3D Printing Technology: A New Advancement for Modular Construction?

William Faustin, Mohammed Ali Berawi, and Gunawan Saroji

Civil Engineering Department
University of Indonesia
Depok, Indonesia

Abstract

It is not an exaggeration to say that the key of a successful construction project is the implementation of good and effective construction methods. As such, engineers have long been trying to apply the best method possible in their project. This research will discuss the advancement for one of the construction methods that has been proven to be highly effective and efficient for the construction industry, which is off-site prefabrication. The advancement will be done by combining modular prefabrication methods with 3D concrete printing technology. This combination is expected to simplify the construction process, while at the same time canceling the limitations. The research will be done based on literature of several studies about modular prefabrication and the application of 3D printing technology, especially 3D concrete printing that has been published prior to this research. Based on that, the author developed a diagram that depicts the process of prefabricated 3D printing construction. Alongside with the process of 3D printed modular construction, this paper will also provide contractors with some benefits and shortcoming of this combined method that can be used as a reference to consider the implementation of this method for their projects.

Keywords

Keywords: Construction Method, Off-Site Construction, Modular Prefabrication, 3D Printing Technology, and 3D Concrete Printing.

1. Introduction

The construction Industry has been proven to have quite a respectable contribution for the economy of a country. This industry contributed to about 9% of a country's GDP and 7 - 8.5 % of job employment around the world (Hossain et al. 2020). Despite that, construction is considered to be one of the sectors that is susceptible to encounter problems. Based on a report made by Safe Work Australia (2015), around 12 600 workers' compensation claims are accepted from the construction industry each year for injuries and diseases involving one or more weeks off work. This number equates to 35 serious claims each day. In addition to safety issues, cost overrun is also a very common problem in construction. According to a study by Flyvbjerg et al. (2003), 9 out of 10 construction projects were indicated to experience a cost overrun with the average being 28%.

One of the best solutions for these problems is to implement a good and effective construction method. Ferrada et al. (2013) defined construction methods as the means used to transform resources into constructed products. It is a highly iterative process that requires a construction team to examine a variety of data sources as well as tap into its own experience base to formulate a set of methods that are mutually compatible and can be used to construct a designed facility in the most efficient manner possible (Udaipurwala and Russel 2002)

One of the widely popular construction methods that has been proved to be beneficial for construction project efficiency is off-site modular prefabrication method (Li et al. 2013). In this method, building components are made in a controlled environment outside the project site. This method has roots that can be traced up to the Roman era (Gardiner 2011), before then modernized and popularized by Sears, Roebuck, and co in early 20th century who used the principle of off-site prefabrication by selling houses through a popular catalog which buyer could expect house kits consisted of 30,000 pieces, implemented with a 75 pages construction manual to be transported by train (Musa et al. 2016).

This research will study the process of how 3D printing technology can be implemented as an advancement of conventional modular prefabrication methods. 3D concrete printing was chosen because while it is still considered to be a new technology in construction industry, yet it holds a big potential to play an important role for construction in the future and replace traditional construction (Sakin and Kiroglu 2017) for its effectiveness and efficiency performance in safety, cost, time, and architectural freedom (Lim et al. 2012).

Even though both prefabricated construction and 3D concrete printing are considered to have performed excellently on their own, they are not flawless. This research is also aimed at reviewing the combination of both methods so that they can eliminate each other's flaws while at the same time also optimizing the benefits.

1.1 Objectives

To provide an input for contractors so they may consider implementing a 3D printed modular construction method for their projects by making a diagram that shows the construction process of 3D printed modular construction method, alongside its benefits and shortcomings.

2. Literature Review

2.1 Modular Construction

Prefabricated construction can be defined as a construction process where building components are fabricated in a factory and transported to a construction site for installation. Based on the degree of the prefabrication, prefabricated construction can be classified into 3 classes, which are: 1D single element, 2D panelized system and 3D volumetric. 3D volumetric constructions are also known as a modular construction, which is the most efficient class in prefabricated construction, with 70-95% of the construction consisting of prefabricated products (Thai et al. 2020). Figure 1 illustrates an exploded view of a modular construction to help the visualization of a modular construction.

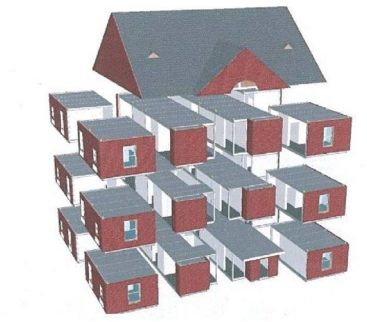


Figure 1. Illustration of a modular construction – exploded view showing individual modules
(source: Mohsen et al. 2008)

Broadly speaking, the process of modular construction can be summarized as shown in Figure 2.

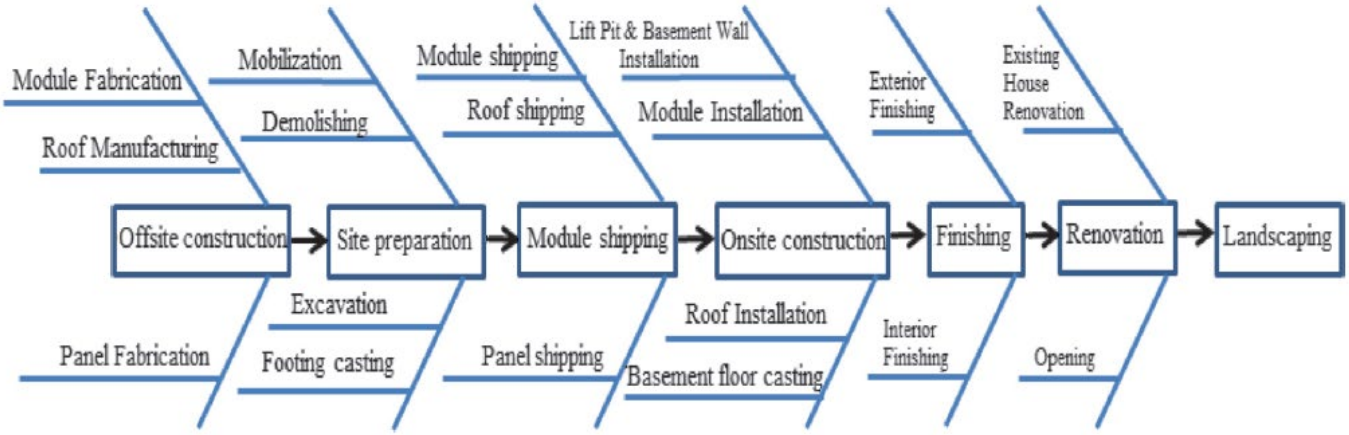


Figure 2. Modular construction process
(source: Li et al. 2013)

2.1.1 Benefits of Modular Construction

The high degree of standardization and the number of repetitions carried out in a controlled manufacturing environment are considered to be important factors in reducing dependence on skilled labor by utilizing semi-skilled operators or even lower skilled operators (Nadim and Goulding 2010). Construction activities carried out in a more controlled environment are said to increase safety, productivity, and quality, but with minimal waste so that it has a good impact on the environment (Boyd et al. 2013, Gibb 2001). Thai et al. (2020), in their research entitled "A review on modular construction for high rise buildings", explained that this method has advantages over conventional methods. By using this method, the efficiency of material use can be increased, and construction waste can be significantly reduced by up to 90%. In addition, the use of this method can also reduce construction times by up to 50% and costs by up to 20%. Figure 3 shows the comparison of a modular construction and a traditional construction method in respect of project time.

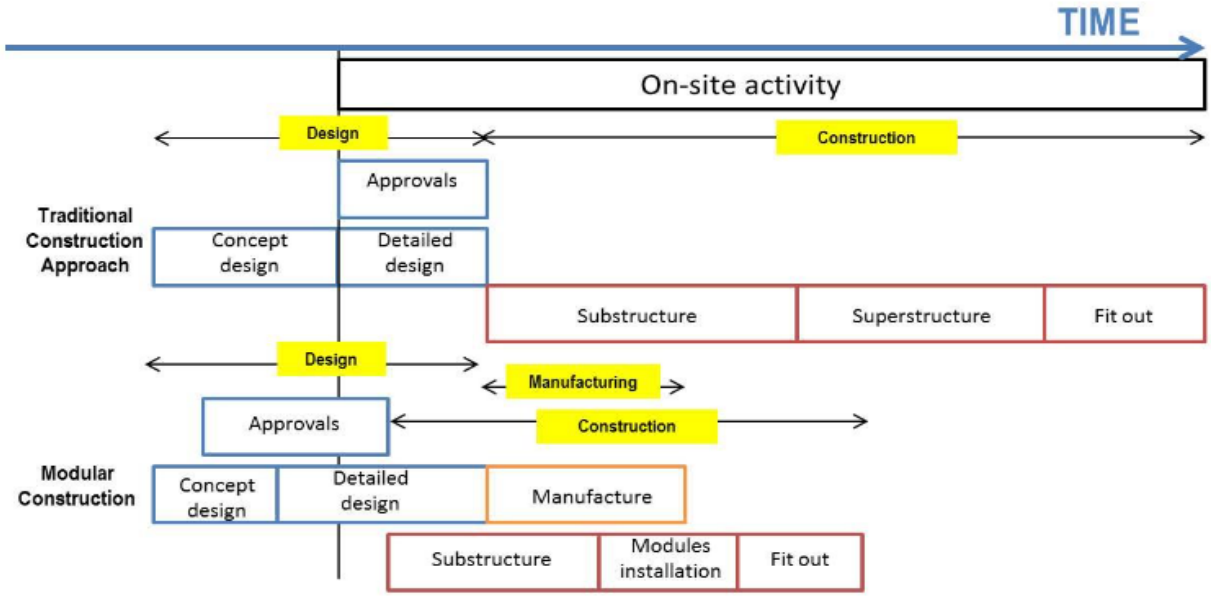


Figure 3. Comparison between traditional construction and modular construction
(source: Musa et al. 2016)

2.1.2 Shortcomings of Modular Construction

While having a lot of benefits, modular construction is not flawless. In its application in the field, there are several obstacles that hinder the application of this method. Research on this has been conducted by Zadeh and Issa (2020), and the findings are as listed in the table 1 below:

Table 1. Constraint of modular construction according to Zadeh and Issa (2020)

Code	Constraints	Code	Constraints
C1	Less flexibility for design changes	C10	Lack of owner's konwledge about the advantages
C2	Unsupportive decisions of designers	C11	More organizational arrangements
C3	Design limitations because of transportation restrictions	C12	Early commitment
C4	Site layout restrictions	C13	Extra planning and design requirements
C5	Shortage of experienced designers	C14	More coordination needed
C6	Shortage of experienced installers	C15	Higher initial cost
C7	The difficulty of protecting the modules	C16	Higher construction cost
C8	More consideration about logistics	C17	More communication among stakeholders
C9	Transportations regulations	C18	Complex codes and inspections

(source: Zadeh and Issa 2020)

Other similar studies have also been conducted by Zhai et al. (2013). Based on the research carried out, the results obtained are in the form of 20 main obstacles that become challenges to modular construction. These obstacles can be seen in the table 2 below.

Table 2. Challenges of modular construction according to Zhai et al. (2020)

Reduced set of 20 variables			
D11	Highly restrictive construction tolerances	D13	Increase in complexity for maintenance
D10	Specific demands for the site logistics for prefinished elements protection	D16	The fragmented nature of the construction industry
D9	Higher skill demands for the labour	D2	Higher initial costs
D12	Poor integration for the supply chain	D1	Higher capital costs
D20	Lack of governmental support	D3	Longer payback period
D19	Lack of available codes and standards	D14	Transportation
D18	Client scepticism and resistance	D17	Poor quality impression
D21	Lack of confidence of the industry in offsite production	D7	Monotonous design with poor aesthetic criteria
D15	Manufacturing capacity	D5	The inability to freeze the design early on
D6	Lack of enough flexibility	D4	Longer lead-in time

(source: Zhai et al. 2013)

2.2 3D Concrete Printing

In 2009, the American Society for Testing and Materials (ASTM) defined 3D printing as "the fabrication of objects through deposition of the material using a print head, nozzle, or other printer technology". In other words, 3D printing is a process of making physical objects by placing layers of material layers based on digital models (Sakin and Kiroglu 2017). The fundamental principle of 3D printing is to reduce the 3-dimensional virtual model to a series of layers of the 3 dimensional virtual model which will then be printed sequentially into real objects (Teizer et al. 2018). The 3D printer was invented by an American engineer named Chuck Hull in 1983 (Nadarajah 2018). Hull explained that 3D printing will become an important technology for many industries in the future, for example in the medical and construction industries. He predicts that the total goods and services produced will be around 3 billion dollars, and is

expected to grow rapidly. In general, the 3D printing process for construction can be summarized as shown in figure 4 below.

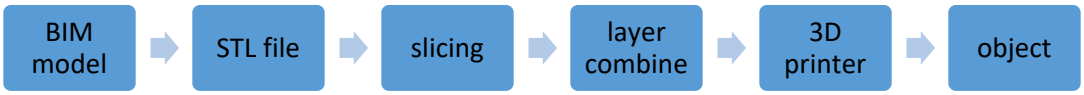


Figure 4. 3D printing process for construction
(source: Sakin and Kiroglu 2017)

- STL File

The Stereo Lithography (STL) file format is the current de facto standard of the Prototype data transmission format. This format will make an approach to the surface of a solid model with triangular geometry (Sakin and Kiroglu 2017). Triangles provide maximum flexibility and efficiency in many applications and visualizations (Nagy and Matyasi 2003). The STL format will only use the 3-dimensional description of the surface geometry without producing information not required for printing, such as surface texture or color. Each triangle represents a surface and is characterized by three vertices and normal related units (Sakin and Kiroglu 2017) as shown in figure 5.

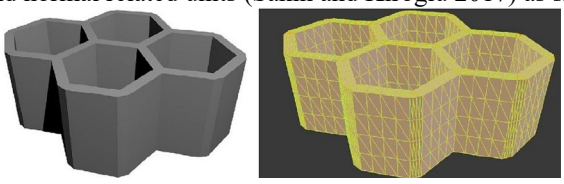


Figure 5. Honeycomb mesh in STL file format
(source: Hager et al. 2016)

Although STL is the most popular input format for 3D printing, it is not the only format that can be used. Printing orders can be generated directly from a module from its original format (Hager et al. 2016)

- Slicing

In the slicing stage, the geometric model will be intersected with parallel planes to obtain the contours of each layer of material. In other words, the 3D model will be converted into a series of 2D stacked models. This stage can be done with a constant layer thickness (uniform slicing) or with a varying thickness (adaptive slicing) (Sakin and Kiroglu 2017). An illustration of this 2 types of slicing method can be seen in figure 6.

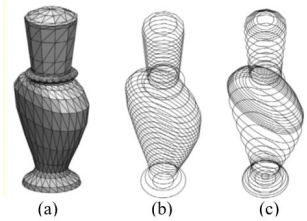


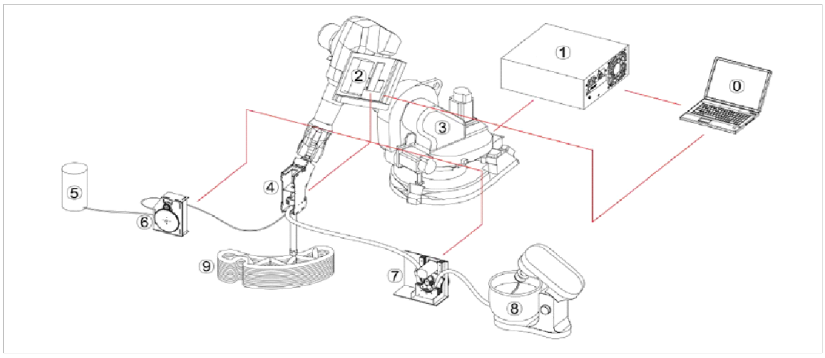
Figure 6. Slicing illustration for a 3D model
(a) STL model of an object; (b) Uniform Slicing; (c) Adaptive slicing
(source: Sakin and Kiroglu 2017)

- Layer combine

In order to develop a new palette of materials, 3D printer machines often combine different polymers in different combinations. This philosophy has attracted the attention of many manufacturers so that they continue to try to develop the multi-material capabilities of the printer (Sakin and Kiroglu 2017)

- 3D printer

At this stage, the concrete dough will be issued by the printer through a nozzle on a path in such a way that the concrete will be arranged layer by layer, and form a 3-dimensional real object from the digital model (Nadarajah 2018). The set-up of a 3D concrete printer set can be seen in figure 7.



0	system command
1	robot controller
2	printing controller
3	robotic arm
4	printhead
5	accelerating agent
6	peristaltic pump for accelerating agent
7	peristaltic pump for premix
8	Premix mixer
9	3D printed object

Figure 7. 3D Concrete printer setting scheme
(source: Gosselin et al. 2016)

In order for 3D printing technology to be used in the construction industry, the business process of 3D printed construction should also be developed. From the business process, many variables that affect the performance of 3D printed construction can be known, so that they can be managed effectively. Bakri (2019) realized the importance of this business process, and in her thesis developed a business process model for 3D concrete printing. The model can be seen in figure 8.

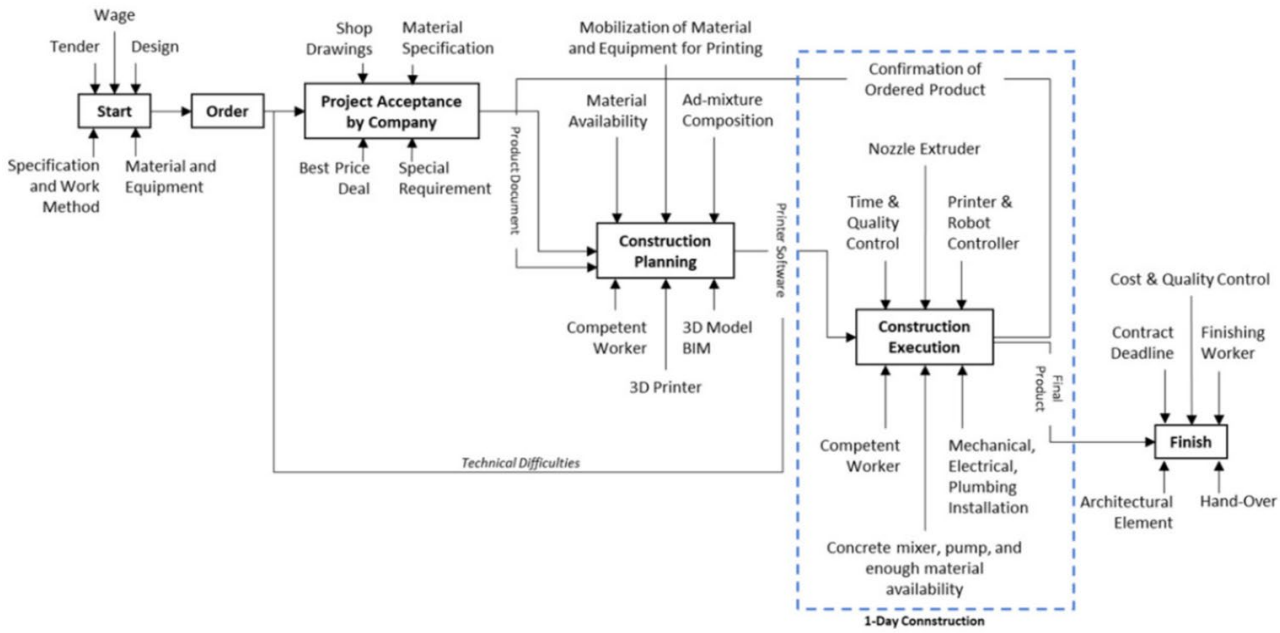


Figure 8. Business process of 3D printed construction
(source: Bakri 2019)

2.2.1 Benefits of 3D concrete printing

There are several reasons for future construction to lean towards automation, with one of the main reasons being a reduction in labor for occupational health and safety reasons, and followed by a reduction in time, costs, and as an attempt to increase architectural freedom (Lim et al. 2012). Vaha et al (2013) adds quality, reliability, life cycle cost savings, and labor simplification as further considerations.

In his research entitled "Conventional Construction and 3D Printing: A Comparison Study on Material Cost in Jordan", Allouzi et al. (2020) concluded that many studies have highlighted the ability of 3D printing to be a solution to problems that exist in conventional construction. For example, from an economic standpoint, construction with 3D printing is faster and more accurate for complex constructions. In addition, the application of 3D printing also minimizes labor and has zero generated waste. Bakri (2019), in her thesis summarizes the benefits of 3D printing

construction. Based on those results, alongside several research that the author has done, the benefits of 3D concrete printing for construction can be summarized as what is shown in table 3 below.

Table 3. Summarized benefits of 3D printed construction

No	Benefits	References									
		Based on Bakri (2019)							author's addition		
		1	2	3	4	5	6	7	8	9	10
1	Flexible design for a variety of architectural geometry	✓	✓	✓	✓	✓		✓		✓	
2	Cost benefit (reducing the use materials because of zero wastes, shorter construction time, minimum work accidents, and concrete printer investment)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	potential for the rapid industrialization of construction in the housing sector		✓	✓	✓						
4	Shorter construction time		✓	✓	✓		✓	✓	✓	✓	
5	Has no need of formwork		✓	✓	✓	✓	✓	✓			
6	has the potential to produce high quality construction with precise material deposition		✓	✓	✓	✓		✓			✓
7	Minimizing construction waste, and have a positive contribution for environmental sector		✓	✓	✓		✓	✓	✓		
8	Integrated function (heater system, isolator, plumbing, and electrical) between printed element, reducing on-site installation	✓	■		✓		✓	✓			
9	Labour simplification	■	■		■		■	■	✓	■	✓
10	productivity improvement	■	■		■		■	■			✓
11	health & safety	■	■		■		■	■			✓
12	components standardizations	■	■		■		■	■			✓
Sources	Wei Ma Guo (2017), Paul, Zijil, Tan, & Gibson (2018), Nematollahi, Xia, & Sanjayan (2017), Faber (2016), Loman D (2015), Asporne & Mercuri (2018), Schutte, Lesage, Mectherine, Nerella, Habert, & Agusti-Juan (2018), Lim et al. (2012), Vaha et al. (2013)										

2.2.2 Shortcomings of 3D Concrete Printing

While having so many benefits, 3D printing is not a flawless construction method. There are still the same constraints and challenges that engineers need to consider before deciding to implement 3D printing technology for their projects. Bakri (2019), in her thesis summarizes the shortcomings of 3D printing construction as shown in table 4 below.

Table 4. Shortcomings of on-site 3D concrete printing

No	Shortcoming	Reference		
		1	2	3
1	Printing process and results quality depended on weather, as it implements on-site printing	✓		
2	Requires a new and sophisticated machine		✓	
3	Using small aggregates (aggregate mortar is finer than concrete)		✓	
4	The size of the printed building is limited, because the size of the 3D concrete printer must be larger than the size of the elements to be printed		✓	
5	Robot printers and automation assistants require a large amount of expertise			✓
Sources	Asprone and Mercuri (2018), Nentollahi, Xia & Sanjayan (2017), Buchli et al. (2018)			

(source: Bakri 2019)

While not being stated as a shortcoming in the thesis, from Bakri (2019) thesis, the author discovers an important point that can be considered as a shortcoming of 3D printing. That shortcoming is the amount of initial investment needed, which is about IDR 22.090.248.190 (equivalent to USD 1,546,233.43 on May 17th 2021 exchange rate).

3. Research Methodology

This research is done based on past studies concerning modular prefabrication and 3D printing technology, especially 3D concrete printing. From those researches, the author will learn the process of how both modular construction and 3D printing construction is done, which will then be combined in order to obtain maximum benefits while eliminating the shortcoming of each method as much as possible. This claim will be proven by presenting the new benefits of the combined method, alongside with the remaining constraints and limitations that has yet to be solved, which then can be compared with the condition of each method before combined.

4. Results and Discussion

4.1 Off-site 3D concrete printing Construction process

The main objective of this research is to review off-site 3D printed modular construction. By the implementation of 3D printing technology, the off-site work of the commonly used prefabrication is expected to be simplified. Therefore, based on the study which has been presented in the previous section, the author developed a diagram depicting the construction process with a modular 3D printing system. This diagram was developed mainly based on the diagram that depicted both modular prefabricated construction and 3D printed construction that has been presented by Bakri (2019)[fig.8], Li et al. (2013)[fig.2], and Sakin and Kiroglu (2017)[fig.4] that has been shown in the literature study section of this research.

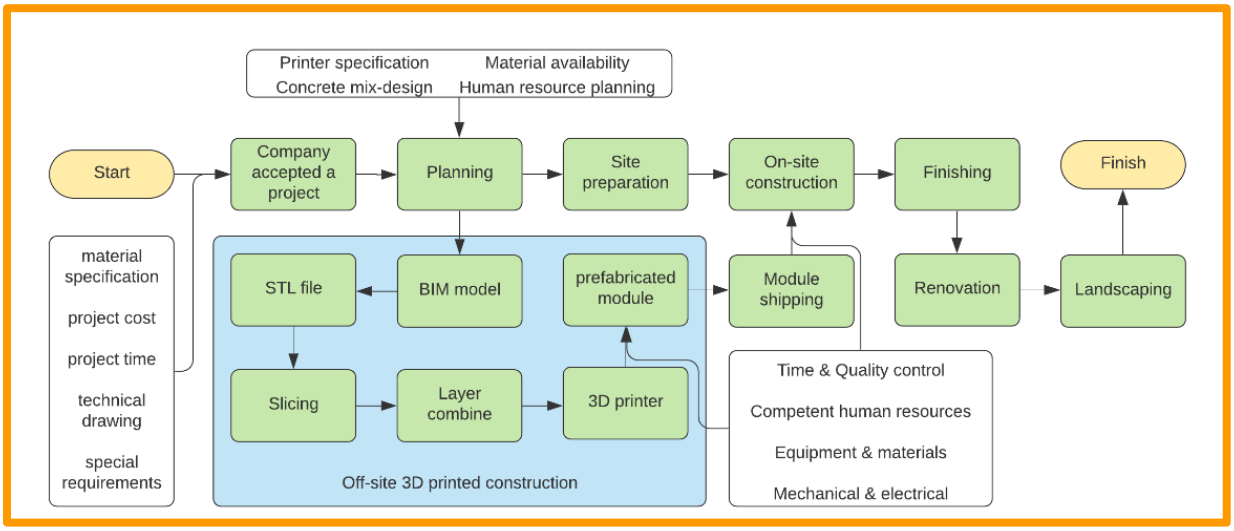


Figure 9. 3D Printed modular construction process

4.2 Benefits and shortcomings of modular 3D printed construction

Both modular construction and 3D printed construction has been proven to be highly beneficial for a construction project. While both of them have loads of benefits, they also come with several limitations and drawbacks. This research focused on the combination of both methods with the expectation that they will complement each other, by eliminating each other's shortcomings while at the same time upgrading the benefits.

Table 5. Shortcomings of modular construction with 3D printing construction method

Aspect	shortcomings
Maintenance	Increase in maintenance complexity
Constructability	Field layout constraints
	Difficulties in finding best mix design composition as it use finer mortar with no coarse aggregates
Logistic & supply chain	Regulations and transportation constraints
	Logistic consideration and protection
	Manufacture capacity
	poor integration for the supply chain
Human & Social	Lack of knowledge, causing skepticism and rejection from stakeholders
	bad quality impression
	the need for adjustments to the organizational structure
	needing better coordination and communication between stakeholders
	Difficult in finding human resources with high experience and skills
Cost	Even larger initial investment as both modular construction and 3D concrete printer already needing a considerable amount of initial investment on their own
	Longer payback period
Other External Factors	complex codes and inspections because of the lack of standard
	lack of government's support
	Fragmented nature construction industry

From the research that has been presented in the previous section, we can see the advantages and disadvantages both methods hold. By combining modular construction and 3D concrete printing, some of the shortcoming they have when they are implemented on their own can be eliminated, (e.g., design constraints of modular construction solved by 3D printing's design flexibility, or on-site 3D printing dependence on weather that is solved by printing moving to an off-site plant). Based on that hypothesis, the author tries to make a new list of constraints, limitations, and shortcomings of the 3D printed modular construction method. This list can be seen on table 5 above.

Aside from eliminating some of each other's shortcomings, the combination of modular construction methods with 3D concrete printing also added more benefits. Based on the data obtained from past literature which has been presented in the previous section, the author developed a matrix that shows the benefit of implementing 3D printed modular construction methods for a construction project, along with the aspects they affected. This matrix can be seen on table 6 below.

Table 6. Benefit matrix of 3D printed modular construction

No	Benefits	Aspects							
		Cost	Time	Quality	Design & architecture	Environment	Human resource	Health & safety	Other
1	Flexible design for a variety of architectural geometry				✓				
2	construction cost efficiency	✓							
3	potential for the rapid industrialization of								✓

No	Benefits	Aspects							
		Cost	Time	Quality	Design & architecture	Environment	Human resource	Health & safety	Other
	construction in the housing sector								
4	Shorter construction time		✓						
5	Has no need of formwork	✓	✓						
6	has the potential to produce high quality construction with precise material deposition			✓	✓				
7	Minimalizing construction waste, and have a positive contribution for environmental sector	■				✓			
8	Integrated function (heater system, isolator, plumbing, and electrical) between printed element, reducing on-site installation	✓	✓						
9	life cycle cost reduction	✓							
10	labour simplification (as this research were done during the COVID-19 pandemic period, this point has an even greater impact)						✓	✓	
11	high accuracy for complex construction			✓	✓				
12	high degree of standardization and number of repetitions carried out in a controlled manufacturing environment ensuring quality, while also reducing the dependence on skilled labour by utilizing semi-skilled operator			✓			✓	■	
13	less dependence on weather								✓
14	lower risk for accident	■						✓	

5. Conclusion & Suggestion

5.1 Conclusions

Based on the research that has been done, it can be concluded that the combination of 3D printing technology and modular construction have a large potential to be used in a construction project, as they complement each other and make up for each other's shortcomings. However, there still are some considerations to be done before deciding to implement this construction method, as 3D printing is still considered new to the construction industry not to mention that both modular prefabrication and 3D printing need a considerable amount of initial investment.

5.2 Suggestions

Nevertheless, 3D concrete printing being a new construction method which still needs a lot more exploration and study, but already showing this much result means that the potential of it is undeniable. For this reason, author encourage other researcher to further improve the result of this research by exploring other possibilities held by this construction method

Acknowledgement

Author is grateful to the University of Indonesia for the support given for the completion of this resea

References

Allouzi, R., Al-Azhari, W. W., and Allouzi, R., Conventional construction and 3D printing: a comparison study on material cost in Jordan, *Journal of Engineering,* vol. 7, pp. 1-14, 2020.

Bakri, H. F., Pengembangan proses bisnis konstruksi penerapan teknologi 3 dimensional concrete printing dengan mempertimbangkan nilai investasi dan manfaat, *Thesis*, Department of Civil Engineering, Faculty of Engineering, University of Indonesia, 2019.

Boyd, N., Khalfan, M. M. A., and Masqood, T., Off-site construction of apartment buildings, *Journal of Architectural Enginering*, vol. 19, no. 1, pp. 51-57, 2013.

Ferrada, X., Serpell, A., and Skibniewski, M. J., Selection of construction methods: a knowledge-based approach, *The Scientific World Journal*, vol. 2013, pp. 1-10, 2013.

Flyvbjerg, B., Bruzelius, N., and Rothengatter, W., *MegaProjects and Risk: An Anatomy of Ambition*, 1st Edition, Cambridge University, Cambridge, 2003.

Gardiner, J., Exploring the emerging design territory of construction 3D printing – project led architectural research*, Thesis,* School of Architecture and Urban Design, RMIT University, 2011.

Gibb, A. G. F., Standardization and pre-assembly – distinguishing myth from reality using case study research, *Construction Management and Economics*, vol. 19, no. 3, pp. 307-315, 2001.

Gosselin, C., Duballet, R., Gaudilliere, N., Dirrenberger, J., Morel, P., and Roux, P., Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders, *Materials and Design,* vol. 100, pp. 102-109, 2016.

Hager, I., Golonka, A., and Putanowicz, R., 3D printing of buildings and building components as the future of sustainable construction?, *Procedia Engineering,* vol. 151, pp. 292-299, 2016.

Hossain, M. A., Zhumabekova, A., Paul, S. C., and Kim, J. R., A review of 3D printing in construction and its impact on the labor market, *Sustainability*, vol. 12, no. 20, pp. 1-21, 2020.

Li, H. X., Al-Hussein, M., Zhen, L., and Ajweh, Z., Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation, *Canadian Journal of Civil Engineering*, vol. 40, no. 12, pp. 1184-1195, 2013.

Lim, S., Buswell, R. A., Le, T. T., Austin, S. A., Gibb, A. G. F., and Thorpe, T., Developments in construction-scale additive manufacturing processes, *Automation in Construction*, vol. 21, pp. 262-268, 2012.

Mohsen, O. M., Knytl, P. J., Abdulaal, B., Olearczyk, J., and Al-Hussein, M., Simulation of modular building construction, *Proceedings of the Winter Simulation Conference, Miami, Florida, December 7-10, 2008*, pp. 2471-2478.

Musa, M. F., Yusof, M. R., Mohammad, M. F., and Samsudin, N. S., Towards the adoption of modular construction and prefabrication in the construction environment: a case study in Malaysia, *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 13, pp. 8122-8133, 2016.

Nadarajah, N., Development of concrete 3D printing, *Thesis*, Building Technology Master Programme, Department of Construction Management/Real Estate, School of Engineering, Aalto University, 2018.

Nadim, W., and Goulding, J., Offsite production in the UK: the way forward? A UK construction industry perspective, *Construction Innovation*, vol. 10, no. 2, pp. 181-202, 2010.

Nagy, M. S., and Matyasi, G., Analysis of STL Files, *Mathematical and Computer Modelling,* vol. 38, no. 7-9, pp. 945-960, 2003.

Safe Work Australia. Available: https://www.safeworkaustralia.gov.au/doc/construction-industry-profile#:~:text=The%20Construction%20industry%20profile%20contains,fatalities%20in%20the%20construction%20industry.

Sakin, M., and Kiroglu, Y. C., 3D printing of buildings: construction of the sustainable houses of the future by BIM, *Energy Procedia,* vol. 132, pp. 702-711, 2017.

Teizer, J., et al., BIM for 3D Printing in Construction, *Building Information Modeling,* Borrmann A., König M., Koch C., Beetz J. Edition, Springer, Switzerland, 2018.

Thai, H. T., Ngo, T., and Uy, B., A review on modular construction for high-rise buildings, *Structures,* vol. 28, pp. 1265-1290, 2020.

Udaipurwala, A., and Russel, A. D., Computer-assisted construction methods knowledge management and selection, *Canadian Journal of Civil Engineering,* vol. 29, no. 3, pp. 499-516, 2002.

Vaha, P., Heikkila, T., Kilpelainen, P., Jarviluoma, M., and Gambao, E., Extending automation of building construction — Survey on potential sensor technologies and robotic applications, *Automation in Construction,* vol. 36, pp. 168-178, 2013.

Zadeh, M. K., and Issa, R. R. A., Constraints of modular construction for fully serviced and finished homes: lessons learned from Canada, *Proceedings of the ASCE Construction Research Congress (CRC), Tempe, Arizona, March 8-10, 2020*, pp. 1-7.

Zhai, X., Reed, R., and Mills, A., Factors impending offsite production of housing construction in China: an investigation of current practice, *Construction Management and Economics,* vol. 32, no. 1-2, pp. 40-52, 2013.