CAD & CAM Design System of 3D Concrete Printing Machine for Building

Nandang Rusmana[a], Heri Setiawan[b] and Muhammad Ghizar Muttaqien Nadhif
Manufacture Engineering Department, Bandung Polytechnic of Manufacturing, Jl. Kanayakan No. 21, Bandung, Indonesia

Abstract: CAD & CAM system is a computer-aided software tool that can simplify the process of 3D printing of buildings, this CAD & CAM serves as a tool that bridges the 3D design of building models with the 3D printing manufacturing process. Based on the results of the CAD & CAM system design on a 3-dimensional building concrete casting machine, the system tends to be almost the same as 3D Print FDM in general but is adjusted to the object to be printed, namely the building. The process of making a 3D CAD design of a building construction model using the SketchUp 2014 software tool, then the 3D building model is converted into a G-Code program using the help of the CAM 3D Slicer Ultimaker Cura v3.5.1 software with the machine parameter approach that is on the 3-dimensional building concrete casting machine. From the results of a simple trial of inputting the G-Code program generated by 3D Slicer Ultimaker Cura on a computer-based Human Machine Interface (HMI), namely Mach3. The tool-path generated on Mach3 is in accordance with that generated from the slicing process by Ultimaker Cura and the G-Code program can also be scanned and read by Mach3 although further testing is needed to adjust the movement of control components controlled by Novusun NVUM 6 Axis Mach3 CNC Controller so that the parameters previously set on Ultimaker Cura can run according to the printing process.

1 INTRODUCTION

Along with the times, the manufacturing industry is always developing continuously so that advances in manufacturing technology can simplify and speed up the manufacturing process, as well as civil technology that applies Additive Manufacturing technology by means of 3D Print for building construction. According to the international standard ISO/ASTM 52900, Additive Manufacturing (AM) is defined as the process of combining materials to make a certain part of the 3D model data, which is carried out layer by layer (Paolini et al, 2019). Thus, the construction of buildings can be operated by 3D Prints. The processing time is relatively faster than the manufacture by human labor.

This 3D Print building or 3-dimensional building concrete machine (3D Concrete Printing Building) has a standard function that is very similar to the standard Fused Deposition Modeling Printer (FDM Printer) (Jay et al, 2019), where the building to be printed can be formed by adding concrete layer by layer through a nozzle whose movement is operated by the program. 3D Print this building requires a computer programming system that is able to act as a bridge between the 3D design of the building construction model and the manufacturing process, so a CAD & CAM system is needed with computer-aided software tools that can simplify the 3D printing process of the building.

CAD is a technology related to the use of computer systems to assist in the creation and modification of designs, while CAM is a technology related to the use of computer systems to plan, manage, and control manufacturing operations (Lee, 1999). The computer system used is in the form of software.

The software used in CAD is SketchUp software, which is one of the popular CAD software used by architecture that can make it easier to make 3D design

[a] https://orcid.org/0000-0001-8772-5626

[b] https://orcid.org/0000-0001-8767-1429

of a building models and in operation it is also lightly processed by computers. In CAM, the software used is the 3D Slicer Ultimaker Cura which is generally used in making FDM 3D Printing processes and its intuitive interface makes it easy to use.

Thus, this study is intended to explain how the CAD & CAM system is used in a 3-dimensional building concrete casting machine (3D Concrete Printing Building) which in the system explains how the compatibility of the CAD & CAM software available with the machine, how to describe the CAD manufacturing process. & CAM with a parameter approach on a 3-dimensional building concrete casting machine, and how the output on the system is in the form of a G-Code program so that it can be read by the machine controller.

2 METHOD

In this method of completion, it begins by looking for references regarding the control system for 3D Print in general and its relation to the CAD & CAM process in 3D Concrete Printing. From the references obtained, it turns out that the working principle of 3D Print is generally the same as 3D Concrete Printing, it's just that there is a development in the control system and there are also adjustments to the CAM process.

The problem was then identified in the CAD & CAM system, where the CAM software available in general is for 3D Print Fused Deposition Modeling while on the 3D Print machine the building uses a Mach3 CNC Controller so it is necessary to adjust the machine parameters so that the resulting G-Code can be read by the controller and works fine.

With the problem identified, the system is then determined so that CAD & CAM can be suitable for the building's 3D Print machine. One of the system designs is made as an illustration of how an activity or process of a CAD & CAM system will run on a building 3D Print machine.

This CAD & CAM system is a computer software so it is necessary to find an alternative to CAD & CAM that is compatible with the three-dimensional printing process of the building. The selection of CAD software used was based on consideration of features that matched the building construction model to be printed and for CAM software was chosen based on the consideration of software compatibility on the Mach3 controller firmware.
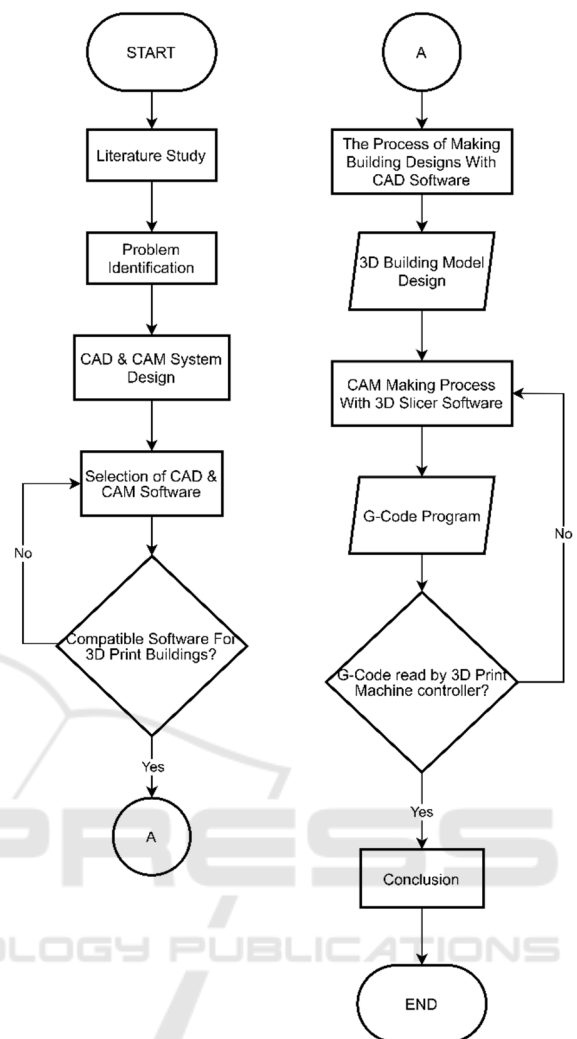

Figure 1: Method Flowchart.

CAD & CAM software needs to be checked first for compatibility of the software used for 3D Print buildings. The pre-determined software options are checked for specifications whether they are suitable and compatible with the control system to be used.

An overview of the CAD process is explained so that the system created can describe the process of making building construction designs with CAD SketchUp 2014 software. Creating a design process with building construction that is designed as much as possible is still within the scope of the building's 3D Print machine capabilities.

The description of the process of making CAM is also explained, this CAM uses 3D Slicer Ultimaker Cura software. The process is carried out using a machine parameter approach in the 3D Slicer software that is used so that the resulting G-Code

program can be read by the building's 3D Print machine controller.

The resulting G-Code program needs to be checked for readability with the Mach3 controller. If it is not readable, it is necessary to return to the CAM manufacturing process to analyze the problem. If the CAM manufacture still gets results that cannot be read by the controller, it is necessary to re-select the CAM software used so that it can be compatible with the machine controller.

3 RESULT AND DISCUSSION

3.1 Design of CAD & CAM System for Building 3D Printing Machine

The CAD & CAM system on the building 3D Print machine, was designed based on existing software tools for most FDM 3D Print machines because there is no software specifically for the building 3D Print machine so it is necessary to adjust the machine parameter approach so that it can be processed by the building 3D Print machine well.

The output generated by this system will be in the form of a G-Code program. The program can instruct the building 3D Print machine control so that the movement of the nozzle can be in accordance with the desired 3D printing process based on what has been set on the CAM.
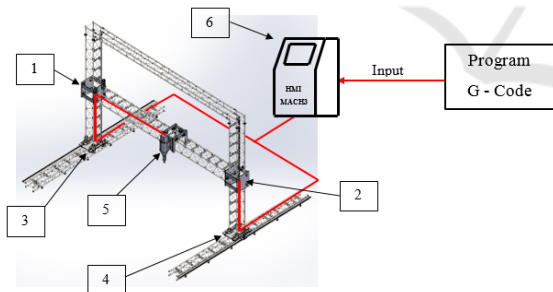

Figure 2: G-Code Program Input Flow.

Description:
[1 & 2] Z Axis Pillar Slider Motor
[3 & 4] Y Axis Pillar Slider Motor
[5] X Axis Pillar Slider Motor and Nozzle
[6] Human Machine Interface Mach3

The G-Code program is inputted through the HMI. HMI integrated with the Novusun NVUM 6 Axis Mach3 CNC Controller will process the G-Code program and then send signals to control components such as the motor on the slider and the extruder motor

on the nozzle. The control components are active and move according to the program instructions on the controllers.

3.1.1 3D Print Concrete Building CAD System

The CAD system used in the 3D printing process of this building uses CAD software tools to facilitate the 3D design process of building models that are usually used by architecture so that it can facilitate the design of special building designs that will be printed later. The default CAD file format saved by CAD software is usually different, therefore it needs to be converted to another standard format such as STL or OBJ that is compatible with the CAM software used.
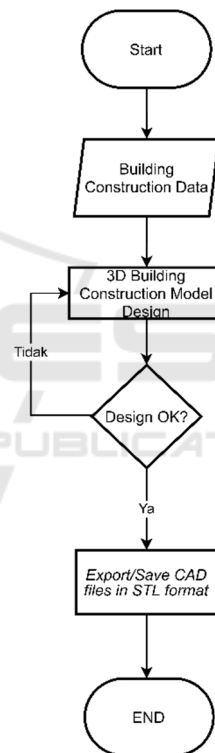

Figure 3: CAD System Flowchart.

3.1.2 3D Print Concrete Building CAM System

The CAM system in this building's 3D Print process includes making special settings for Custom Printers, Custom Materials, and Custom Profiles. Special arrangements need to be made because this CAM software that is available is generally made for 3D Print FDM, where the extruded material is thermoplastic so that there are some parameters that will not be used and some must be added in order to

adapt to the building's 3D Print machine. For example, there is a heating temperature parameter in the nozzle area to melt thermoplastic filaments, while printing with this geopolymer material basically does not require a melting process.
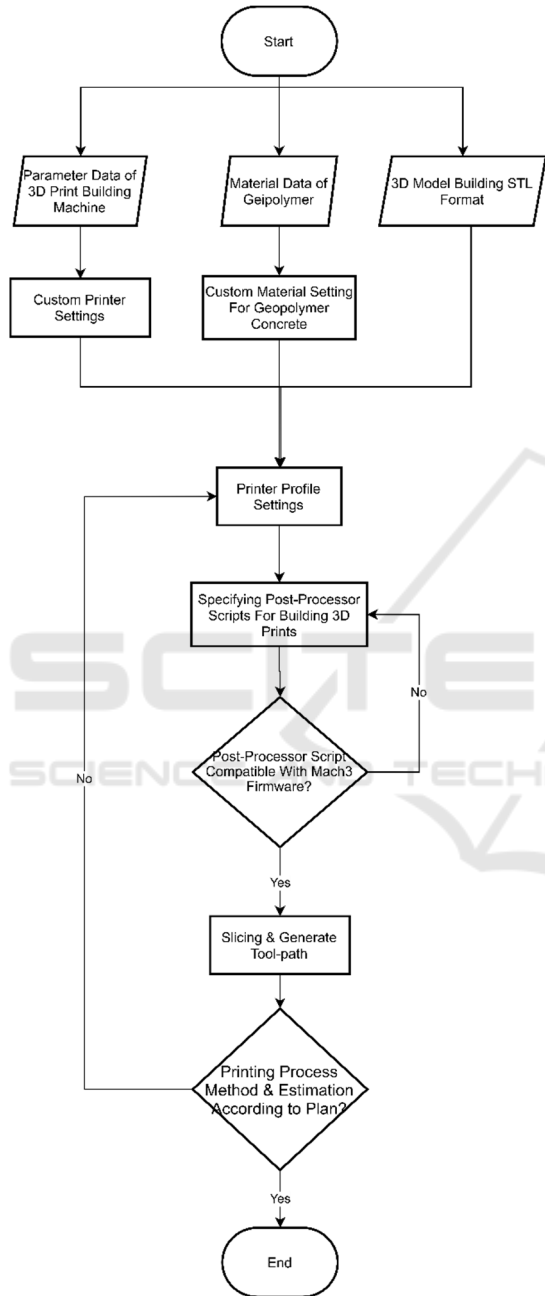

Figure 4: CAM System Flowchart.

This CAM is also programmed to produce standard 3D Print G-Code, while the controller used in this 3D Print machine is CNC Mach3. Thus, there will be a slight difference in the G-Code program read

by the machine controller and cause some G-Code programs to malfunction or be ignored. Even so, the program can continue to run until the end. As for the post-processor script which is needed to facilitate special work on the building printing process, the post-processor script itself is programming code that reads the G-Code generated by the CAM when slicing the model and modifies it to the desired result before Cura sends the final result to 3D printers.

3.1.3 Selection of CAD & CAM Software

CAM computer software for the 3D printing process is generally available only for thermoplastic Fused Deposition Modeling 3D Printers, so this selection is necessary so that the CAM software used can be compatible with the 3D Print machine for the building to be made. In general, there are many choices of software in CAD for various engineering fields, as well as in CAM software so that it needs to be narrowed back to its application function. 3D Print of a building is a job whose application is more directed at the realm of civil engineering because the object it prints is a building construction, therefore, for the 3D CAD model design process, CAD software is needed that is able to support building construction design work.

3.1.4 CAD Software

SketchUp 2014 was chosen as computer CAD software for making 3D models of building construction on a 3D Print machine because it is easy to use and the computer specifications required are not too high. But in reality all these CAD software are the same depending on what they are applied for, the convenience of the user, and the capabilities of the computer they are using. So that the choice of CAD software for a building 3D Print machine can be said to be relative as long as the most important thing is that the stored 3D CAD digital design file must be in STL file format so that it can be compatible with many 3D print CAM software.

3.1.5 CAM Software

In practice, this CAM serves as a bridge between the construction of a digital 3D model (which is created through CAD) and a manufacturing process system by translating the digital 3D object model into a program of instructions to be executed by the machine. However, most of the 3D printing technology process is not carried out with the term CAM software but with 3D Slicer software, where the 3D Slicer is not categorized as a CAM in general even

though it performs the same function so that in subsequent writings will use the term 3D Slicer as a CAM 3D Print (Grames, 2021). This 3D Slicer software is compatible with 3D print technology in general because of the features in it that support Printer Fused Deposition Modeling (FDM) parameters, similar to those in 3D Print buildings.

Ultimaker Cura version 3.5.1 was chosen as 3D Slicer software because, Cura's interface is intuitive and user-friendly for beginners, but there are more complete settings if needed so that it can be adapted to the 3D Print engine building. Compatible with many 3D Printer machines, especially on firmware other than 3D Print machines, namely Mach3 CNC Controller. Compatible with various types of 3D CAD file formats. There is a custom post-processor script on Cura that can be used for the construction process on the overhang of the building. The version chosen is 3.5.1 because in another version there is a bug in the G-Code flavor Mach3 so it is not compatible with 3D Print building controller.

3.2 CAD Process on 3D Printing Building Machine

The CAD process of the 3D Print building machine is the creation of a 3D model of building construction with the help of CAD software. From what has been determined previously, the CAD software used is SketchUp. Before entering this process, some information data is needed in advance about building construction as an example of the CAD manufacturing process, including:

1) The available working area is 5 x 4.5 x 3 meters with an offset of 0.5 meters as a safe distance for the printhead nozzle with X, Y, and Z pillar construction. After an offset of 0.5m is made from the working area the size of the house to be printed becomes 4m x 3.5m x 2.5m.
2) The 3D model objects created in CAD are building constructions that will only be printed by geopolymers, which are mostly walls.
3) The building construction to be printed is a building in the form of a non-standard house (not based on the standard type of house in Indonesia) which only has one floor level because it is limited by the working area of the building's 3D Print machine.
4) The house building consists of one main room and one bathroom.
5) The thickness of the walls of the house is 15 cm.
6) There is one main door, two main windows, and one bathroom door.

7) With its non-standard type, the building of this house is more like a premium boarding room with an attached bathroom which is suitable for the upper middle class.

3.3 Export CAD File into STL

CAD files need to be saved or exported into STL files because they are easy to manipulate in the process planning system (Zhou, 2005) (CAM), especially in the slicing process by 3D Slicer Ultimaker Cura software. without showing color, texture, and other general attribute models so that it is quite simple to process in the slicing process.
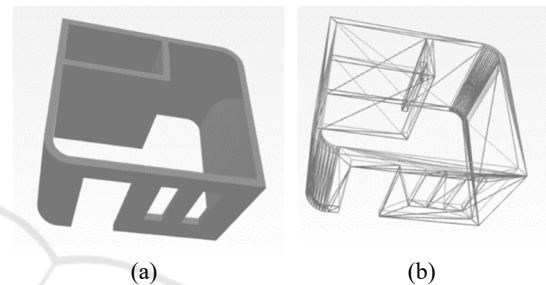

(a)   (b)

Figure 5: (a) 3D CAD Model (b) 3D CAD Model After Converting to STL.

3.4 CAM Process with Ultimaker Cura Software

The process of making CAM on the 3D Print building machine is carried out with the 3D Slicer Ultimaker Cura software, this process begins with making special settings for the printer machine, special settings for materials, special settings for printer profiles, and in addition to setting post-processor scripts. Thus, although this Ultimaker Cura 3D Slicer is not intended for 3D printing with geopolymer materials, it can be adjusted by making profile settings that are close to the parameters of the 3D Print building machine.

3.4.1 Custom Printer Settings on Ultimaker Cura

This custom printer setting is made in such a way because Cura defaults machine profile is unavailable for a building 3D printer, this building 3D Printer machine is a machine made in the final project at the Bandung Polytechnic of Manufacturing and is not commercially available.

Information on building 3D Print engine parameter data is required, which include:

1) The available working area is 5 x 4.5 x 3 meters with an offset of 0.5 meters as a safe distance for the printhead nozzle with X, Y, and Z pillar construction.
2) The working area is square.
3) The controller uses CNC Mach3, so the G-Code flavor used is Mach3.
4) It only has one extruder on the nozzle.
5) The height of the gantry or the distance between the base of the working area and the construction of the X pillar is assumed from the height of the working area plus the thickness of the X pillar, which is about 3m + 0.5m = 3.5m.
6) Because the material to be printed uses a geopolymer, the compatible filament diameter material is the same as the nozzle hole diameter.
7) Start and End G-Code are left default.

From the data above, it can be input to the custom printer machine settings in Settings → Printer → Add Printer → Custom FFF Printer.

3.4.2 Custom Material Setting for Geopolymer

Ultimaker cura does not provide material profiles for types of materials that are cement or mortar such as geopolymers, so it is necessary to add special settings in the Material Settings section. Geopolymers have material properties as shown in the following table:

Table 1: Geopolymer Concrete Material Properties (Meng et al, 2019).

Properties	Geopolymer Concrete
Mass density	2,40 g/cm³
Poisson's ratio	0.21
Bending strength	10.1 Mpa
Compressive Strength	93.6 Mpa

The material properties for this custom material setting are only the mass density, so other information is ignored. For settings, it can be done by selecting Settings → Extruder 1 → Materials → Manage Materials.

3.4.3 Custom Printer Profile Settings

Before specifying the custom printer profile settings, first import or enter the object to be printed by selecting File → Open File(s) and then selecting the 3D CAD file of the building to be printed in STL or OBJ form. Then readjust the size and scale of the object, also adjust the position of the object so that it loads the working area properly and correctly.

Custom printer profile settings are settings for the printing process method which can affect the nozzle movement pattern as well as what instructions are needed so that the machine can print objects according to what has been designed. Therefore, the resulting output will be in the form of a G-Code program. These settings include:

3.4.4 Layer Height

Determining the layer height can affect the quality of print detail that will be obtained. The smaller the height resolution of each layer, the better the surface detail obtained but the longer the printing process (Grames, 2021). The layer height in the 3D Print of the building is assumed to be 1 inch or 25.4mm. The height is uniform with the hole inside the nozzle diameter.

3.4.5 Shell

The shell is the outline or the outer boundary of each layer of the object to be printed (Wobith, 2019). This shell can affect the stability of the model. In determining the parameters of this shell, there are several settings in it, namely the thickness of the shell wall (wall thickness), the number of layers of the shell wall (wall line count), and the thickness of the top/bottom thickness (top/bottom thickness).

In setting the shell for 3D Print printing of buildings, from many video references on the internet that most house walls are printed with a shell wall as thick as a nozzle diameter that is 25.4mm in this case and there is only one layer of wall so that it will produce a cavity in the wall of the house which has a thickness of 15cm. The cavity will later be filled with infill with a certain pattern and density to strengthen the building construction.

3.4.6 Infill

The arrangement of this section plays an important role in influencing the strength and weight of the building construction to be printed (O'Connel, 2022). There are two important parameters in the infill setting, namely the infill density and the infill pattern.

Fill density for standard printing is around 15% - 50% with simple patterns such as Grid patterns, too dense infill and too complex patterns can cause the printing process to be very long and increase the complexity of nozzle movement so it is not recommended for home wall printing. The infill density is sufficient at 20% to speed up the printing process but is still quite sturdy.

3.4.7 Printing Speed and Flow Rate

Printing speed and flow rate can also affect the quality, accuracy, and even the strength of the construction to be printed. Too fast causes inaccuracy of the dimensions of the printed object and can also reduce the quality of object details.

Printing speed and flow rate for building 3D Print is in the range of 60 mm/s to 120 mm/s and 37,9 ml/s to 51,3 ml/s, respectively. The printing speed and flow rate refers to the research conducted by Daniel Tay et al. in 2019. Where in this range, the prints tend not to break and do not experience cracks so that the prints will be better and stronger. The fastest printing speed is selected, which is 120 mm/s with flow rate 51,3 ml/s so that the printing process time is shorter.

3.4.8 Travel

Travel is a setting in Cura to control nozzle traffic at the time of printing. This setting contains several important parameters, including Combing Mode, Avoid Printed Parts, Avoid Supports, and Z Hop When Retracted (Anon, 2022).

Combing Mode functions in reducing the possibility of defects on the outer surface of the mold by recalculation of all traveling nozzle movements so that they remain within the mold limits. Avoid Printed Parts and Avoid Supports if enabled will make the printhead avoid parts that are printed while the nozzle is traveling, assuming the safe distance is one nozzle diameter which is 25.4mm. While Z Hop When Retracted allows the printhead to move over the print without the nozzle touching it, but this parameter is not really necessary because it will increase the printing process time.

3.4.9 Post-Processor Script Setup for Building Printing Process

Post-processing scripts in the 3D Print process of buildings are needed because they can be used as a method that can facilitate the installation of manual support on the overhang section of building construction. The post-processing script is "Pause At Height". The method the script will use is to read all the G-Code lines, then detect the G-Code at which the printer will reach the desired height, and add a pause G-Code, such as the M0 (Unconditional Stop) command.

To install the Post-processing script this plugin can be done by selecting Extensions → Post Processing → Modify G-Code → Add a script → Pause at height. After that, the Post Processing Plugin

window will appear and the parameter fields that must be filled in.

3.4.10 Slicing on Building Objects to Be Printed

The object that is ready will then be sliced into several layers, after which the tool-path line and its layers will appear, so you can see if the nozzle movement path is in accordance with what was planned.

The display in Figure 4 is an overview of the tool-path on layer 52 out of a total of 100 layers. You can see the red lines that show the nozzle movement path in the formation of the shell wall and the yellow lines that show the nozzle movement path in the formation of the filling.
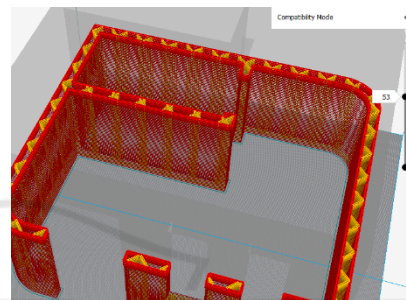

Figure 6: Layer View and Slicing Tool-path Pattern.

3.5 Simple Testing of G-Code Program on Mach3

This simple test simply checks the G-Code program whether it can be read by Mach3 and the resulting tool-path is exactly the same as that produced by Cura's Ultimaker CAM 3D Slicer. The G-Code program is inputted through a computer-based Human Machine Interface (HMI), namely Mach3. After that Mach3 will scan the loaded G-Code program before it can be executed.

When the scan is complete, Mach3 will display tool-path lines on the Display indicating that the next G-Code program can be executed. However, if after scanning there are no tool-path lines on the Display, it means that an error has occurred in the G-Code program.

G-Code programs that do not experience errors after being scanned can be seen for their detailed tool-paths in the Display section, so that it can be easily checked whether the tool-paths represent the G-Code programs that have been loaded.

The tool-paths previously generated from the CAM 3D Slicer Ultimaker Cura process with Tool-paths displayed on Display Mach3 have similarities,
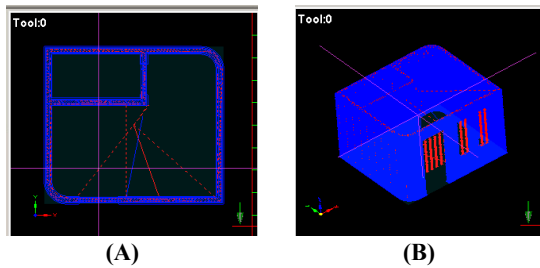
Figure 7: Tool-path view (A) Top and (B) Isometric.

but there are limitations to the Display Mach3 feature which cannot display tool-paths in more detail. Even so, the G-Code program can still be read by Mach3, it just needs further testing to adjust the movement of the control components controlled by Mach3 so that the previous parameters set on the CAM 3D Slicer can run according to the printing process.

It is proven that Ultimaker Cura 3D Slicer software is compatible with Mach3 CNC controllers, so that the software can be used in a 3D Print approach to the 3D printing process.

4 CONCLUSIONS

The CAD & CAM system on the building 3D Print machine is almost the same as the FDM 3D Print in general. The process of making a 3D CAD design of a building construction model using the SketchUp software tool, then the 3D building model is converted into a G-Code program using the help of the CAM 3D Slicer Ultimaker Cura software with a 3D Print machine parameter approach of the building.

SketchUp software compatibility meets STL and OBJ standard file storage, while Ultimaker Cura 3D Slicer software can be compatible with Mach3 CNC controllers on building 3D Print machines.

The CAD process in the 3D Print of the building begins with the creation of a 3D design of the building construction model and the process of exporting the file into STL type format with SketchUp software.

The CAM process in the 3D concrete printing building process consists of making custom settings for custom printers, custom materials, and custom printer profiles.

The G-Code program generated by 3D Slicer Ultimaker Cura can be read by Mach3 CNC controller.

If using open-source software such as Ultimaker Cura, pay attention to the updated version. In some versions there are bugs in the Mach3 firmware that have not been fixed by the software developer so that the resulting G-Code program is not compatible.

Overall, using this software produces performance for 3D building concrete casting with good execution speed.

REFERENCES

Paolini, A et al (2019). *Additive manufacturing in construction: A review on processes, applications, and digital planning methods*, Additive Manufacturing, 30. 2.

Jay G, S et al (2019). *3D Concrete Printing for Construction Applications*, 3D Concrete Printing Technology. 4.

Lee, K. (1999) *Principles of CAD/CAM/CAE Systems*, Boston: Addison Wesley Publishing Co.

Carolo, L. (2020). *What Is a 3D Slicer? – Simply Explained*. From https://all3dp.com/2/what-is-a-3d-slicer-simply-explained. (Accessed 2022-05-23).

M.Y.Zhou. (2005). *STEP-based approach for direct slicing of CAD models for layered manufacturing*, International journal of production research, 43(15), pp. 3273-3285.

Meng, Q et al (2019). *Experimental and numerical investigation of blast resistant capacity of high performace geoplymer concrete panels*, Composites Part B: Engineering, 171. 5.

Grames, E. (2021). *3D Printing Layer Height: How Much Does It Matter?*. From https://all3dp.com/2/3d-printer-layer-height-how-much-does-it-matter. (Accessed 2022-06-25).

Wobith, E. (2019). *3D Printing Shells – All You Need to Know*. From https://all3dp.com/2/3d-printing-shells-all-you-need-to-know/. (Accessed 2022-06-24).

O'Connel, J. (2022). *3D Printing Infill: The Basics Simply Explained*. From https://all3dp.com/2/infill-3d-printing-what-it-means-and-how-to-use-it/ (Accessed 2022-06-26).

Daniel Tay, Y.W et al (2019). *Effect of printing parameters in 3D concrete printing: printing region and support structures*, Materials Processing Technology, 271. 14-16.

Anon. (2022). *Travel Settings*. From https://support.ultimaker.com/hc/en-us/articles/360012611299-Travel-settings. (Accessed 2022-06-26).