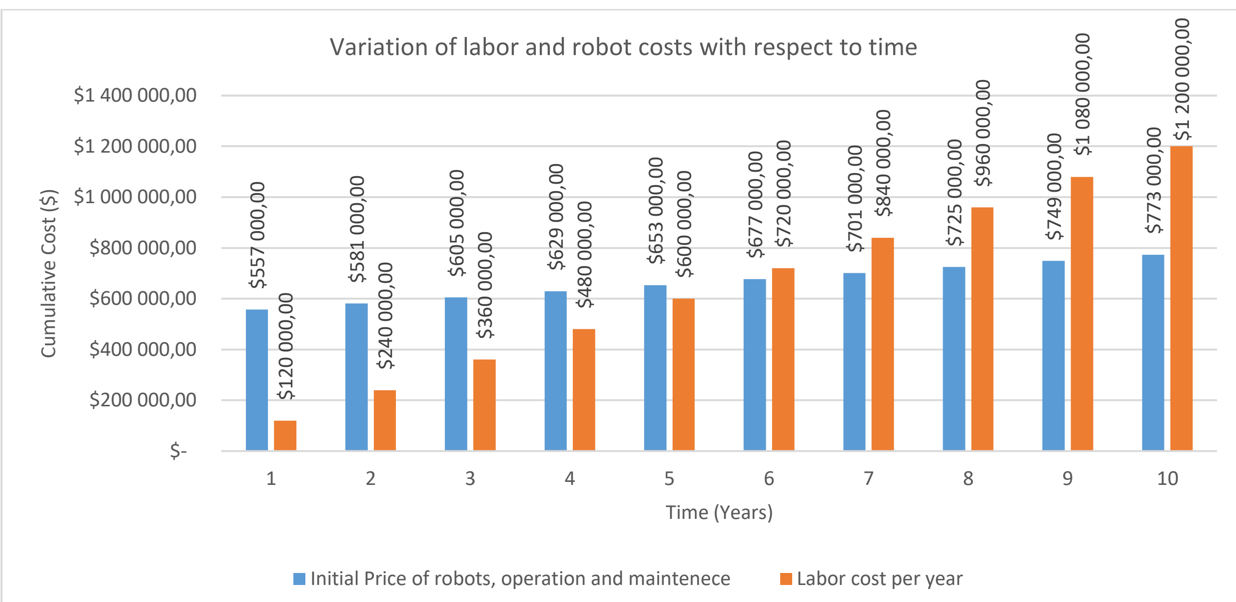

Fig. 5. Comparison between the variation of robot initial and operation cost with labor cost with respect to time

It is shown that after 6 year, the cumulative labor cost would be more than the cumulative cost of the robot initial and operational cost (if 3 steel and 1 concrete robots were used).

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9. Conclusions and Future Work

In this study, the latest advancements in concrete and steel 3D printing were summarized. It was shown that concrete 3D printing is well utilized in the AEC industry, whereas steel 3D printing is mostly used in manufacturing and not utilized for AEC yet. The necessity for using steel and concrete 3D printing is arising in construction, not only to automate the construction process and reduce waste but to accommodate for the arising design complexities accompanied with the common use of generative design in architectural design and its possible adoption in structural design later. An agent based model was constructed to simulate the workflow of the steel and concrete printing robots and to generate data for later use in finding optimized configuration for the number of printers used. The results showed that there is a big gap between the capacity of concrete 3D printing and steel 3D printing. This calls for more detailed research on the utilization of steel 3D printing for the construction industry. In addition, further research is required in simulating 3D printing of different steel reinforcement diameters, varying thicknesses of walls and different column sections and correlating the time values of the proposed methodology with the fresh properties of 3D printed concrete mainly the open time which greatly affects the bond strength, which can compromise the structural integrity of the printed elements. Ongoing advancements in robotics, steel and concrete 3D printing will enhance the process studied and lead to wide adoption of robots and 3D printing in the AEC industry for a cleaner, safer, highly adaptable and more automated process.

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