NEXUS NETWORK JOURNAL
Architecture and Mathematics

DIDACTICS

Learning by Doing: Integrating Shape Grammar as a Visual Coding Tool in Architectural Curricula

Deena El-Mahdy[1]

Abstract

Computational design and shape grammars hold a growing appeal in the architectural curricula. This paper aims to assess shape grammars as a visual teaching method that integrates manual exploration based on "learning by doing" in early education curricula without digital software. As a primary outcome of a visual design course at the British university in Egypt, four self-structured pavilions are fabricated by first-year architecture students. Experimentation occurs through a process of visual computing which develops a deeper understanding of material qualities. A comparison of design parameters is conducted through hands-on experiments that include design principles, unit transformations, connection types, assembly process, and functional aspects. The paper examines the skills that students acquired during the course. This study concludes that by applying shape grammars in design studios, students are adequately prepared at the foundational level for their transition towards learning computational design.

Keywords Shape grammars · Algorithms · Computational design · Geometry · Design education · Parametric design

Introduction

In 1971, Stiny and Gips devised the shape grammar (SG) method that was used and integrated into many architecture applications and design studios as a generative and computational design (CD) method. Trial-and-error processes were commonplace in both education and construction through experimenting with different materials, using hands as tools before introducing any machines. The new digital revolution, has transformed this situation using fabrication machines to translate what the minds explore and think (El-Zanfaly 2015). This resulted in new digital fabrication (DF) labs that started to appear in architecture schools (Celani 2012), where they

✉ Deena El-Mahdy
  deena.elmahdy@bue.edu.eg

1 The British University in Egypt, Suez road, El-Sherouk City 11837, Egypt

aided in the creation of tools to develop architectural curricula to enhance students' experience.

Although many conventional teaching modules are still compatible with the digital revolution (Schleicher et al. 2019), students are, nonetheless, independently discovering ways to develop their CD skills. Consequently, they fall into the trap of being fascinated by the tools to generate complex forms, as opposed to the logic, processes, and material implications beyond these tools (Varinlioglu et al. 2016). This situation results in students treating the materials as a final representation instead of a critical part of the design process. Reflecting this gap in Egyptian universities based on Salama and Crosbie (2010), it was observed that DF in design is reacting in a slow manner in the early stages of the architecture curriculum.

Accordingly, approaches such as "make to learn" and "learn by doing" shed light on the trial-and-error processes that can develop the students' experience (Özkar 2007). With the important role of CD and DF tools in the process of making, this paper assumes that teaching these tools is not enough without understanding, manually, the computational process behind them. Supported by Alalouch (2018), the present study claims that introducing CD using manual means in earlier education stages might be more effective than if introduced at a later stage. Therefore, understanding the nature of architecture pedagogies' is the first step to determine when computer applications should be integrated as a making process rather than merely as a software (Doyle and Senske 2017; Soliman et al. 2019).

With the importance of integrating externalization of visual reasoning through shape formalism in first-year design studios (Özkar 2011), the present study will approach this method in terms of material testing and fabrication to raise the students' awareness of design as a computational tool. Thus, this paper aims to highlight the impact of integrating SG and CD as a visual teaching method throughout undergraduate architecture design modules. It investigates how to generate forms based on visual approach, and material visualisation as a design process. This is done via manual exploration based on learning and "making by doing" as design generative driver tools, to enrich material understanding rather than just being a model-making representation. The paper deals with challenges associated with the fabrication process of four self-structured pavilions carried out by first-year students. The method targets implementing visual rules during the design process to reach third-dimensional units without digital software. The paper extends the SG into the process of fabrication and self-assessment based on making and materiality. It concludes by discussing possible changes in the architectural curricula to raise the awareness of both instructors and students.

Background

Learning by Making in Architectural Education

Over the past few years, the widespread integration of CD and DF has had a growing appeal in many architectural curricula, which has changed the way of teaching (Duarte et al. 2012). These approaches provided self-learning methods

as a design process (Eversmann 2010). Correspondingly, this was reflected in developing a pedagogical method in design studios to balance between paper, computer, and tools (Özkar 2007; Prakash et al. 2017). Thus, the development of DF tools with the spread of computational methods increased the focus towards exploring materiality and fabrication processes in design (Gürsoy and Özkar 2015). Since then, many types of visual computing representations and programming software have gained popularity among architects (Blikstein 2013). Dunn (2014) argued in his book *Architectural Modelmaking* that programming and coding have become easy and effective methods of communication for architects to learn. For instance, Grasshopper which is a parametric and visual programming language includes many plug-ins that allow for computing and optimizing complex forms easily. Unfortunately, such tools were preferable to students to generate complex forms, due to their very quick nature, without taking into consideration the logic behind them, treating the material as a visual representation tool in models (Lyon and Garcia 2011; Garber and Jabi 2014). Nevertheless, according to Cannaerts (2009), the representational role the models can provide is to assist in the design explorative process to create a three-dimensional (3D) form that is more than just a representation after the design process.

Özkar (2007) argued that the appearance of DF allows "learning by doing and making" concepts in design studios, which remains important in early education where software is not allowed. This experiential learning pedagogy allows for experiencing tectonic transformation based on hands-on experience, where students become familiar with materials as a fabrication process (Yazici and Tanacan 2020). In this sense, materiality is an exploration-making tool that introduces unpredicted results where seeing and touching became part of the design decisions (Gürsoy and Özkar 2015) rather than a representation.

Pioneers like Gaudi, Fuller, and Otto used materials not only as a representation but as an exploration tool to guide fabricating structural forms. Models that target the material as a driver became essential to test the forces and stability which feedback to update the design accordingly. Tackling materiality from this perspective – as argued by Yazici and Tanacan (2020) – opens doors for "learning by doing" through using physical modelling in form-finding during the design process. However, CD is not fully integrated into architectural curricula but is conducted independently at the higher or postgraduate level (Angelo et al. 2012; Varinlioglu et al. 2016). Accordingly, it is important to introduce a learning process based on actions that develop the students' experience in making (Yakeley 2000; Celani and Gabriela 2002). With Lehman's (2015) proposal to design ideas based on various computer-controlled processes, such as additive and subtractive, the present paper claims that implementing such processes on the physical model enriches material understanding through user interaction, especially at early stages in education.

Many researchers argued that modes of production based on exploration tools such as model making give students experience, through sensing and expressing any idea in 3D form (Lehmann 2015). This sheds light on the possibility of integrating SG as an algorithmic generative tool to introduce practical fabrication exploration in design modules, which extends to the material. As a basic element, SH provides "solids" that can be translated into 3D shapes and transformed based on material,

size, and shape (Knight and Stiny 2015). The transformation process includes addition, subtraction, and folding rules which can provide stability and manually turn two-dimensional (2D) surfaces into 3D shapes (Jackson 2011). Thus, this is the present paper's focus to challenge traditional pedagogical methods that would help students to be familiar with visualising the process easily.

Shape Grammars in Architectural Education

Stiny's and Gips' SG, as the first design-oriented generative system, was used later in many architecture applications (Stiny and Gips 1971). Since then, SG has been integrated into design studios in several forms as a generative and CD method (Knight 1999). Unlike implementing digital and advanced fabrication tools, SG presents a simple process to emulate and automate what we see and do with our hands by using Algebra theory. That is a prerequisite to a general computer implementation, which can be translated into basic elements such as; points, lines, planes, and solids (Stiny 2006). These elements can be combined based on a set of spatial transformation rules such as addition and subtraction, which can result in different form sizes, orientations, and scales. Knight and Stiny (2015) defined SG as a rule-based language that can be applied step-by-step to describe, compute, and generate a design. This language provides a visual approach that can be seen throughout the design based on shape transformation in 2D or 3D, rather than text (Cenani and Cagdas 2006; Eilouti 2019). Its applications expanded to be used as an algorithmic tool for analysis and synthesis that allows writing rules, where different configurations and non-standardized forms can be generated (Prakash et al. 2017). Ibrahim's (2011) comparative study in showed that integrating SG in pedagogy mostly targets advanced graduates or post-graduates rather than beginners. This emphasizes the need to teach basic mathematical knowledge of how SG works through hands-on learning experiences.

Introducing SG in curricula requires a suitable teaching strategy, which raises the question "should teaching SG be theory-based or practice-based?" (Prakash et al. 2017) Several educators have found answers to this question through integrating the concept of "learning by doing" based on SG. For example, Colakoglu and Yazar (2007) presented a graduate module design entitled "designing the design" which focused on integrating SG and computational thinking. In this course, SG was used as a tool for introducing design computing for seniors without previous knowledge of computational theory. Students generated modular house units manually and digitally using algorithmic design experiments. Özkar (2007) offered a design teaching approach of "learning by doing" through design thinking and computing to the first year in architecture. The approach assists students to generate by hand, small-scale prototypes. In Egypt, a study integrated SG as a rule-based description using manual sketching as a visual experience for year one students (Ibrahim et al. 2012). Despite this integration, the results did not target self-structured units based on visual rules in non-design studios, which is the present paper's focus. Accordingly, the method in this paper aims to be well-suited for beginners as a manual exploration approach, with no need for digital computation. The projects'

analysis followed three key features identified by Ibrahim et al. (2012), analytical skills, knowledge repository, and algorithms. The analytical grammar skills require students to extract common features in the design with critical comparison to reveal a variety of vocabularies. The knowledge repository depends on the rules' selection after several experiments, while algorithms are to understand the symbolic description behind the theory of SG.

Methodology

According to Özkar (2007), design is considered the conscious activity of establishing a relation between small parts to achieve unity. In light to this definition, this paper focuses on requiring that the design process for creating new shapes is based on visual perception following specific transformation rules in assembly. This paper presents the effectiveness of integrating SG and CD approaches as a design tool for 3D visual compositions in architectural education. The paper considers three aspects based on making grammars definition by Knight and Stiny which are things, doing, and sense, by focusing on shapes in the third-dimension and seeing rules visually.

Four group projects are carried out by year one students in the Department of Architectural Engineering at the British university in Egypt. As an integral part of the visual design course, an experimental method is performed to fabricate self-structured two-meter high pavilions using 4 mm cardboard. Students select the rules they implement to describe and self-evaluate the making process. Different design parameters are implemented regarding the design principles, units, connections, assembly, transformation, and functional analysis. The method adopted in this study is conducted in a visual design course where students have neither knowledge in computational software nor design studios. In this course, SG and CD are introduced using the "learning by doing and making" process to teach the students how to be able to write, visualize, and turn the 2D shapes into 3D units manually.

The method implemented is in line with Sheppard et al's (2009) semi-structured based on a units' exploration to generate a structure model, which ended with scaling it up for those who are unaware of any advanced software. It is divided into three main phases.

(i) The theoretical background which includes the fundamentals of SG, CD, form-finding, and extraction rules from nature.

(ii) The making process of a small-scale pavilion based on modular units documenting all the trial-and-error processes. This phase is divided into three stages as in Fig. 1. The first stage includes turning the 2D units into 3D shapes through unit exploration, material understanding, and folding techniques followed by written algorithmic rules. The second stage focuses on the design principles transformation of the units such as scaling, rotating, tessellation, movement, symmetry, balance, and focal point. The units are labelled/numbered and connected with designed or external joints. The third stage distributes the units among a grid according to the rules created. This
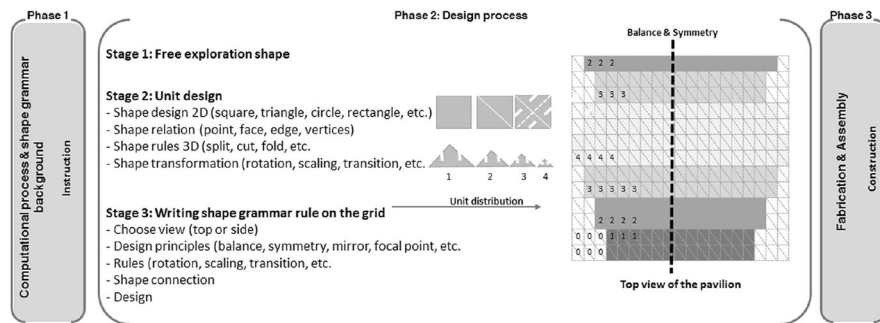
Fig. 1 The three phases of the process

approach helps understand how computational logic works manually. A small prototype is made to test the structural stability before scaling up.

(iii) The assembly and fabrication of the large-scale pavilion take into consideration climatic factors and site location. The projects are analysed based on three key features: analytical skills, knowledge repository, and algorithms. The evaluation criteria were based on stability, creativity, rules implementation, form generation, and porosity studies.

Results

This section shows the results of the four projects presenting the logic, design principles, and algorithms used to generate the units, connections, and assembly process. The results demonstrated a significant improvement in the stability of the structure after a series of experiments. Figure 2 illustrates the process of the design principles and the rules followed to distribute the units manually through a grid system. The units, connections, and relations between solid and void are presented to show the achieved patterns. Based on the trial-and-error process, the final installations equip students with an analytical design thinking process to adjust the design and detect problems earlier. All the full-scale projects were constructed in 1 day at the campus.

Project 1: Prismatic Wave

This pavilion was inspired by the wave-free form where students extracted vocabularies and rules as an analytical skill. Based on a four meter long curve, and two meters high to host a service inside, around 240 cardboard units were used. Square was the main form that was folded into two triangles to turn the 2D sheet into a 3D unit generating three different sizes (50, 40, 30 cm base). The folding techniques provided strength and stability to the unit to hold another unit. Slots were cut from both triangles' sides for assembly purposes to permit interlocking at a perpendicular angle above each other. The final units were labelled and distributed
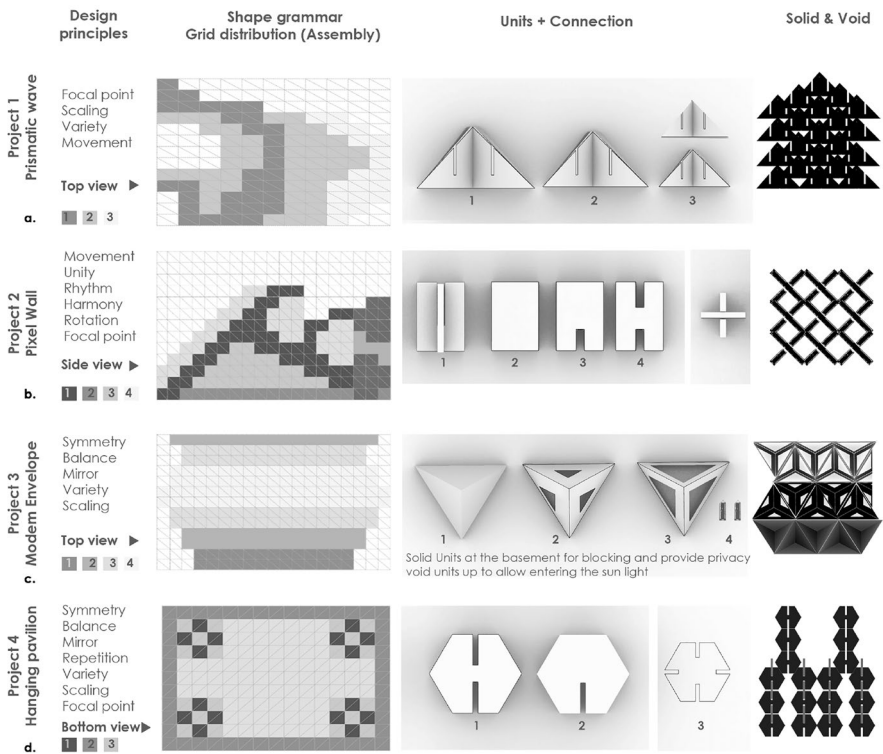
Fig. 2 The process of each project

among the grid system using design principles selected by the students based on the transforming rules as a focal point, scaling, movement, and asymmetry (Fig. 2a). The arrangement of the units based on the rules allowed generating different iterations.

Figure 3 shows the units' assembly in both small and full-scale models where different porosity resulted from the connections for light entry. This experiment helped the students to define the relationship between units and connections. For structural stability, the curvature of the model was caused by the units' weight that was controlled by locating the lighter small-scale units in the upper part. During scaling-up, students realized that they needed more depth to achieve the curvature after changing the thickness of the units. Many transversal curvatures can be generated by controlling the units' distribution and orientation based on the distribution rules according to their size and weight.

Project 2: Pixel Wall

Pixels were the inspiration for this wall, to extract vocabularies and rules as an analytical skill. The challenge was to reach a curved wall from two sides with a size
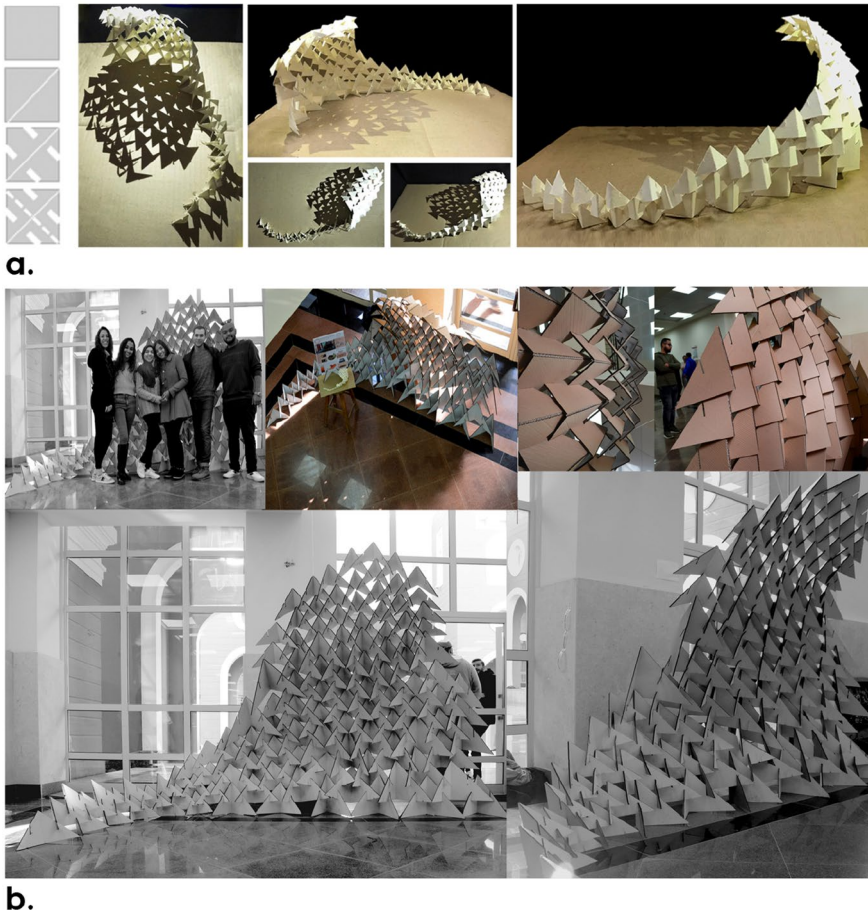
Fig. 3 **a** Form generation of the small-scale model, **b** the pavilion installation

of 2.5 m and 1.8 m high. Around 300 modular units were made from cardboard. Four rectangle units were used with variation in the position cut to host the connections with dimensions of 20×30 cm. The transformation of the 2D sheet into a 3D unit was based on the interlocked connection position either from two or four sides to generate the chain. Slots for assembly purposes were cut to permit interlocking at a perpendicular angle that provides strength and stability to the wall. The small-scale prototype taught students to control curvature from both wall sides for self-stability.

The units were distributed along with the grid system (Fig. 2b) based on the rules; repetition, harmony, movement, unity, and rotation. Several assembly iterations were explored in the small study model using foam Fig. 4. The similarities of the units generated symmetrical repetitive (X) shape at the top and squared form at the side as a relation between solid and void as in Fig. 2b. This installation can be used as an outdoor landscape feature to control and direct human movements.

Fig. 4 **a** Exploration of the small-scale model, **b** the final installation

Project 3: Modem Pavilion

The dimensions of this pavilion were 3.5 m and 2 m high, and it was inspired by the coral reef rocks that include solids and voids, which students extracted rules from. The team developed a 3-base pyramid with four triangle faces. Three main units were used with the same size of ($20 \times 20 \times 20$ cm). Around 320 units were used including solids and voids with different scales to mimic the rocks' perforations.

To provide privacy, the solid units were located at the bottom to block the vision, while the units with voids were located at the top to allow sunlight entry. A 250 mm "zip tie" was used as a connection through holes that were made in the units to connect edge by edge. The units with voids were denser located in the centre, while they decreased gradually in both left and right sides with more solid units to be able to hold the structure weight.

Along with the grid system, as shown in Fig. 2c, the units were distributed manually based on the rules used such as repetition, symmetry, movement, unity, repetition, and transition. Several iterations of the assembly were conducted in a small study model using paper sheets as shown in Fig. 5a. The similarities of the units generated symmetrical form that looks like the coral reef with its voids and solids that were caused by the variation of the pores as shown in Fig. 2c.

Project 4: Hanging Pavilion

The challenge of this pavilion was hanging columns by gravity to create space beneath. The units were inspired by the beehive, selecting the hexagon form as a modular unit. The installation formed a squared space with a size of $2 \times 2 \times 2$ m with
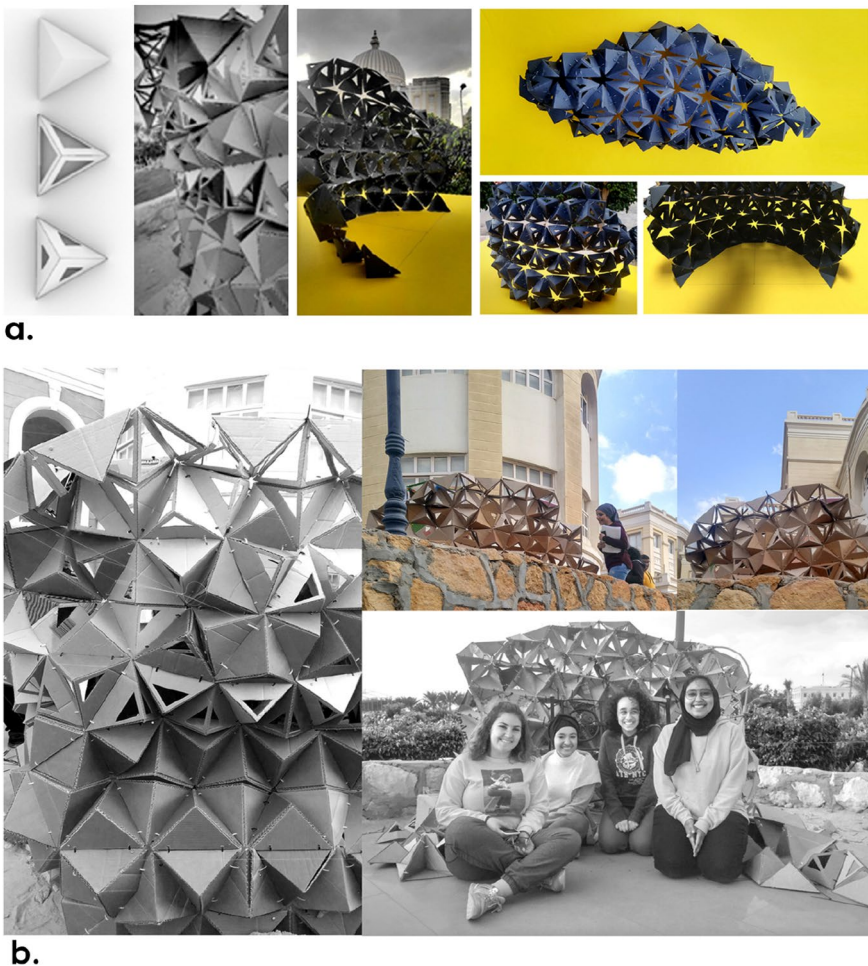
Fig. 5 **a** Small-scale model, **b** the final Installation

around 780 units. Four columns were hung from the top to act as a structure and borders. Three hexagon units were used; two of them varied in the position of the cut and the other had a smaller size which acted as a connection between the two hexagons with dimensions of 9, 7, and 5 cm.

The transformation of the 2D sheet into 3D units depended on the interlocked connection position on either two or four sides. Slots were cut from the hexagons to permit interlocking at a perpendicular angle. The four columns were tessellated with a consistent pattern caused by the variation of six hexagonal units connected vertically and horizontally by platted 2D units. The assembly of the units enabled more strength and stability to the columns to be self-standalone. The rest of the installation used different connection types as a 2D chain. While the arrangement of the units was based on the movement descending where the top view hosted the small units and gradually enlarged till reaching the floor.

Figure 2d shows the labelled units' distribution along the grid based on design principles as repetition, scaling, movement, rotation, transition, and tessellation. The variation of connectors' sizes and solid and void porosity manipulated the light entry causing different shadows reflected underneath the installation (Fig. 6a). The full-scale assembly was under the stair at the building entrance (Fig. 6b).

Discussion

Computational formalism gave the students exposure to a sensory experience that is in direct interaction with model-making through material manipulations. This allowed handling and anticipating the ways materials behave. The students' experience was developed using a trial-and-error process, where they succeeded to achieve a stable structure after developing more confidence with materials.

It was noticed that applying spatial transformations and folding techniques on the same shape/unit with the same materials generated infinite forms. The line in the grid referred to the location of a connection either by interlocking or by a connector. Continuing this series generated an infinite expansion unless the borders meet. The similar rules implemented in the first two projects and the last two projects with different distribution resulted in different structural forms. Thus, students learned that controlling the form can be done through unit distribution among the grids.

The strength of the interlocked folded units in project 1 acted as one chain, while the separated 3D units in project 3 gave freedom to flip in both directions. The interlocking connections from the same units in projects 1,2 and 4 showed more stability unlike project 3 which used a zip tie giving more flexibility. Unlike the stability of the small prototype, scaling-up was challenging to reach the same bend. The analysis and the self-evaluation allowed the students to notice the difference between the scale transformation where materials' width and weight play a big role to explore the problems unlike doing it digitally.

Implementing the project on-site increased the students' engagement with full-scale material besides the ability to make decisions based on material thickness and environmental and climatic factors to shade the pavilions. Students realized the relationship between the unit's porosity to the sun's movements throughout different
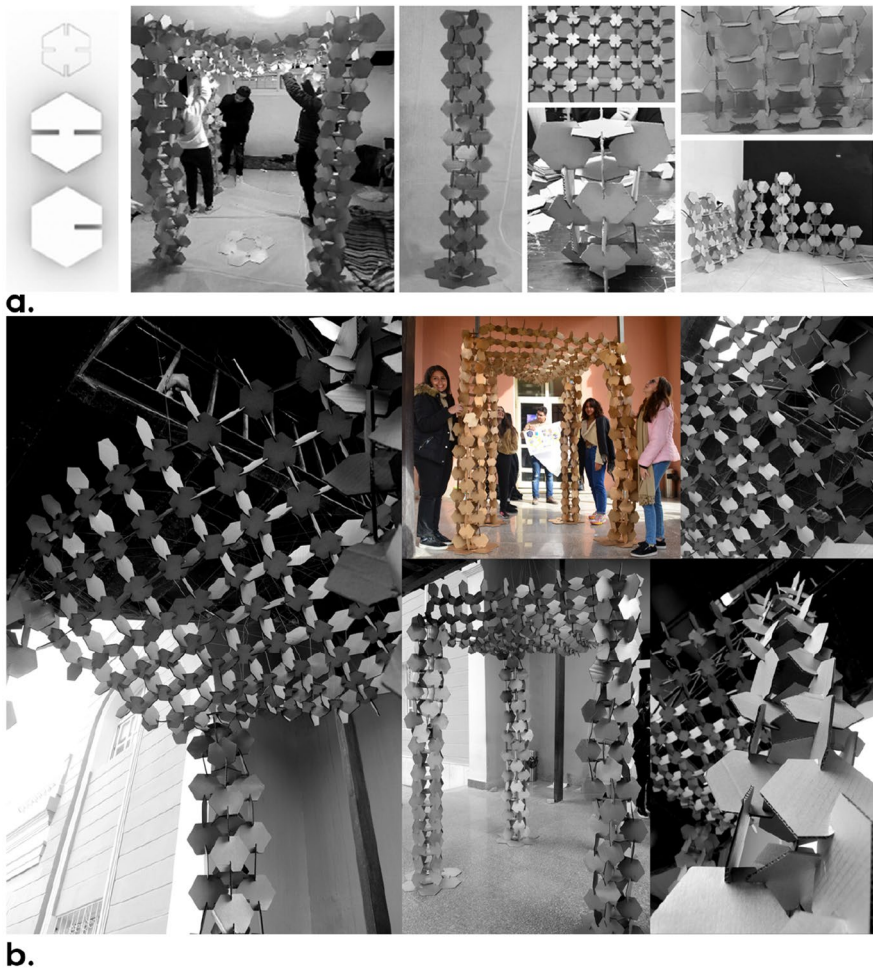
a.

b.

Fig. 6 **a** The units' assembly, **b** the exterior of the pavilion

timing during the day. Correspondingly, they located the units with more porosity at the top to control the light entry as in projects 1 and 3. The students gained the experience during assembly that denser units with fewer voids should be located at the base for more stability. The location of the solid and void units was responsible for stability to hold the weight of the above units, which decreased gradually reaching the top as project 3. Some failures occurred during the fabrication of the installations, due to the instability and materials' weight, where the students started to make minor changes in the design on-site. For instance, flipping the unit to control the form allowed more balance to the whole structure.

"Learning by doing" enriches students' skills and knowledge as a tool of measurement in two ways. First, the fabrication of the small-scale models and the 3D folded units during the large-scale transformation and second, learning from

each other and re-evaluating their work according to the feedback of their peers. The hands-on application of SG enabled students to carefully understand the logic behind the CD and to comprehend how rules work effectively unlike integrating early computer implementations. During the pin-up, different solutions encouraged discussions that required implementing trial-and-error processes to reach the desirable outcome. Through scaling-up, the students were nervous regarding the failures that happened to the model, which taught them to value stepping back to study the relationship between the scale, design, and material behaviour on a bigger scale. Comparing the pavilion structure results with the output resulted in the study by Özkar (2007) and Ibrahim et al. (2012) based on SG, it was noticed that their prototypes were more into a small building scale unlike the 1:1 scale of the four projects in this paper that focus on fabrication, construction, and assembly on site. Teaching CD methods manually improved the way the students can approach the digital age through model making before introducing advanced tools.

In this study, several limitations were observed and are left for further exploration. Although the results were achieved without using any digital software, knowing some basics would be essential for time-saving. With the limited four weeks for designing, experimenting, and fabricating the installations, more time could be devoted to focus on the structural strength such as compression and tension for advanced results. As the installations were temporary, thus, different materials could be explored for permanent large-scale projects. A further recommendation is to provide cooperation between juniors and seniors who are aware of DF and optimization software, to assist in evaluating the projects digitally. This could help to decrease the number of trials that consume time and materials before fabrication. Instructors need to integrate hands-on and dare-to-build experience in their modules, especially in the early stages and to balance the mathematical-based design and technology teaching during the experimental studios. Further explorations can compare the results of the projects with different universities worldwide for a deeper understanding of the making processes.

Conclusion

This paper presented a non-computerized manual fabrication method to integrate CD and SG in early architecture education, to enhance the informal education processes. Some lessons can be seen upon using visual coding as a method for non-expert or non-programming students off-site. Introducing the large-scale pavilions was difficult for students until they had hands-on practice, which enabled them to explore problems through trial-and-error processes. This paper did not present any specific digital software, but it provided an understanding of writing and coding, which are manually translated into orders based on mathematics.

The projects emphasized the relation between manual fabrication and CD in design studios based on Sheppard's semi-structured experiment which confirmed the students' motivation to be proactive and more confident in problem-solving. This study is an attempt to draw attention to "learning by doing, making, and computing" for design education through visual representation of CD. Scaling up

with materials attempt to provide structural assessment in the design phase. The results showed the feasibility of implementing SG, which will let students value CD earlier.

In this regard, we are aiming to continue developing our architectural curriculum alongside the traditional ones with an assessment of measuring students' performance after moving to a higher degree. Correspondingly, in future work, investigating SG in digital design at the basic design level may offer proof of sharing experience, where seniors assist juniors during such experimental methods. This solution can be accommodated at an early stage as part of design studios which could help integrate CD methods into everyday thinking prior to digitalization.

Declarations

Conflict of interest None.

References

Alalouch, Chaham. 2018. A pedagogical approach to integrate parametric thinking in early design studios. *International Journal of Architectural Research Archnet-IJAR* 12(2):162–81. doi: https://doi.org/10.26687/archnet-ijar.v12i2.1584.

Angelo, Monika Di, Peter Ferschin, and Galina Paskaleva. 2012. Shape grammars for architectural heritage. 107–116. in *1st International Conference on Architecture & Urban Design*. Artan Hysa Tirana. Albania, Epoka University Press.

Blikstein, Paulo. 2013. Digital fabrication and 'making' in education: The democratization of invention. In *FabLabs: of Machines, Makers, and Inventors,* ed, Julia Walter-Herrmann, Corinne Büching, 203-221. Germany: Transcript Verlag

Cannaerts, Corneel. 2009. Models of / models for architecture: physical and digital modelling in early design stages. 781–786 in *Computation: the New Realm of Architectural Design: eCAADe*.

Celani, Caffarena, and Maria Gabriela. 2002. CAD-The creative side - An Educational experiment that aims at changing students' attitude in the use of computer-aided design. 218–221 in *SIGraDi 2002 - [Proceedings of the 6th Iberoamerican Congress of Digital Graphics]*. ed. Eduardo Miralles, & Pedro Luis Hippolyte. Caracas,Venezuela.

Celani, Gabriela. 2012. Digital fabrication laboratories: pedagogy and impacts on architectural education. *Nexus Network Journal* 14(3):469–482. doi: https://doi.org/10.1007/s00004-012-0120-x.

Cenani, Sehnaz, and Gulen Cagdas. 2006. Shape grammar of geometric islamic ornaments. 290–297 in *eCAADe 24 Shape grammar*. ed. Vassilis Bourdakis & Dimitris Charitos. Volos, Greece. eCAADe.

Colakoglu, Birgul, and Tuğrul Yazar. 2007. An Innovative design education approach: computational design teaching for architecture. *METU Journal of the Faculty of Architecture* 2. doi: https://doi.org/10.4018/978-1-61350-180-1.CH022.

Doyle, Shelby, and Nick Senske. 2017. Between design and digital: bridging the gaps in architectural education. *Charrette:Essay AAE* 4(1):101–116.

Duarte, José P., Gabriela Celani, and Regiane Pupo. 2012. Inserting computational technologies in architectural curricula. 390–411 in *Computational design methods and technologies: applications in CAD, CAM and CAE education*.

Dunn, Nick. 2014. *Architectural modelmaking*. London: Laurence King Publishing; 2nd Edition.

Eilouti, Buthayna. 2019. Shape grammars as a reverse engineering method for the morphogenesis of architectural facade design. *Frontiers of Architectural Research* 8:191–200. doi: https://doi.org/10.1016/j.foar.2019.03.006.

El-Zanfaly, Dina. 2015. [I3] Imitation, iteration and improvisation: embodied interaction in making and learning. *Design Studies* 41:79–109. doi: https://doi.org/10.1016/j.destud.2015.09.002.

Eversmann, Philipp. 2010. Digital fabrication in education: strategies and concepts for large-scale projects. 1: 333–342 in *eCAADe 35: Computing for a better tomorrow, Education-Teaching*. ed. Anetta Kępczyńska-Walczak and Sebastian Białkowsk. Lodz, Poland, eCAADe Publisher.

Garber, Richard, and Wassim Jabi. 2014. Control and collaboration: strategies in academia. *International Journal of Architectural Computing* 4(2):121–143. doi: https://doi.org/10.1260/1478-0771.4.2.121.

Gürsoy, Benay, and Mine Özkar. 2015. Visualizing making: shapes, materials, and actions. *Design Studies* 41:29–50. doi: https://doi.org/10.1016/j.destud.2015.08.007.

Ibrahim, Mohamed Sobhy, 2011. Structuring the design studio education: crafting the projects of the beginning studio using shape grammars. Doctorate thesis. Faculty of Engineering, Alexandria University, Alexandria, Egypt.

Ibrahim, Mohamed Sobhy, Alan Bridges, Scott Curland Chase, Samir Bayoumi, and Dina S. Taha. 2012. Design grammars as evaluation tools in the first year. *Journal of Information Technology in Construction* 17:139–332.

Jackson, Paul. 2011. *Folding techniques for designers: from sheet to form*. London: Laurence King Pub.

Knight, Terry. 1999. Applications in architectural design, education and practice. Workshop report, MIT, Cambridge.

Knight, Terry, and George Stiny. 2015. Making grammars: from computing with shapes to computing with things. *Design Studies* 41:8–28. doi: https://doi.org/10.1016/j.destud.2015.08.006.

Lehmann, Ann-sophie. 2015. The matter of the medium: some tools for an art theoretical interpretation of materials. 21–41 in *The Matter of Art: Materials, Technologies, Meanings 1200-1700. ed.*, C. Anderson, A. Dunlop, and P. H. Smith. Manchester: Manchester University Press.

Lyon, Arturo, and Rodrigo Garcia. 2011. Interlocking, ribbing and folding: explorations in parametric constructions. *Nexus Network Journal* 13(1):221–234. doi: https://doi.org/10.1007/s00004-011-0051-y.

Özkar, Mine. 2007. Learning by doing in the age of design computation. *Computer-aided Architectural Design, CAAD Futures*. 99–112. *ed.* Andy Dong, Andrew Vande Moere, John S. Gero. The Nertherland. Springer.

Özkar, Mine. 2011. Visual schemas: pragmatics of design learning in foundations studios. *Nexus Network Journal* 13(1):113–30. doi: https://doi.org/10.1007/s00004-011-0055-7.

Prakash, Anant, Harsh Shekhawat, and Gaurav Goyal. 2017. Visual calculation through shape grammar in architecture. *International Research Journal of Engineering and Technology (IRJET)* 4(11):293–301.

Salama, Ashraf M., and Michael J. Crosbie. 2010. Design education: explorations and prospects for a better environment. *International Journal of Architectural Research Archnet-IJAR,* 4(2-3):10-18. doi: https://doi.org/10.26687/archnet-ijar.v4i2/3.92.

Schleicher, Simon, Georgios Kontominas, Tanya Makker, Ioanna Tatli, and Yasaman Yavaribajestani. 2019. Studio one: a new teaching model for exploring bio-inspired design and fabrication. *Biomimetics* 4(34). doi: https://doi.org/10.3390/biomimetics4020034.

Sheppard, Sheri D., Kelly Macatangay, Anne Colby, William M. Sullivan, and Lee S. Shulman. 2009. *Educating engineers: designing for the future of the field*. San Francisco, Wiley.

Soliman, Sara, Dina Taha, and Zeyad El Sayad. 2019. Architectural education in the digital age computer applications: between academia and practice. *Alexandria Engineering Journal* 58:809–818. doi: https://doi.org/10.1016/j.aej.2019.05.016.

Stiny, George. 2006. *Shape: talking about seeing and doing*. Cambridge, MA: The MIT Press.

Stiny, George, and James Gips. 1971. Shape grammars and the generative specification of painting and sculpture. in *Information Processing* 71, ed. C. V. Freiman, J. E. Griffith, J. L. Rosenfeld, 1460–1465. Amsterdam.

Varinlioglu, Guzden, Suheyla Muge Halici, and Sema Alacam. 2016. Computational thinking and the architectural curriculum: simple to complex or complex to simple? 253-259. in *eCAADe 34 Complexity & simplicity*. ed. Aulikki Herneoja, Toni Österlund, Piia Markkanen. Finland: Oulu. eCAADe.

Yakeley, Megan. 2000. Digitally mediated design: using computer programming to develop a personal design process. Doctorate thesis. Massachusetts Institute of Technology, MIT, Massachusetts, United States.

Yazici, Sevil, and Leyla Tanacan. 2020. Material-based computational design (MCD) in sustainable architecture. *Journal of Building Engineering* 32. doi: https://doi.org/10.1016/j.jobe.2020.101543.

Deena El-Mahdy is an Assistant Professor in the Architectural Engineering Department at the British University in Egypt. She holds a degree of BSc., MSc., and Ph.D. from Cairo University. Her research interests are digital fabrication process, parametric design, computational design, and additive manufacturing techniques in both education and construction. Her interest in digital fabrication and 3D printing led her to peruse a postgraduate program at the Institute for Advanced Architecture of Catalonia related to 3D printing with clay.