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Reverse Layered Manufacturing for Moldable Composites using CAD/CAM Technologies

Kenfield A. Griffith[1] and Ayodh V. Kamath[2]

[1]Massachusetts Institute of Technology, kenfield@mit.edu
[2]Massachusetts Institute of Technology, ayodh@mit.edu

ABSTRACT

This paper investigates a novel reverse layered manufacturing process for the production of building components as an assembly system. The solution introduced in this paper is a system of computed layered manufactured molds for fabricating unique blocks. The goal was to create a system that can be influenced and tailored to incorporate culture, design preference, and geographical innovation. Based on the Global Fab Lab initiative (Neil Gershenfeld, MIT), that offers tools and CNC technologies to developing countries, this research investigates technology systems for building infrastructures with the impact of community intervention. The current research is twofold: it derives a systematic process that can be locally and globally repeated; and investigates the principle of sustainable technology using a repeatable system developed from CAD/CAM technologies. The layered manufacturing approach couples Laminated Object Manufacturing (LOM) and direct geometry slicing. The technology described in this paper is a cradle molding system used for producing block assemblies from moldable composites

Keywords: CAD/CAM, CNC, assembly systems, reverse engineering.
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1. INTRODUCTION

There is a substantial need for sustainable infrastructures in developing countries. Currently, housing units in shanty towns in South Africa represent an ad hoc juxtaposition of materials for shelter that do not provide sustainable living conditions. Due to limited long term resources for maintenance, the current approaches are limited to investing substantial capital for building infrastructures that are not guaranteed for longevity. The approaches offer the end product rather than an endogenous solution. There are limited examples that prove these methods as sustainable systems; therefore they fall in the category of exogenous aid. There is need for a system that offers ways of building infrastructure through technology and repeatable production. This research explores CAD/CAM technologies to challenge this concern using a layered manufacturing system for computing molds.

Most methods of Computer Numerically Controlled (CNC) layered manufacturing are restricted to scales smaller than actual buildings. An alternative will be the division of the building form into interlocking assembly components to be manufactured using existing CNC technologies. In addition, most CNC fabrication methods are limited to rigid materials that have difficulty with intricate shapes. However, a solution is the production of molds using flat-stock material for universal application using CNC fabrication. Subsequently, the molds can be used to cast different building components from different composite materials. In this paper, we use the term composite to mean mixtures such as adobe, cob, concrete mix, or poured earth; a mix that can be poured but hardens when cured. This paper examines the general steps that can be taken to apply CNC fabrication to a building assembly system (Figure 1). The goal is to produce a logistics system for simple and complex design geometries, and is generic enough to incorporate the cultural influences and perspectives of global communities as design innovation.

The method discussed in this paper investigates both Laminated Object Manufacturing (LOM) approach and direct geometry slicing. However, this process eliminates the need for additional materials or adhesives used in the traditional LOM processes for binding. We develop a generic method for the production of molds that are used with moldable composites such as concrete mix and adobe mixes.

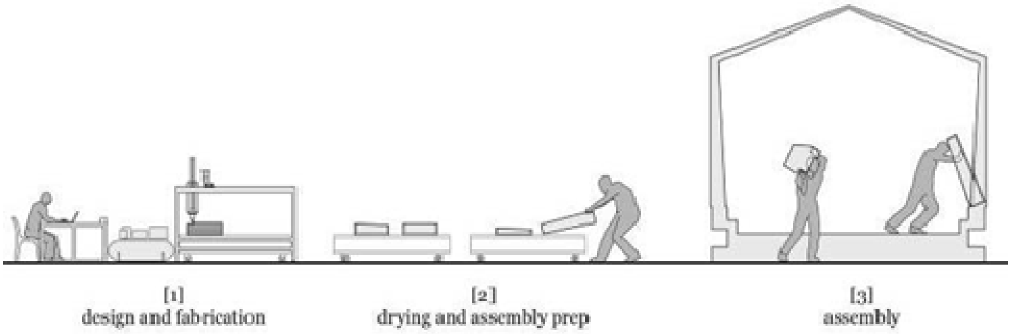


Fig. 1: Layered manufacturing process.

2. RELATED WORK

One of the oldest and most common methods of using components for building assembly is masonry systems. Historically, masonry has been used to build anchoring elements as foundation, vertical supports as walls and columns, unidirectional spanning elements as arches and bidirectional spanning elements as domes and vaults. Even today, masonry systems are a significant component based construction system, especially in regions where construction is not industrialized. The main advantage of using masonry systems is that the raw materials for production can be obtained economically and often locally. The laying of bricks does not require specialized technology, and can be combined with a variety of other materials and construction systems (Lynch 1994). Traditional methods of manufacturing masonry include hand molding, soft-mud, semi-dry and stiff plastic mechanized methods, and extruded wire cutting (International Labour Office 1984).

It is observed that all these methods are restricted to extrusion based processes where the composite material is passed through a profile (mold). This may be one of the reasons for the unpopularity of non-standard shapes for masonry units that are required for interlocking masonry systems. If this limitation is overcome it will increase the feasibility of interlocking masonry. The advantages of interlocking blocks are that they are self-aligning, accurate, and easy to assemble (Thanoon et al. 2004).

2.1. Layered Manufacturing

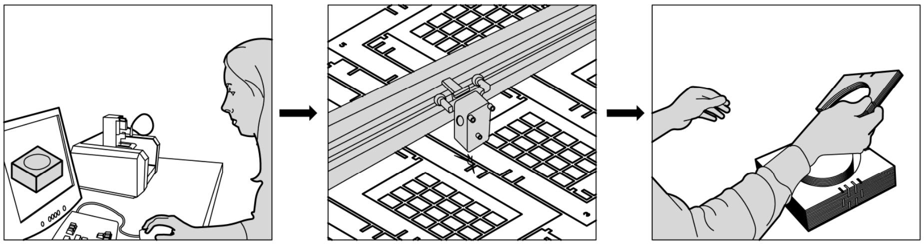
Rapid prototyping (RP) and rapid tooling (RT) manufacturing has had significant and promising research results in efficiency and production times for layered manufacturing. However, these examples involve creating algorithms for producing data for conventional 3D printing devices. Processing of the design geometry undergo calculation of the geometry by either slicing the CAD geometry, or a process of triangulation for creating a representation of the geometry. Although these methods are successful and derive physical 3D solutions, they subscribe to the material dictated by the device and the limited volume size properties of the machine. As a result, the design geometries are limited to conceptual prototypes or small scale technical prototypes (Armillotta 2008). Armillotta's analytic hierarchy process (AHP) highlighted the spectrum of processes used for creating physical objects. The study offers great quantitative data for explaining the method selection challenges faced for achieving the physical results desired; one which was discovering the importance of LOM to achieve large material thicknesses.

The research conducted in this paper looks at large building components therefore incorporates LOM and direct slicing (Starly et al. 2005) as a hybrid system. Starly's investigation explained that multiple translations of geometric data as pre-processing planning for 3D devices can be susceptible to errors in the system; therefore, a direct slicing of the geometry in its design state is preferred. The process outlined in this paper is inverse to the traditional layered manufacturing approaches but aligns with direct slicing approach. The process slices the bounding geometry of the design geometry for creating a negative volume. The negative volume is used with moldable composite materials for creating the final physical object.

Other studies explained the potential advantage of using LOM processes for manufacturing large molds (Prechtl et al. 2005). Prechtl investigated producing technical prototypes using a welding process of planar pieces. The molds produced in this paper use a similar principle of LOM. However, the introduction of welding or other glue-like adhesives are not necessary as the planar pieces are aligned and stabilized from the alignment of the physical tabs embedded in the geometry. This paper outlines a system that uses a 2D CNC manufacturing device to produce 3D physical objects; therefore, the sizes of the end product are variable and scalable as building components.

3. METHODOLOGY

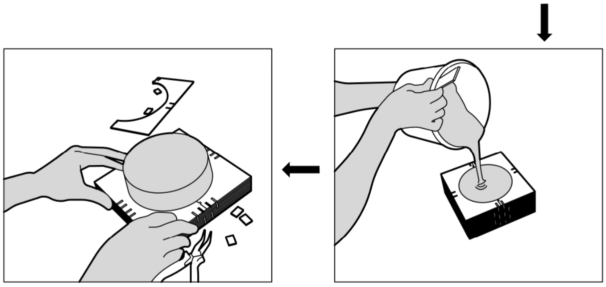
A computational analysis approach is used to physically produce molds from flat-stock material. The research conducted in this paper uses a low-grade ½" CDX plywood material, ½" straight edge, equine recyclable rubber material, Quikrete® concrete mix, a Techno LC Series CNC router, Rhinoceros 4.0 scripting, Ruby scripting, HTML, and Google Sketchup API environments, and level vials. The process starts after the design is generated as 3D geometry, then reduced to 2D layers using a layered manufacturing algorithm developed in this paper. The 2D information is created for physical production on CNC devices such as lasercutters or routers. The process is described as materialization (Sass 2006): a transformation of a 3D shape or set of 3D shapes designed in a CAD environment to 2D geometries for cutting (Figure 2) using CAM.



[1]
Computing the mold layers from a given 3D shape

[2]
Cutting layers from flat-stock material

[3]
Mold assembly



[5]
Mold disassembly

[4]
Casting the shape

Fig. 2: Materialization process starting with an initial shape.

3.1. Case Study

In our experiment, we tested a hollow cube mold. The major constraint for this study is material thickness that will reflect in the generic use of the system for universal application. The process illustrates the translation of information for an initial 3D shape produced in a CAD environment to a finished product using both a lasercutter and a router. The advantage of a computable process such as this one is the reduction of non-systematic steps found in legacy production. In particular, the reduction of steps in measuring material for cutting and by removing repeated processes of rough cuts and finished cuts.

3.2. Mold Calculation for CAD geometry

The approach taken was to first produce a bounding box of the object to calculate the limits of the object in 3D (X, Y, Z). The calculation computes where the geometry lies in Cartesian coordinate space, so that the design geometry is contained within [min(x), max(x)], [min(y), max(y)], and [min(z), max(z)]. The limits are calculated for the efficient use of material which translates to the width of material needed for a structurally sound mold and the height of the mold geometry for number of layers. In this example, we deemed the minimum distance (d_{min}) between the poured composite (interior edge of mold) (m_{int}) and the exterior edge (m_{ext}) of the mold (in the X-Y plane) to be 2”. The 2” material is the peripheral structure that will contain the composite to be formed. Once the bounding box of the geometry is calculated, the 2” is added to the limits to get the height and width of the mold (Eq. 1). The offset dimension defines the maximum 3D geometry for the mold. The limits are used to create a 3D solid polygon object which is used as the mold geometry for computing the numbers of layers (l) for manufacturing (Figure 3).

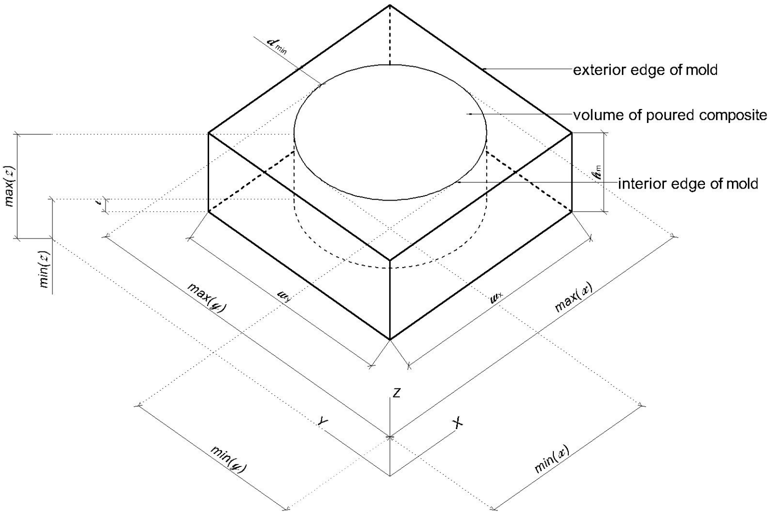


Fig. 3: Bounding box and lateral slicing.

h_m = *height of mold (geometry)*

w_x = *width of mold in x-direction*

w_y = *width of mold in y-direction*

m_{int} = *interior edge of mold*

m_{ext} = *exterior edge of mold*

$d_{min} = |m_{ext} - m_{int}|$

minimum distance from outside edge of mold material to interior edge of mold

l = *number of layers for mold*

t = *thickness of material*

$$
\begin{aligned}
h_m &= [\max(z) - \min(z)] \\
w_x &= [\max(x) + d_{\min}] - [\min(x) - d_{\min}] \\
w_y &= [\max(y) + d_{\min}] - [\min(y) - d_{\min}]
\end{aligned}
$$

Eq. 1. Height and width calculation of mold.

3.3. Lateral Slicing

The design shape is subtracted from the 3D solid polygon using a constructive solid geometry (CSG) approach for calculating the intersection between the two shapes. The remaining geometry defines the void that represents the shape of the mold to be produced. The 3D mold geometry is then processed for manufacturing using a slicing algorithm approach. The algorithm intersects the mold geometry with horizontal planes 2D(X, Y) distributed at an equal distance apart dictated by the material thickness (*t*)(Figure 2). Since the 3D mold geometry is reoriented to the origin (0, 0, 0), the number of lateral slicing has a direct relationship to the height of the mold (Eq. 2). The intersection of planes and the mold construct the layers that are translated for production using a CNC device.

$$
\mathrm{l} = \left\lceil \frac{\mathrm{h_m}}{\mathrm{t}} \right\rceil
$$

Eq. 2. Number of layers required for mold.

3.4. Production of Layers for CNC Manufacturing

Each layer is translated to the origin (0, 0, 0) and further translated in an arrangement that will fit in the bounding 2D (X, Y) dimensions of the flat-stock material (4’-0” X 8’-0” for a CNC router, 18” x 33” for the laser cutter). The layout for cutting is denoted as a ‘cut sheet’(Figure 4). Each layer outline represents a physical layer for constructing the mold, so therefore is cut directly from the material. Layout orientation can be optimized, but was not investigated in this phase of the research. The cut sheet is a computer representation of the path the CNC router will take to cut away the material. However, the intermediate step is to translate the geometric information to be read by the CNC router. The translation process is done using preexisting algorithms that translates geometric data into a series of Cartesian instructions known as G-Code (Ross, 1978). The CNC router is guided by a cutting path that is calculated for each cut sheet. The cutting path which is represented in the form of G-code instructs the drill (cutting head) position within a bounded area of the material (4’-0” x 8’-0”). The cutting head of the router uses a subtractive method of manufacturing; therefore the outline of each layer is removed from the cut sheet leaving the physical geometry (layer) for assembly.

3.5. Rocking Mechanism

Unlike conventional layered manufacturing processes that use a system of printing or fuse deposition, this process uses a composite mix which is poured to form the physical object. As with any composite mix such as concrete, the mix needs to be distributed evenly throughout the mold. This is typically done with an active agitation mechanism such as a vibrator that vibrates the composite throughout the molding device. In this paper, we developed a human-powered rocking device that allows the material to settle in the mold. The mechanism developed has an open bed for stacking the layers and a rocking mechanism used for agitating the flow of the composite (Figure 9.0).

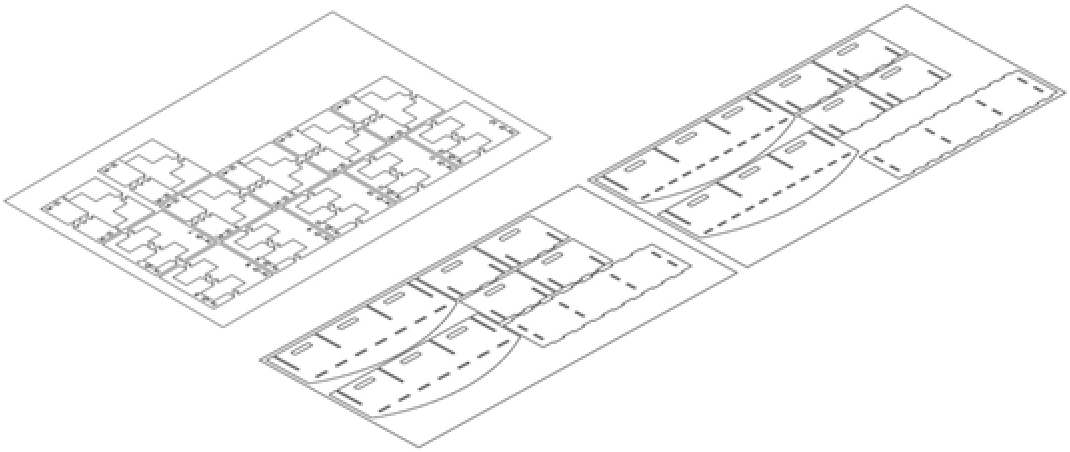


Fig. 4: Production for mold manufacture.

The molding device may consist of a minimum of four flat interlocking panels that are assembled together using embedded connections. However, the number of cross-sectional panels can increase based on how many objects are needed and are manageable. The assembly of these panels is the cradle molding rocking device. The device has four main pieces that make up the outer structural shell of the cradle system (Figure 5). There are two pieces that have a specified radius at the bottom end in the direction of rocking. The remaining two panels interlock orthogonally with the other two panels using a sliding system that creates the rocking cradle and a pocket for placing the layers. The rocking of the device requires limited hand power that allows the moldable composite to settle and form until hardened. The four panels create an inner volume for stacking the rubber polymer layers. We used rubber polymer and Murphy's Oil Soap as this helped in the release of the mold from the physical object without the need for additional release chemical agents. The gauge of the material can have variable thicknesses. The layers are fitted to the interior dimensions of the rocking mechanism. Each layer consists of two interlocking pieces. The pieces are connected using an embedded joining system that connects a channeled notch and a protruded tab. The two adjoining pieces for one layer construct an interior void when stacked in elevation (Z-direction). The moldable composite is poured in the void of layers to create a hardened object when cured.

The device is used to shape objects from simple orthogonal geometries to more complex non-orthogonal geometries. The cradle molding system also provides a natural formwork that shapes the poured composite to the desired shape. The molding system mechanism includes the layering of rubber polymer materials. The material chemistry is very flexible and does not adhere to the composite material for the ease of mold release. The device discussed in this paper does not require extra release tools or chemicals. However, Murphy's Oil Soap was used. The need for reuse is important in developing countries, therefore the device is made to be reusable and is easily stored after disassemble. The two panels are made with handles for assembly, disassembly, and mobility. The device also includes level vials for leveling the cradle after the composite material had been poured.

The cradle molding system is adaptable and intuitive to implement. The system is designed to be adaptable to many environments as a result of its simple rocking application. The molding device discussed is applicable to a range of uses from provincial to more cosmopolitan applications. The rocking device requires a back and forth motion for the flow of the composite material in all parts of the void cavity before settling.

3.6. Assembly

After the cradle system is assembled, the layers are stacked using a laminated object manufacturing (LOM) approach. However, instead of adhesives, each layer is aligned to the previous layer with the use of alignment tabs that conform to the interior volume of the cradle. The layers sit on top of each other packed contained in the body of the cradle. The novelties of the molds are the reusability using a very low-cost system, rather than the conventional metal and plastic mold products; and the ease of assembly that can be used by a novice user for production. The cradle is easy to be disassembled. The layers are removed individually, which releases the mold geometry from the finished component. The mold pieces are removed laterally due the presence of parting lines attributed to each layer for disassembly. As a result, there is no need for additional mold release treatments or methods. After the cured composite is removed, the mold is reassembled and used for successive pours.

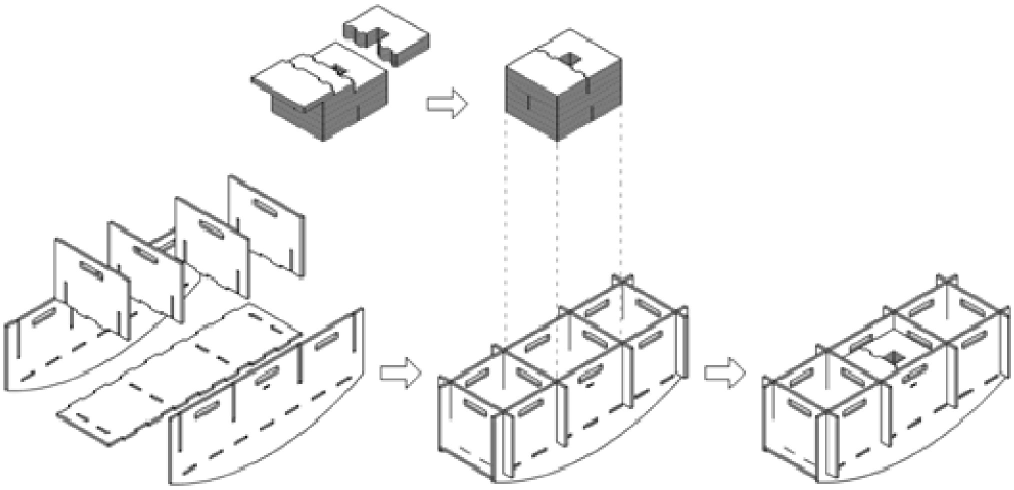


Fig. 5: Cradle assembly system.

3.7. RESULTS

The methodology outlined in this paper investigates a hybrid manufacturing process of LOM and direct geometry slicing. The molds produced were of two different scales. We created molds for production on an 18” x 33” laser cutter bed at a 1’-0” = ¼” scale, and molds for production on a 4’-0” x 8’-0” CNC router bed at full scale. The molds were created of 4 primitive shapes: cube, sphere, cone, and cylinder. Each mold was 8” x 8” x 6” (L x W x H) (Figure 5) in overall dimension for production on the laser cutter and 2’-8” x 2’-8” x 2’-0” (L x W x H) (Figure 6) for production on the CNC router. All shapes were poured in halves to gauge precision of the mating of components and the reusability of the mold.

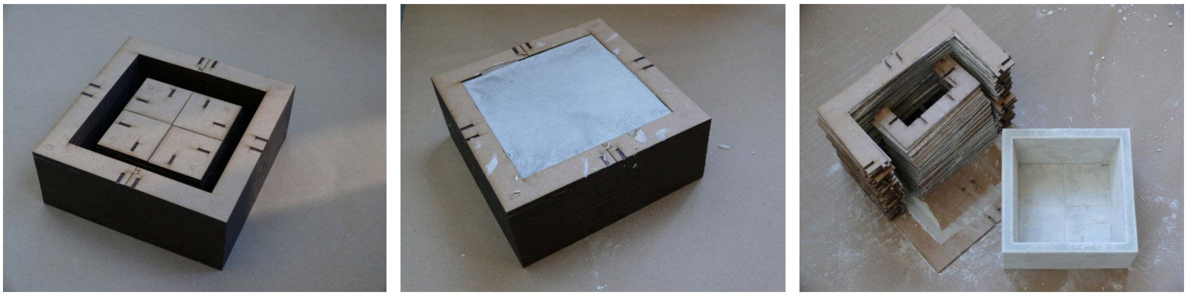


Fig. 6: Lasercut mold of 6”x6”x6”(1/2” perimeter thickness) hollow cube.

Our results illustrate the feasibility of making highly precision molds from low-grade, flat stock material for moldable composite. We used CDX plywood sheets that were stacked for constructing a 3D composite component. The measurements of the end components were within 0.001” and 0.01” precision versus 0.0625” – 0.125” precisions observed in legacy practices of construction and production. This system is very unique as it implies that complex walls and building forms can be reduced to components that can be produced from the initial design data rather than the estimated measurements used in conventional masonry. This system offers precise measurement of the solution from the data produced in a CAD environment. The results prove the systems potential to reduce on-site measuring and cutting that highly impact production, efficiency, and precision.

Fig. 7: CNC routed mold of 2’-0”x2’-0”x2’-0” (2” perimeter thickness) hollow cube.

The plywood systems above proved successful when molding primitive shapes. However, it became difficult to use when molding more intricate forms (Figure 7). As a result the cradle rocking system had to be developed that used the same principles of layering with the rubber polymer, and a new method for helping the composite flow throughout the mold. The premise of this research is to develop a molding system for use in developing countries. Therefore, this research had to consider the use of human power to help in distributing the composite throughout the mold. The rocking mechanism was embedded in the molding system. The new system allowed the user to rock the cradle device back and forth in a steady motion to help with the flow of the composite throughout the mold. This helped in achieving more complex shapes. The shapes were used as blocks for constructing a prototype wall using the cradle molding system (Figure 9). We designed a set of interlocking blocks that used the cradle molding system for production. A set of blocks were poured, given a day to cure and assembled after completely cured.

Fig. 8: Distribution of composite in non-rocking device.

Fig. 9: Rocking mechanism for curing blocks.

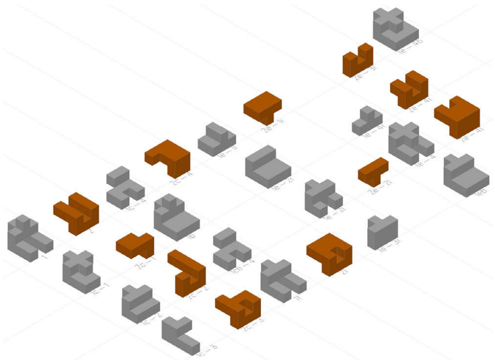


Fig. 10: Complex block for wall construction.

Fig. 11: Wall assembly system using block components.

4. CONTRIBUTIONS

The research presented serves as a generic platform for the manufacturing of building components from moldable composite materials. Using CAD/CAM technologies, the vision is that the methodology can be repeated as a global platform for development. The application of the system is rather intuitive and simple, which makes production time rather efficient and highly receptive to novice users. The system was researched with the premise of an open system than can be modified and used universally to incorporate culture, vernacular, and future design decisions which will be part of future research. Future empirical studies will investigate the integration of CAD/CAM technologies as a seamless process from design to materialization for global application.

Fig. 12: Complete wall assembly made from blocks using cradle molding system.

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