

Pedagogical Approach for Additive Manufacturing of Molds to Produce Topological Interlocking Assemblies

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ABSTRACT: With bespoke fabrication on one end and mass production on the other end of the fabrication spectrum, this paper focuses on custom repetitive manufacturing. It reviews the process and outcomes of a studio offered at Illinois School of Architecture. The objective of the studio was to enable students to design building components for assembly, followed by digital fabrication of the components. The pedagogical methodology employed a project-based learning (PBL) method in the first project, and a problem and project-based learning (PPBL) method for the second project. In the first project, students developed an understanding of precast elements as well as acquiring a set of skills in additive manufacturing (AM) and mold making by analyzing a built precast case study. In the second project, students were tasked with designing topological interlocking assemblies (TIA) while designing a reusable mold for casting the modules. Pedagogy encourages reflecting on past architectural projects by exploring the rationale and limitations of traditional production techniques, before rethinking design and production methods by using advanced building technologies. This manuscript explains the process and outcome of the second project. Among the challenges to be solved in the second project was 1- designing a block geometry with complex curvatures on all sides for mortarless assembly; 2- designing the assembly resulting from the design of the block and iterating while assessing the daylighting and structural performance of the assembly; 3- digital design and fabrication of a plastic mold for repeatable casting of the block geometry. The projects were assessed based on responding to these three challenges. The studio resulted in installations that were exhibited at the end-of-semester showcasing students' projects. The installations demonstrated a proof-of-concept for 3D printing plastics as a formwork for repeated casting of interlocking concrete blocks.

KEYWORDS: Pedagogy, Additive Manufacturing, Topological Interlocking Assemblies, 3D printed molds, precast.

INTRODUCTION

This manuscript explains the pedagogy of a studio offered at Illinois School of Architecture. The studio is at the intersection of understanding additive manufacturing (AM) technology, designing topological interlocking assemblies (TIA), and AM of plastic molds. Therefore, the paper is structured around three pillars: 1- employing problem and project-based learning (PPBL) method for teaching AM in a studio setting; 2- designing TIA; and 3- using AM for fabricating plastic formwork as an emerging construction method for precast. The background on each pillar is explained in section 1.0. Next, section 2.0 discusses the pedagogy methodologically. Afterward, section 3.0 reviews the students' projects and briefly explains the design and fabrication approach. Section 4.0 discusses the development of students' skills in relation to the three pillars of pedagogy throughout the semester, and the criteria for assessing the projects, before the Conclusion section.

1.0 BACKGROUND

1.1. Employing a PPBL approach for teaching AM

According to Celani (2012), digital fabrication laboratories have a potential of promoting experimental methods in architecture together with a scientific approach, which is the basis of contemporary architecture practice (Celani 2012). Focusing on pedagogical approaches around experimental learning, problem-based learning (PBL) and learning by doing (LBD) are two teaching methods based on knowledge gained in the experiential process of learning. PBL enables students to improve their learning styles by offering similar experiences to real-life professional practice. LBD on the other hand focuses on active learning style (Özman and Selçuk 2023). Ilkovič expands on PBL method by presenting "problem and project-based learning (PPBL)" method. In PPBL, the teacher sets a problem in an assignment which is solved in a project development way (Ilkovič, Ilkovičová, and Špaček 2014). Project-based learning is adopted in many courses across US universities where students collaborate in groups to develop 3D printing skills while working on creative and demanding projects. Examples include the course implemented in MIT's 'additive manufacturing' course (Go and Hart 2016), a course offered at University of Texas at Austin and Virginia Tech (Williams, Tech, and Seepersad 2012), and finally Missouri University of Science and Technology's course on 'Rapid Product Design and Optimization' course (Liou, Leu, and Landers 2012). From a different perspective, researchers have focused on studying different contexts in which 'university students are taught about 3D printing'. These categories include teaching students about either the '3D printing technology itself,' or about '3D printing through project-based learning' (Ford and Minshall 2019). Celani (2012) explains that in some schools the initial impact of digital fabrication laboratories in architectural education was simply the increase in the number of physical models produced. However, it is important that students learn to use the machines and

understand the concept behind each different digital fabrication strategy in specific courses. This will allow students to become closer to the production process and to have better control over building parts and materials (Celani 2012).

1.2. Design of TIA

The knowledge embedded in centuries-old techniques offers unique opportunities in the context of digital design and fabrication. Stereotomy, a traditional construction technique, allows architectural structures to be built from discrete stone elements. In this sense, stereotomy is understood as the shaping of solid structural materials to form unique parts that integrally comprise an assembled whole. Stereotomy is seen in design and construction of topologically interlocking assemblies (TIAs) such as Abeille and Truchet flat vaults (Brocato and Mondardini 2012). TIAs comprise solid elements, and their overall structural integrity relies on each element being kinematically constrained by its neighbors. Such systems establish equilibrium through compression forces, with the weight of each heavy block used against itself. Given fixed boundary conditions, the assemblies can resist forces without any additional binding material such as mortar—adjacency replaces mortar. In addition, the global geometry of the assembly can be controlled to minimize deflections and increase the efficiency of the system.

Giuseppe Fallacara and Maurizio Barberio have put forward the term *digital stereotomy*, characterized as the “union between stereotomy and three-dimensional computer modeling techniques in relation to topological transformations and deformations” (Fallacara 2009). Architects and designers have studied the design and assembly of TIA using digital design, computational simulation, and digital fabrication techniques. Many previous studies have focused on parametric design of TIAs to create differentiation either in terms of modules’ porosities (Tessmann 2012). Some have focused on structural performance assessment of the assemblies through simulation (Schaare, Riehemann, and Estrin 2009), while others have emphasized prototyping the assemblies using digital fabrication techniques (Brocato and Mondardini 2015). While the term digital stereotomy aims to characterize the capabilities of computer modeling and subtractive CNC techniques, researchers propose ‘Additive Digital Stereotomy’ (ADS) to describe the way that formwork can be 3D printed for casting topological interlocking modules (Emami and Holmquist 2020). They argue that in calculating and fabricating discrete, structurally interdependent units, ADS is an innovative and true form of stereotomy. ADS is furthermore a potentially more effective method of stereotomic fabrication since it allows for optimizing the weight of modules by geometric design, using low density concrete for casting, as well as reusing formwork for multiple castings.

1.3 AM of formwork for precast concrete

Concrete has excellent structural properties and can be shaped into many complex shapes. However, the required materials and skill sets for molding concrete add to its construction cost, and ultimately CO₂ emissions of this construction method. AM is an evolving construction process that is revolutionizing concrete construction. For creating 2.5 dimensional geometries, the formwork can be eliminated altogether, allowing direct digital fabrication of concrete also called 3D concrete printing (3DCP). For creating complex 3-dimensional geometries with intrinsic surface pattern, 3D printing mold is the leading method. This approach is an indirect digital fabrication of concrete referred to as 3D printed formworks (3DPF). Advances in recycling and material science hold promises for future plastics made from renewable sources and reused numerous times during their lifecycle. Considering the reusability of the formwork during digital fabrication phase followed by plastic recycling could take us one step closer to a circular economy. Many research studies have used bespoke 3DPF where the formwork has been destroyed with a heat gun (Jipa et al. 2019), stayed in place (Aghaei-Meibodi et al. 2018), or dissolved (Sitnikov 2019). However, the 3DPF needs to be used multiple times to be compatible with the economics of scale. Therefore, custom repetitive manufacturing, where unique elements are designed and fabricated for a specific project is the focus of this paper. There are a few recent research studies that have focused on repeatability in design and reusability of the 3DPF. Examples include the Min-Max panels (Aghaei-Meibodi, Odaglia, and Dillenburger 2021); the topologically interlocked blocks of a stereotomic arch that were repeatedly cast into 3D printed elastic molds (Emami 2021); the topologically optimized beam realized through the reusable casting of a 3D printed TPU formwork (Xu et al. 2022); and the façade panels cast in reusable TPU formwork (Emami 2023).

2.0 PEDAGOGY

2.1. Project description

The project description provided to the students tasked them with designing and prototyping a sunscreen made of topological interlocking blocks. Both sides of the screen were required to be exposed and to be designed in a way that allows having a view from one side to the other. Students needed to make decisions on the perforation ratio and material distribution of the modules and consider achieving the highest strength with the least material use. The screen was required to be a self-standing structure that is not attached to a sub-structure for support. Thus, each row needed to support the weight of the blocks above it up to 3 meters (~10 feet). The method of fabrication was constrained to using 3D-printed formworks for the repeatable casting of the modules. Students were offered two materials for AM. Polylactic Acid (PLA) and Polyvinyl alcohol (PVA) which is a water-soluble filament. Finally, students were asked to create an installation by using at least ten modules that show a portion of the wall.

A total of ten students were enrolled in the studio: six first-year graduate students and four second-year graduate students. At the beginning of the semester, students’ *familiarity*, *comfort*, and *proficiency* with computational design and digital fabrication tools was assessed. *Familiarity* was defined as having encountered the tool before by having opened it at least once. *Comfortability* was defined as being able to use the tool to some extent. *Proficiency* was defined as having the ability to effectively use the tool. Rhino NURBS modeling platform (Robert McNeel & Associates 2018) was recommended as the preferred computational aided design (CAD) platform to be used by the students. Regarding computational aided manufacturing (CAM) skills, AM was the key skill that was surveyed.

The students' skillset in CAD and CAM prior to the start of the studio is summarized in Table 1. Synthesizing the information presented in Table 1, all students expressed having some level of familiarity with Rhino. 40% of the students stated that they are comfortable with it, while 30% of them indicated that they are proficient in using it. Regarding digital fabrication techniques, all students expressed that this studio is the first digital fabrication studio that they are taking. Students' knowledge in using 3D printing was explicitly assessed. All students expressed familiarity with the concept of 3D printing. However, they had never used it in any of their school projects, and they expressed that they had never directly operated a 3D printer. This assessment reinforced the instructor's approach in structuring the pedagogy around teaching the students about AM technology first and foremost. It was anticipated that the students' CAD skills would improve during the Design of TIA. Next section further expands on the three pillars of pedagogy.

Table 1: Students' level of proficiency, comfort, or familiarity on a scale of 0 to 3 regarding CAD and CAM techniques. Source: (Author 2024)

	Student 01	Student 02	Student 03	Student 04	Student 05	Student 06	Student 07	Student 08	Student 09	Student 10
CAD skills: Rhino	3	2	1	1	2	1	3	2	3	2
CAM skills: AM	1	1	1	1	1	1	1	1	1	1

0 Not familiar at all; 1 Familiar; 2 Comfortable; 3 Proficient.

2.2. Three pillars of Pedagogy

The pedagogy is organized regarding the three pillars that were explained in the background. First, the studio is an example of employing a PPBL approach for teaching AM in a studio where students collaborated in teams of two or three. During the first few weeks of the studio, students were taught about AM through a series of workshops. This included learning about employing AM for creating physical models, in addition to the 3Dprinting technology itself. The workshops covered some details about the hardware, the mechanics of the machines, and safety to enable them to operate the machines. This was an implementation of learning by doing (LBD) approach in teaching AM. It should be noted that project-1 was specifically designed to allow skill development, and the grading was forgiving. Therefore, the learning curve did not put unnecessary stress on students. Rather, it demonstrated the importance of paying attention to the process of running a 3D printer machine.

Second, the studio is an example of teaching Design of TIA using a NURBS modeling platform. Students were presented with examples of historical cases of mortarless TIA vaults made of stone. Each group was then asked to design four to six TIA concepts depending on the number of students per group. For example, a group made of two students versus three students was asked to present a total of four and six TIA concepts respectively. The students were also asked to 3D print four modules of their designed TIA to demonstrate their interlocking mechanism. This approach helped the teams to start with a good number of concepts that were later combined or allowed the students to pick one among many. Also, the physical models allowed them to develop the interlocking mechanism through feedback, in-class conversations, and iterations.

Third, the studio is an example of teaching about AM of formwork for precast as an emerging construction method. First, the students were introduced to rubber mold making in the first project to familiarize them with the sequence of mold design and mold making. It is important to note that the topic of AM of molds is closely aligned with the instructor's research area. Therefore, there were many built models and cast instances of the mentioned construction method in the Digital Technologies in Architecture (DiTA) research lab that were presented to the students to help them understand the idea. Students had a good platform to start designing the mold for their TIA, followed by digitally fabricating them.

Since educating each pillar required a timeframe, the curriculum was designed in a way that the students are first provided with a window of opportunity to learn about each topic. The first quarter of semester focused on teaching and learning about AM. During the second quarter of the semester, the students were provided with the project-2 description and were introduced to the concept of TIA. During the third quarter of the semester, students focused on the design and fabrication of formwork for their designed blocks. The timeline for teaching each topic and the overlaps between the three topics are demonstrated in Figure 1.

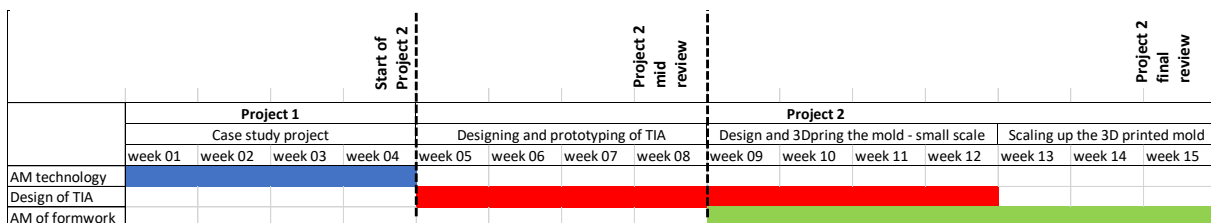


Figure 1. Timeline for introducing the three components of the studio and the time allowed for developing students' skillset in each topic. Source: (Author 2024)

3.0 REVIEWING THE PROJECTS COMPLETED IN THE STUDIO

The studio resulted in a total of four projects that were showcased as installations at the end of the semester. Three out of four projects which are shown in Figure 2 are reviewed and discussed in this manuscript. The following subsections are focusing on each project.

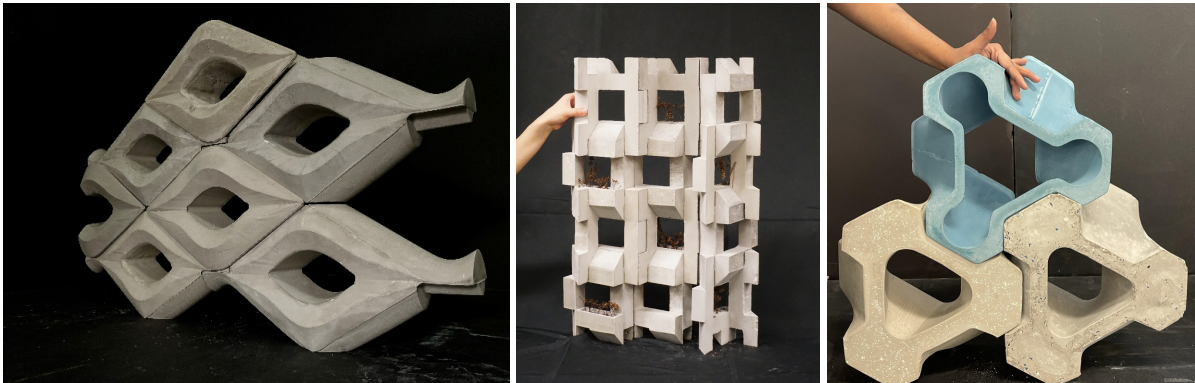


Figure 2. TIA assembly of the three projects: The Wave (left); Polyomino (middle); Re-Block (right). Source: (Author 2024)

3.1. The Wave

A team made up of three students designed, iterated, and prototyped “The Wave” project. All of the team members were first-year Graduate students with an undergraduate degree in Architecture. The Wave aimed to achieve a seamless and organic geometry that acts as a decorative perforated courtyard wall resonating with the landscape. The proposed sunscreen was designed as a courtyard wall, an internal partition wall, or a sculptural element. This was inspired by the study that courtyards with perforated walls are extensively used in hot and humid climates such as India and Sri Lanka. The interlocking system that the team designed for their systems consisted of designing a concave/convex surface on the edge of the module which would restrict the movement of the modules in the z-direction. They then designed connecting parts of the module that constrained the movement in the x and y-direction. A total of two module types were designed. Module A, the module with two tails at each end forming the first row of the assembly, measured 14” wide and 6.81” tall with a thickness of 2.41” (Figure 3-left). Module B, the module forming the second row of the assembly, measured 11.53” wide and 6.81” high with a thickness of 2.8” (Figure 3-middle). The team iterated at three different scales, and scaled up as they resolved design and fabrication issues. Their first model was 2”-wide, increasing to a 7”-wide model, and the final prototype was a 14”-wide model.

Regarding mold design, the team designed a six-part mold that comprised of a plug, a base with an elliptical bump that would hold the plug, and four walls (Figure 3-right). All parts were printed out of PLA and were reusable. The full-scale 3D printing of the mold was challenging. This was because the bed size of the 3D printer (Raise 3D Pro3 plus with a bed size of 620, 626, 1105 mm or 24.4” x 24.6” x 43.5”) was smaller than the size of the mold’s base. To overcome this challenge, the base of the mold was divided into three pieces and was placed vertically on the print bed. Ultimately, only the central part of the base which had undulations was 3D printed. The other two parts, which were flat pieces, and were designed for clamping the walls and the base to each other were made from wood. Due to the heat generated during the casting process, the plug deformed after using it two to three times as it had less infill density. To avoid this happening in the future, the core should be printed with higher density so that it is more durable. The TIA assembly demonstrated excellent stability when installed during final review.

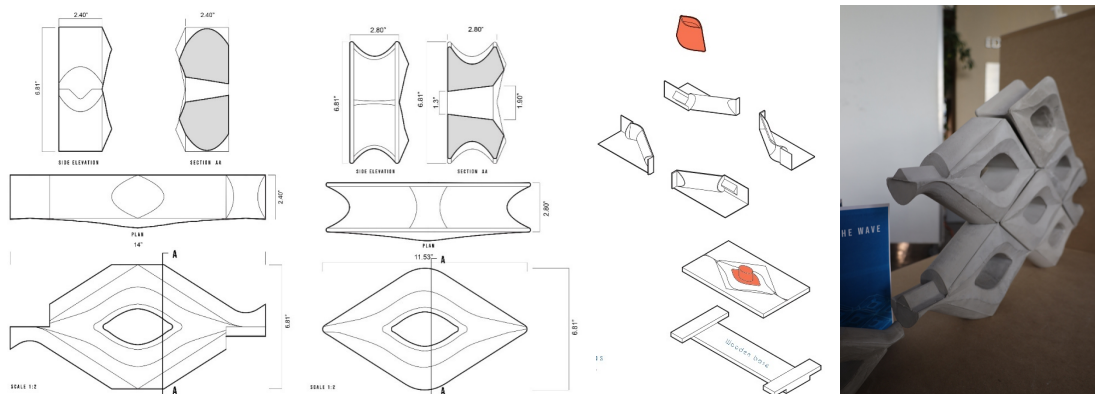


Figure 3. Project Wave: Module-A drawing (left); module-B drawing (middle); A six-part mold was designed (left). Design and drawings by Bryant Nunez, Harshini Varanasi, and Samruddhi Shirdhankar. Source: (Author 2024)

3.2. Polyomino

A team made up of three students designed, iterated, and prototyped “Polyomino” project. All the team members were Graduate students with an undergraduate degree in Architecture. One of them was a second-year graduate

student whereas the other two members were first year graduate students. Polyomino is a demonstration of micro-design impact on macro scale. This project seeks to innovate construction methods in the precast concrete industry by designing one module that could be assembled in three different ways to each other: two ways horizontally and one way vertically (Figure 4-left). This allowed flexibility in assembly and the possibility of achieving numerous ways that the system could grow in different sites and conditions by just using a single module. The complex design of the module went through many iterations at the small scale before a final mold design was achieved. The final mold iteration consisted of 11 reusable mold parts and one central core that had to be melted. The final mold design and multiple cast pieces assembled into each other is shown in (Figure 4-right). The TIA assembly demonstrated excellent stability when installed during final review.

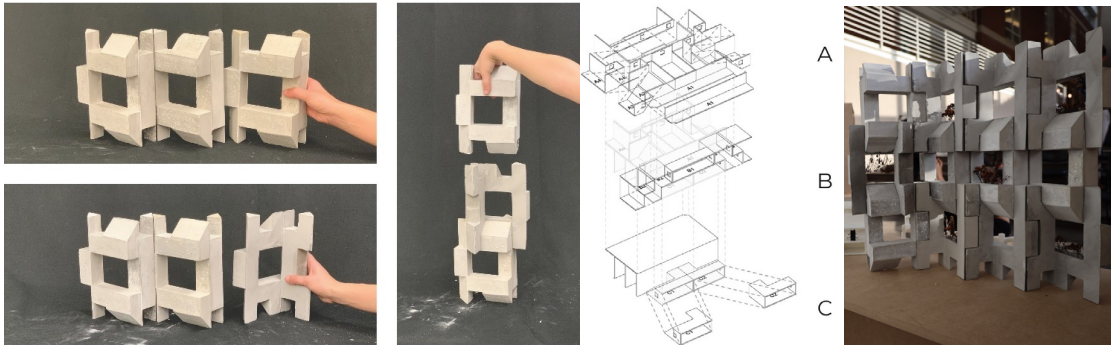


Figure 4. Project Polyomino. One module was designed to assemble in three different ways to other modules horizontally and vertically (left); final mold design (right). Design and drawings by Amir Zarei, Atousa Esmaeili, and Franchelle D’Souza. Source: (Author 2024)

3.3. Re-Block

A team made up of two students designed, iterated, and prototyped “Re-Block”. Both team members were second-year Graduate students with an undergraduate degree in Architecture. Re-block typological element was designed to investigate the characteristics of the geometry to reflect those in the construction. The module was designed to integrate aesthetics, functional technology innovation and production efficiency. It investigated the potential of digital fabrication in traditional concrete construction. With the design of this module, the students aimed to replace traditional ornamental brick which needs expertise for construction with a more efficient module. This team approached geometry design by following the Albeit vault modules. The team investigated an array of geometries that were interlocking with each other using single curvature and double-curvature surfaces (Figure 5- left). Ultimately, a geometry with double curvature surfaces was selected. The geometry demonstrated excellent stability once it was assembled with the neighboring modules (Figure 5- middle). They tested various mold making methods and varying scales of interpretation to understand the way that concrete behaves in different portions of the geometry. With each iteration of the mold experiment, gradual scaling up helped them better understand the overall strength of the geometry and its interlocking accuracy. The mold design iterations were done at a 1:4 scale. The final mold design comprises three reusable outer PLA shells that were retracing the exterior geometry (Figure 5- right). The internal mold wall was a single piece of PLA that would have been destroyed before each demolding cycle using a heat gun. The TIA assembly demonstrated excellent stability when installed during final review.



Figure 5. Project Re-Block. A series of topological interlocking geometries were explored (left); the selected interlocking geometry was 3D printed in PLA (middle); Final mold design (left). Design and drawings by Avinash Verma and Krishna Jayachandran. Source: (Author 2024)

4.0 DISCUSSION

4.1. Timeline of students’ skill development regarding the three pillars of pedagogy

Students’ skill development regarding the three pillars of pedagogy, namely *learning about AM technology*, *Design of TIA*, and *AM of formwork for precast* that were explained in section 2.2 are qualitatively demonstrated in Figure 6. Looking at the figure, the x-axis is the number of weeks into the semester. The y-axis shows a scale ranging from one to five. One is an abstract starting point that presents *Poor Ability*, whereas five represents *Excellent Ability*. It should be noted that five does not refer to absolute professionalism in any certain area. Rather, it demonstrates the maximum potential that a student could reach during a 15-week semester and/or reaching a point where no further improvement was planned for a certain skill. Also, it should be noted that these are an average trend for the whole studio based on the observation of the instructor and do not consider the performance of the outlier students who

were quicker or slower in grasping a concept compared to the average. The definition of the scale ranging from Excellent to Poor is organized based on *Outcome* and *Learning Trajectory*, summarized in Table 2.

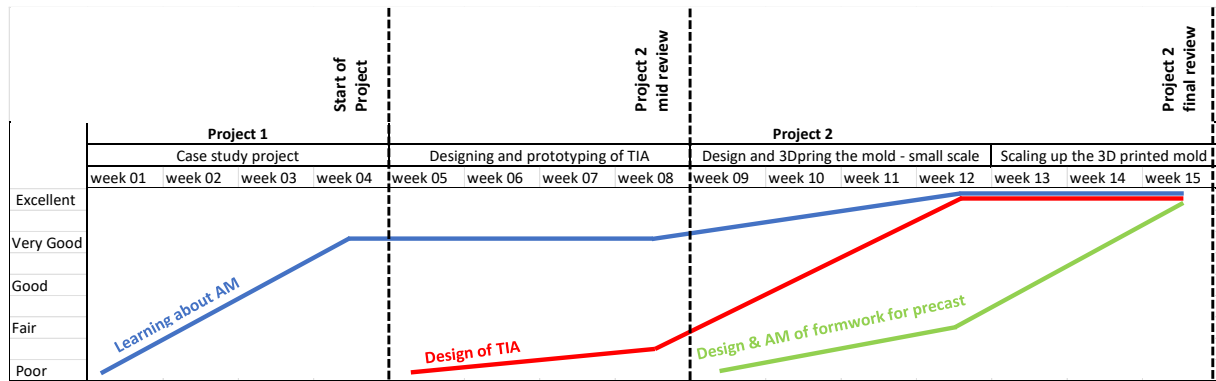


Figure 6. Students' skill development timeline in three pillars (AM technology, Design of TIA, Design and Am of formwork) in a 15-week studio project. Source: (Author 2024)

Table 2: Definition of the rating scale regarding students' skill development throughout the semester. Source: (Author 2024)

<i>Performing ability</i>	<i>Outcome</i>	<i>Learning trajectory</i>
<i>Excellent</i>	<i>Outcome is consistently produced and is optimized through detailed control of the process.</i>	<i>Students appear confident in the topic and demonstrate an excellent grasp of the topic.</i>
<i>Very good</i>	<i>Outcome is consistently produced.</i>	<i>Students appear confident in the topic.</i>
<i>Good</i>	<i>Outcome is consistently produced.</i>	<i>Students have had many failure/success cycles and are at a stage that obtaining an outcome can be predicted.</i>
<i>Fair</i>	<i>Some random outcome is produced.</i>	<i>Students are still learning about the topic through failures.</i>
<i>Poor</i>	<i>No tangible outcome is produced.</i>	<i>Students are at the beginning of the learning process.</i>

Looking at Figure 6, students' skill development in *learning about AM technology* was significant in the first quarter of the semester. Putting students in charge of operating their designated 3Dprinters presented challenges and opportunities. One of the main challenges was that students were not accustomed to paying attention to how a machine works. Therefore, the first couple of prints sent by many students failed since they did not follow the detailed instructions. The delay caused by failed prints negatively affected students' progress. After that learning curve, students' attention to how the machine works increased significantly, and their success rate in operating the machine increased. Students' skill reached a *Very good* level by week 04 that allowed them to utilize the AM technology effectively during working on project 2. The development of this skill stopped in the second quarter of the semester, as students focused on understanding the project requirements and developing their design concepts. However, it started to improve again in the third quarter of the semester when students needed to print thin-shelled plastic molds. They developed an in-depth perspective about the limitations of the material and the machine upon printing thin-shelled plastic. They learned about extruding filaments other than PLA, such as PVA, and its required printing settings. Also, as they were using the machines more frequently, and the size of their artefacts was increasing, they paid more attention to optimizing the print time. They optimized print time by controlling the orientation of the object on the print bed, reducing the infill percentage, and printing in 'draft resolution' versus 'high resolution' by changing the printing speed.

Looking at the Figure 6 regarding students' skill development in *Design of TIA*, it started in week 05, and the slope of development was gentle during the second quarter of the semester. By the end of the second quarter, it had barely reached a *Fair* level. It was challenging for students to grasp the concept of topological interlocking blocks for creating mortarless assemblies. Many of the first design iterations created by them were employing typical methods of assembly such as stacking or weaving. The initial blocks that the students designed went through many iterations through having in-class conversations to demonstrate how the perimeter surface curvatures can be altered to constraint its movement in x, y, and z-axis. Furthermore, not all students were proficient in using a NURBS modeling platform for designing and manipulating curved geometries at the detail level. Therefore, there was a learning curve for many of them (70% of the students) to develop an in-depth knowledge of the NURBS CAD platform before their skill reaches a level that serves their project. There was a sharp increase in students' understanding of TIA after mid review and during the third quarter of the semester. This shows that students simply required more time to grasp the idea and test their prototypes for making TIA. Also, they started to incorporate other aspects of the project description, such as view requirements, optimizing the thickness of the blocks affecting weight, etc., during this time. The Design of TIA was nearly unchanged during the last quarter of the semester.

Finally, Figure 6 represents students' skill development in *design and AM of formwork for precast*. This phase started after mid review and at the beginning of the third quarter of the semester. Design and AM of molds coincided with the sharp development in Design of TIA, thus it started with a gentle slope. However, it was the key focus of the project during the fourth and last quarter of the semester. Many design and fabrication iterations of the formworks were conducted during this phase. Since the printing time was becoming more significant with increasing the size of the components, students were developing other aspects of their studio project in parallel to this activity, such as creating diagrams and drawings, and improving their project presentation.

Looking at the overall trend and overlaps of three plots, the second quarter of the semester seems to have the least amount of development in the three areas cumulatively. The second quarter is the period that project-2 was introduced to the class, and students were focusing on understanding the concept of TIA, while they were developing their concepts. From another point of view, the third quarter of the semester was the most intense period of the semester for the students regarding the development of their skills and making progress in completing the project. During this quarter, students were grappling with developing the Design of TIA, designing and 3D printing the molds, and learning about the limitations of the machine on creating thin shells out of PLA and extruding alternative materials such as PVA.

4.2. Assessing final projects

After discussing the development of students' skills in various areas during the semester, project assessment and specifications are discussed in this section. All teams succeeded in having a stable and mortarless assembly of the topologically interlocking modules. Their projects were assessed based on three criteria:

- i. Designing a block geometry with complex curvatures on all sides for mortarless assembly.
- ii. Designing an assembly comprised of the blocks and iterating back if needed.
- iii. Digital design and fabrication of plastic mold for repeatable casting of the block geometry.

All three projects fulfilled the first and second criteria. This was demonstrated through their successful installation at the end of the semester (Figure 7). All three projects achieved casting the modules through additively manufactured molds. 'The Wave' had mold parts that were all reusable, whereas 'Polyomino' and 'Re-Block' had reusable mold parts except for a core that needed to be melted to release the cast part. Table 3 summarizes the number of module types and the specifications of the molds that were designed in each project.



Figure 7. Final installation of the studio projects. Source: (Author 2024)

Table 3: Summary of the projects completed in the studio along with its mold design and fabrication specifications. Source: (Author 2024)

Project name	Number of module types	3D printing material	Total number of mold parts.	reusable vs. sacrificed mold parts.
<i>The Wave</i>	2	PLA	6	6 reusable parts (1 base, 4 walls, 1 plug).
<i>Polyomino</i>	1	PLA	12	11 reusable parts. 1 sacrificed part (the inner core).
<i>Re-Block</i>	1	PLA	4	3 reusable parts (3 walls). 1 sacrificed part (the inner core).

CONCLUSION

This manuscript demonstrates the production of lightweight concrete formwork using PLA only for the construction of discrete blocks that can be assembled without mortar through their topological properties. The topological interlocking blocks have complex curved surfaces on their perimeter, which makes constructing them very difficult through typical construction methods. Furthermore, many of the designed blocks have ornamental and intrinsic patterns on one side, which makes them impossible to be built through methods other than molding. Finally,

designing a reusable mold was a key consideration in the studio, to be compatible with the economics of scale towards a future circular economy. With advances in recycling plastics, utilizing plastic formwork for repeatable casting of complex building elements is a viable method. Regarding pedagogy, students were taught about 'employing 3D printing', as well as '3D printing technology itself,' through a project and problem-based learning. Students were introduced to AM technology from the beginning of the studio through a case study project. By the start of the second project — the design project — students' skills in AM technology had reached a 'very good' level that allowed them to effectively use that skill for developing the project. Ultimately, students pushed their learning about the limitations and opportunities of AM further by fabricating plastic molds during the third and fourth quarters of the semester.

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