Virtual Reality and 3D Printing in Architectural Design. Case study: the Conceptual Model.

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Abstract

Two disruptive technologies have had an important approach to the field of Architecture. The first is Virtual Reality which has shown significant advantages in the visualization, simulation, and evaluation of architectural designs. The second is Digital Fabrication and more specifically 3D printing which has shown strength in rapid prototyping of previously unbuildable forms. This research argues that the use of immersive virtual reality tools complemented with 3D printing tools in the process of creating a conceptual idea can be an advantageous alternative to the traditional architectural design workshop. To demonstrate this hypothesis, the design process of conceptual models has been addressed from two approaches, the first one has developed the traditional and artisanal methods and the second one has introduced immersive virtual reality and 3D printing. The experimentation has been carried out with two groups of students of the subject Architectural Design 1 of the Faculty of Architecture and Urbanism. The results have been compared in five criteria, multiple solutions, compositional principles, shapes and volumes, relationship with the environment and communication of the idea. It is concluded that the complementarity of both technologies does not alter the cognitive processes of architectural ideation and, on the contrary, it offers important advantages over the traditional and artisanal way of creating conceptual models.

Keywords

Architecture, Digital Fabrication, 3D Printing, Virtual Reality, Architectural Design, Conceptual Model

1. Introduction

The teaching of architectural design is traditionally done in design workshops where theory and creativity are linked in a manual work. For this, an efficient didactic strategy in the training of future architects is done through drawings and models. These traditional methods of teaching design develop manual skills, and in turn develop creative skills in the design process from a critical, experimental, and collaborative environment. However, since the 1980s, the development of computer technology has made increasing incursion in the different phases of the design process and in the different levels of design, displacing manual craftsmanship. The model as a mechanism for representing architecture has remained throughout history, but with the emergence of the digital model, it has been strongly displaced. And although there is a hybridization between both systems nowadays [1], digital models and lately virtual models have not been able to displace the model in terms of its function of three-dimensional approximation in the configuration phases of the project idea, and the generative function itself, understood as a kind of three-dimensional sketch, which enables the ideation of the formal structure itself through physical manipulation [2].

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The purpose of this research is to compare the use of traditional manual and handmade methods, versus methods that incorporate technological tools such as virtual reality and digital fabrication in the approach of an initial architectural concept through small conceptual models. From both approaches, a conceptual model was designed and built that allowed the student to carry out a volumetric study of the architectural project. This research argues that the complementarity of these two disruptive technologies does not alter the cognitive processes of architectural ideation performed through the creation of a conceptual model and on the contrary, they offer many advantages compared to manual and handmade creation.

2. Literature review

2.1 The conceptual model in architectural design

Although the architectural design process is not linear, it is recognized that it has different stages or phases. After the preliminary phase of analysis or known as pre-design, the schematic design phase follows, which is the most complex because it requires the participation of various cognitive processes such as critical thinking, imagination, and creativity. This phase, also known as ideation, is critical in the whole process, both for teaching and learning. It establishes a design concept or an abstract idea to solve the design problem, which is the most relevant part of the narrative of the design. This design concept must be expressed visually through shapes and it has traditionally been the drawing the most efficient and quickest way to make such ideas and concepts visible [3]. But when the three-dimensional complexity of the shape exceeds the possibilities of manual drawing, which is more recurrent in new students, the model is shown as the ideal tool that allows the manipulation of complex shapes and geometries [2]. Unlike the presentation or relief model, the conceptual or configuration model is a working artifact that could be compared to the sketch. This "three-dimensional sketch" incorporated as a strategy in the design workshop allows an important approach to the concept as a complex volumetric object [1].

The pedagogical strategy of using small conceptual models to complement the conception drawings has the following characteristics and advantages: They are three-dimensional synthesized expressions of the conceptual idea. They share with the conception drawing an expressive synthesis that makes them instruments of knowledge of the ideas underlying the architectural form [4]. They have scale and proportion which allows to perceive the relationships between its different parts and to have an idea of the human scale. “Full of excitement, I move to models. Then models absorb all the energy, and so they require information about scale and relationships which cannot be fully perceived on drawings” [5]. They have a materiality that was assumed and decided according to the scale and forms. These models take on technical problems such as the choice of material because they constitute in themselves a "project" that turns them into autonomous and abstract objects [4]. They react to light as a real building does, which makes it possible to study the volumes and their shadows under the sun. A model allows the space represented there, to scale, to react truthfully when placed under the sun “A model (...) allows the space represented therein, to scale, to react in a truthful way when it is put under the sun”[6]. They are easy to modify and correct to express the best three-dimensional form of the conceptual idea. "The mock-up can and should be made step by step expedient in easily manipulated material, suitable for quick modification, destruction, and correction" [7]. They generate a haptic link between the hand and the material. The materiality of the model allows a direct experience of touch, learning the value of haptic, textures and materials [8]. They allow the reflection of the relationships between the created volumes. With the model the light is seen because the shadow is detected, the emptiness is perceived because the fullness is detected, the remoteness is understood by the observed proximity. "In the elaboration there is reflection of the dialectics of all the elements, there is an intellectual exercise" [8]. They achieve a better maturation of the idea because of the time required for its execution. The participation of the hand in the models makes time a moment of maturation of the architectural project. The hand and the time will be guarantee of a reflected, thought, projected result [8]. And they allow rapid and comparative learning. The model has a traditional didactic capacity in the teaching of architecture because of its easy execution in the early stages of learning and because of its small size, easy handling and collective comparability [4].

2.2 Architectural design education and digitalization

Teaching in architectural design has undergone a deep transformation in the era of digitalization. In recent years, digital design seems to be a dominant phenomenon. Therefore, digitization in architectural education is and remains a controversial process [9]. Recent studies indicate that the introduction of computer-aided design tools has revolutionized the way students approach architectural projects [10, 11]. In this sense, these technologies allow for greater accuracy and efficiency in the conceptualization and representation of designs. In addition, teaching has become more accessible thanks to the proliferation of online resources, such as courses and tutorials [12].

While change has been exponential since the 1960s, it is not difficult to assimilate architecture without the digital part. In this way, digital design theory tends to acquire a presence in the academic discourse in order to create theoretical bases for new design processes that transform traditional education models, as well as architectural projects [9]. This evolution in architectural education has led to more interaction between students and a more focused approach to the development of practical skills and creativity.

Furthermore, it is relevant to highlight that the various responses to digitalization have shown the need to analyze the teaching of design and the profile of the future professional of students [13]. Specific studies indicate that the specific quality of architecture should push architects to conceptualize a dimension of architectural research with good feedback between research and practice, as already happens in other professions [14, 15].

2.3 Architectural Design and Digital Fabrication

Since the beginning of this century, digital fabrication laboratories (FabLab) have been implemented as centers of innovation, entrepreneurship and as allies to personal design and production [16]. Its definition indicates the digitization of manufacturing processes, the term is broad, ranging from the technical to the social, where a range of tools and concepts converge, from nanometer precision to machines capable of self-replication, to programming languages for digital manufacturing in virtual reality [17]. Digital fabrication creates finished parts from computer-designed models based on manufacturing processes [18] that open the way to flexibility and productivity in industry.

Digital fabrication laboratories are essential elements in contemporary education and scientific research. Digital fabrication, which includes technologies such as 3D printing among others, has revolutionized the way researchers prototype and produce components, accelerating the development process. These labs allow students to apply that knowledge in the creation of real prototypes. Several researches highlight the importance of this combination in training practical skills and preparing students to solve real or everyday problems [19]. In addition, the availability of online resources and open source software have democratized access to digital fabrication tools, expanding learning opportunities worldwide [20].

The integration of digital fabrication techniques into architectural design processes is a major challenge to create a digital building culture but is of enormous impact since traditional construction techniques and complex forms difficult to implement in the past are challenged [21]. On the other hand, 3D Printing can favor a better communication of ideas in the design process among participants generating a collaborative approach is the generation of innovative and sustainable design processes [22].

2.4 Architectural Design and Virtual Reality

Virtual laboratories have gained relevance in science education due to their ability to provide hands-on experiences through digital environments [23]. Several studies indicate that virtual laboratories allow students to explore scientific concepts in a safe and repeatable manner [24, 25]. Virtual design refers to the creation and manipulation of three-dimensional objects and spaces in digital environments [26]. In addition, digital design tools are fundamental to the creation and editing of graphic and architectural content since they provide a range of options for conceptualization and representation of designs.

These methodologies and tools have expanded the creative possibilities. Therefore, several authors [27, 28] point out that virtual reality and 3D rendering have raised the quality of presentations, which is crucial for conveying design ideas effectively.

Virtual models allow architects and designers to visually explore a project before it is built, which can be valuable for decision making and communication with clients. Various research has highlighted the effectiveness of virtual models in architectural design evaluation [26, 15, 29]. On the other hand, traditional architectural models are physical mock-ups made by hand with materials such as cardboard, wood or foam. Research indicates that traditional models can be more useful for evaluating tactile and scale aspects, but are less efficient in the evaluation of light and views, compared to virtual models [30]. It should be noted that virtual and traditional models are valuable tools in the architectural design process, each with their own advantages and disadvantages. The choice between the two depends on the specific project objectives and representation needs. Therefore, combining both approaches can provide a more complete and effective understanding of an architectural design.

3. Purpose of the research

The purpose of this research is to determine the impact of the adoption of emerging technologies on architectural design processes. Specifically in the early stages of architectural design where the cognitive processes of critical thinking, creativity and imagination must maintain their natural flows without mediations that alter or distort such processes. To determine this impact, a case study has been carried out with new architecture students in the creation of conceptual models. In this case study, a group that has developed traditional, artisanal methods of creating and constructing conceptual models has been compared with another group that has developed a method that has incorporated immersive virtual reality with haptic controls and 3D printing. By comparing the two methods, results can be obtained that will help architects and designers make more informed decisions about when and how to use each approach based on their specific goals and the needs of each project. These results can contribute to the improvement of the design process and decision making in architecture.

4. Methodology

The methodological design to determine the advantages and disadvantages of innovation in the teaching and learning strategies of architectural design in the elaboration of a conceptual model was based on the case study of students in the first cycle of architecture. For this purpose, a comparison of two experimental groups was made. Each group consisted of students enrolled in Architectural Design Workshop 1 at the Faculty of Architecture and Urbanism of the Universidad Nacional de San Agustín de Arequipa in Peru. This subject is of a theoretical-practical nature and its main competence is the approach to knowledge and experimentation of form and space in the design process. Within this process, it is the phase of conceptual ideation of the first forms that requires the greatest contribution of critical thinking, creativity, and imagination on the part of the student, and it is in this phase that this research has focused its analysis. The case study for this research was the final practical work of the subject, which consisted of the design of a small boat landing and viewpoint located on the banks of the Chili River in the city of Arequipa. The students conducted an analysis of the site, the user and the activity to define an architectural program for three spaces. The students then had to define a conceptualization and a first three-dimensional solution through a conceptual model. The time allotted for the conceptual ideation process was five days.

The experimentation was carried out with the 33 students enrolled in group B of that subject. The group was divided equally according to their previous grades and randomly, so that their previous learning would not be a variable that would distort the experimentation. Group 1 consisted of 15 students who were assigned to work in the virtual reality and digital fabrication laboratory and Group 2 consisted of 18 students who worked in the conventional design workshop classroom.

Table 1
Characteristics of student groups

Group	Amount	Characteristics	Workspace
01	15 students	7 women y 8 men	Digital fabrication and virtual reality laboratory
02	18 students	13 women y 5 men	Classroom - Architectural design workshop

The students in Group 1 worked in a differentiated manner as follows. On the first day they had training in the handling of the HTC Vive HMD and Google's "Blocks" software. This application allows creating 3D objects using simple geometric shapes, a color palette, and a set of helper tools. This session ended with each participant using the equipment and software for 20 minutes (Figure 1). On days 2 and 3 they did work in the design workshop classroom. On the fourth day, according to the previously established schedule and for 45 minutes they used the hardware and software to create their three-dimensional proposal in the virtual environment (figure 1). Immediately after finishing the three-dimensional conceptual model, the file was exported. The file was processed with the free Ultimaker Cura software to be sent to three Creality 3D printers in the Digital Design and Fabrication Lab (Figure 2). On the fifth day, the 15 students in this group were given the printed pieces for assembly and presentation together with the students in Group 2. Group 2 students worked independently in the workshop, applying the traditional strategies of the design workshop, and making a model with cardboard, cardboard, and other materials.

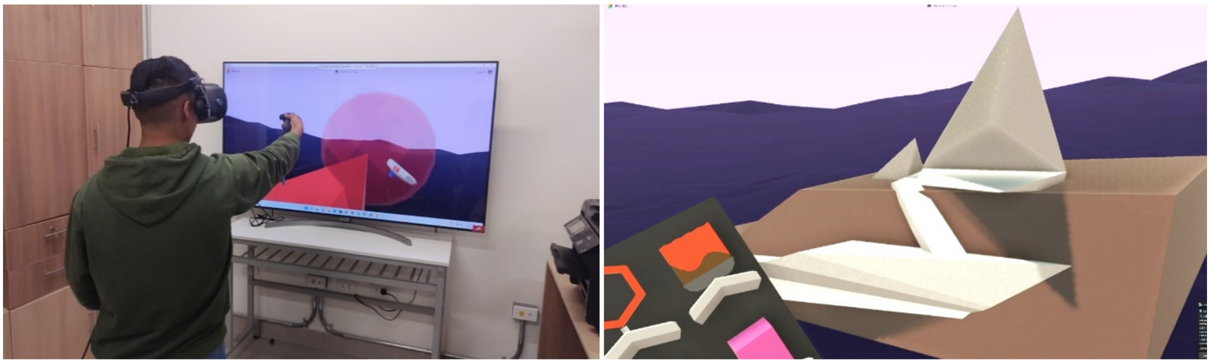

Figure 1: On the left is one of the students with the HMD and haptic controller creating his model. On the right the Google Blocks application interface.

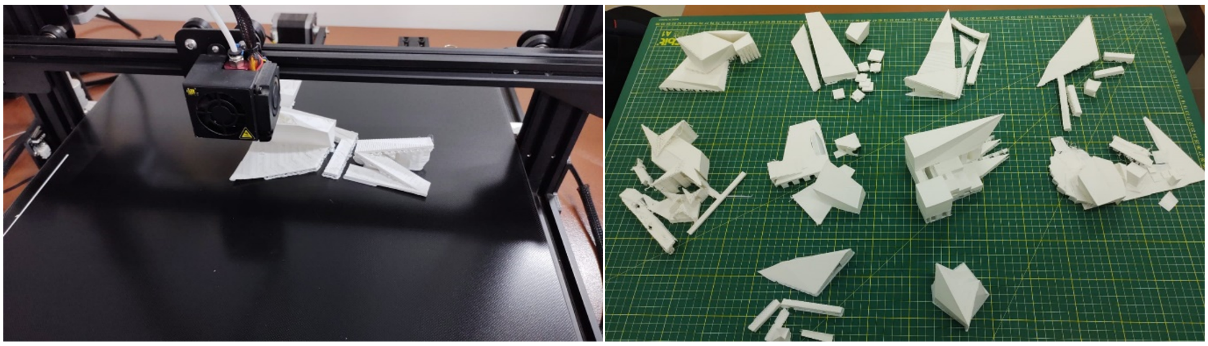

Figure 2: On the left, the 3D printing process. On the right the printed parts ready to be assembled.

The comparison of the conceptual models was carried out using the following evaluation instrument based on five criteria: (i) multiple solutions, (ii) compositional principles, (iii) shapes and volumes, (iv) relationship with the environment and (v) communication of the idea.

Table 2
Instrument for evaluation and comparison of the conceptual models

Criteria	Description
Multiple solutions	Development of several models exploring all possibilities or solutions to find the best idea.
Compositional principles	Application of compositional principles such as unity, balance, direction, center of interest.
Shapes and volumes	Creation of solutions with new and ingenious forms in response to the main idea of the proposal.
Relationship with the environment	Integration of the volumetry to the idealized slope of the terrain and orientation towards the surrounding visuals.
Communication of the idea	Communication of the idea through the finalized conceptual model.

5. Results

Regarding the first comparison criterion, multiple solutions, it was found to be quick and easy to create several alternatives in the immersive environment. Most of the students created between two and five virtual models. On the other hand, the creation of hand-made models did not allow this multiplicity. The delay in the construction of a model, even a schematic one, prevented students from creating more than one. Only in the few cases in which the construction of the model did not respond to the student's idea, they created a second model (Figure 3).

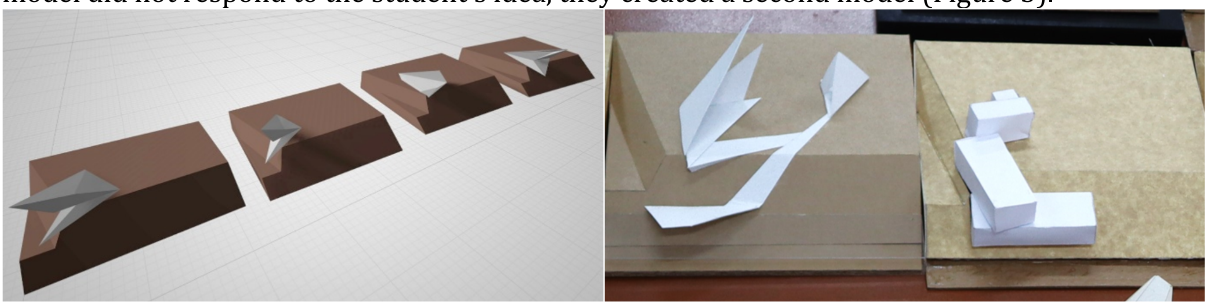

Figure 3: Multiple solutions: on the left the multiple IVR solutions, on the right the unique handcrafted solutions.

For the second criterion, called compositional principles, it was observed that the virtual models presented a greater development of the conceptual idea and therefore a greater presence of compositional criteria. The compositional criteria that were evidenced were rhythm, repetition, balance, unity, and movement. On the other hand, the manual models showed simpler solutions with basic compositional principles such as unity and symmetry (Figure 4).

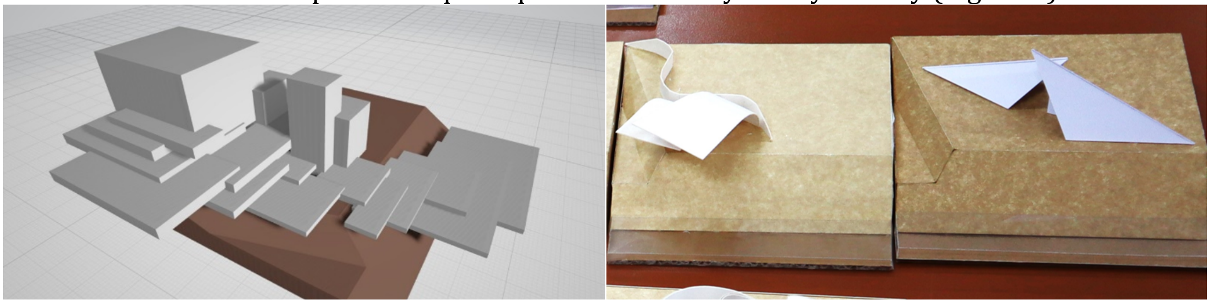

Figure 4: Composition principles: on the left a model in IVR, on the right two handmade models.

For the criterion of shapes and volumes, we found in the virtual models the predominant use of polyhedral volumes such as cubes, parallelepipeds, and pyramids. Despite this, most of them were complex volumes with inclinations, deformations, intersections, etc. On the other hand, in the manual models, curved shapes were used in addition to polyhedral shapes (Figure 5).

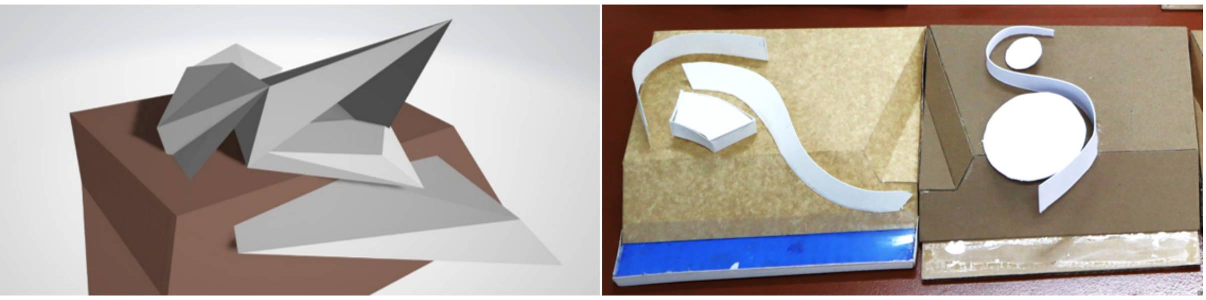

Figure 5: Shapes and volumes: on the left a complex polyhedral model in IVR, on the right two simple curved models.

In Figure 6, relationship with the environment, it was observed that the manual models mostly present a limited relationship with the site (specifically with the slope). In several works it was observed that the proposal simply overlaps superficially with the terrain. On the other hand, in the virtual models, the responses use the slope in favor, constituting a better response as a pier and consistent with the topography of the site (Figure 6).

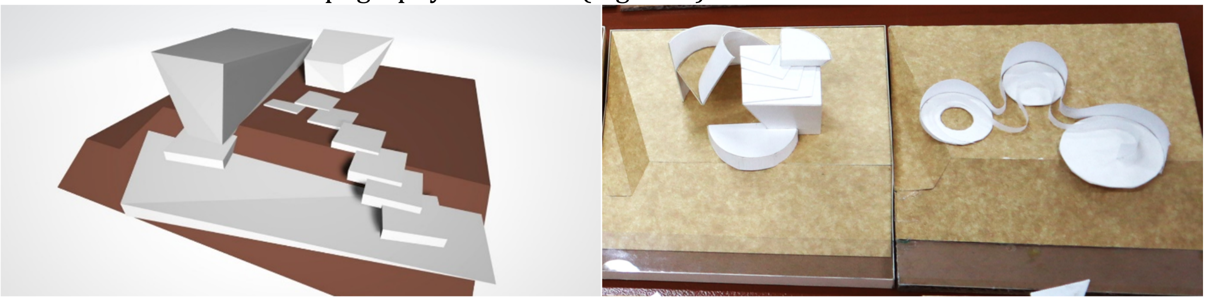

Figure 6: Relationship with the environment: on the left a model using the slope in IVR, on the right three handmade model with little adaptation to the slope.

Finally, for the criterion comparing the communication of the idea, the responses from both groups presented a variety of characteristics. In the case of the virtual models, which were then materialized with 3D printing, they showed the same physical qualities as the manually produced models. On the other hand, it has been found that printed models in general present a more complete conceptual idea than manual models that have been shown to be unfinished or incomplete. It has also been found that the 3D printed mockups present a greater three-dimensional development, unlike the manual models that have shown conceptual ideas more thought out in two dimensions, usually in plan (Figure 7).

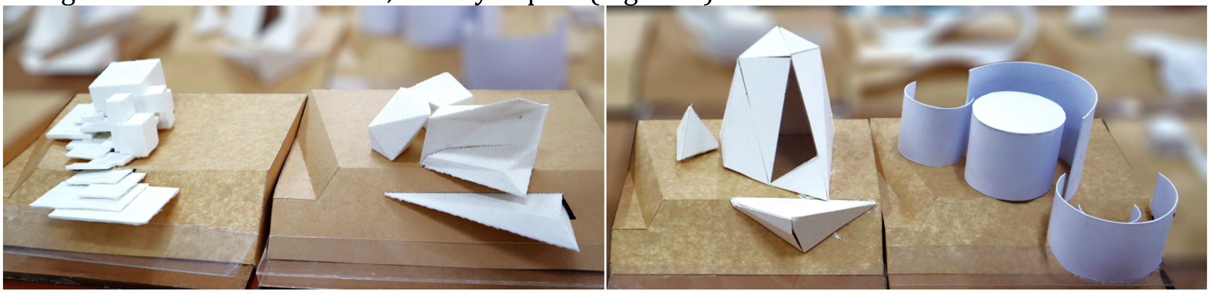

Figure 7: Idea communication: on the left a model created in IVR and 3D printed, on the right the handmade model.

Three findings were found outside the comparison criteria. The first one has to deal with the execution time of the models. The execution of the models first created in a virtual environment and then printed in 3D was much shorter than those created manually. In the first case, such construction has only been reduced to the assembly of the pieces on the base terrain. The second finding is related to the previous one. By having the pieces of the models printed in 3D, the students in the process of assembling them have been able to have that ideal haptic linkage that is conferred to the manual model and that has also allowed the students to make final adjustments of proximity (Figure 8). The last finding is that the printed models are very difficult to modify unlike the manual models built with cardboard.

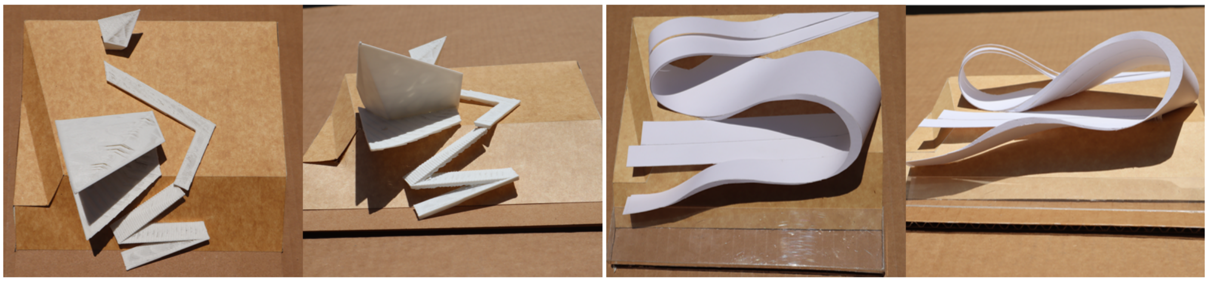

Figure 8: Idea communication: on the left the a model created in IVR and 3D printed, on the right a handmade model. Both models studied under the sunlight

6. Discussion

The first disruptive technology used to develop the conceptual model was immersive virtual reality. The immersive environment provided by this medium added to the interaction and the benefits of Google Blocks software has shown to have the following advantages compared to the creation of handmade models. It allows the quick and easy creation of polyhedral shapes as well as free forms (curves) in direct relation to the movement of the hands. This form is very similar to traditional drawing where thinking, sight and hand movement are linked with a pencil on a sheet of paper, but this time with three-dimensional strokes. This form of creation generates a haptic link between the body and the hand with the created object [8], a characteristic that digital models created in other ways do not have. Therefore, the processes of critical thinking and creativity are not affected by the mediation of this technology. It allows the creation of many solutions and their variants achieving a quick arrangement for the application of more compositional principles. At the same time, the easy and direct modification of the object has generated a process of instant reflection and feedback, a necessary feature in conceptual models [7, 8]. It allows a better perception of the three-dimensional idea due to the possibility of rotating around the object and giving it different scales. This is one of the most compelling advantages that cannot be achieved in other digital media [29]. Finally, it facilitates the creation of a conceptual model in a reduced time compared to the traditional handmade way. On the other hand, it has been found as disadvantages the intangibility of the object that distances it from a real and direct haptic experience of manipulation of shapes and materials and that, in addition, does not allow to experience the behavior of the model under natural light. The unavailability of software to create materials (only colors can be assigned) limits any conceptual idea based on materiality. Finally, virtuality does not allow having the model in front of the student permanently for reflection and feedback processes, except for the exported three-dimensional models capable of being viewed on cell phones, tablets, or PCs.

The second technology applied was digital fabrication. In this case the use of 3D printing with FDM technology has proven to have the following advantages. It has favored the materialization of any shape previously created in virtual reality. This workflow has been very simple since the exported virtual reality file was recognized by the software to laminate the 3D models for subsequent printing. This material creation of the conceptual model made it possible to solve the disadvantages of the virtual model, that is, its intangibility, its immateriality and its permanent physical presence [1, 4]. Although the printing of the 15 models (on three printers at the same time) took 7 hours, this time was not charged to the student's work. This can also be considered a disadvantage if it is considered crucial that the time spent in the construction of the model allows for maturation and reflection [8]. By printing the conceptual model in several parts, it allowed the student not only the haptic experience of manipulating it for final assembly, but also the possibility of making readjustments based on direct perception [1, 8]. The printed model, like the handmade ones, also allowed to perceive its scale and proportion and the reaction of the object under sunlight [1, 8] The disadvantages found are the impossibility of materializing the models with any material other than the printing filaments, as it happens in traditional models with cardboard, micas, sticks or others. In addition, it has been found that it is difficult to modify the model once printed, becoming almost a finished sculpture.

The inclusion of digital tools in the methodology of the architectural design process, from the early years of training promotes openness to new models and ways of dealing with design, which complement the traditional physical models to give better results in the academic performance of students. In this context, it is important to include digital fabrication and virtual reality laboratories within the methodology of the architectural design process to explore other attitudes and qualities in university students in addition to the aforementioned.

7. Conclusions

After carrying out a case study to determine the advantages and disadvantages of using immersive virtual reality and 3D printing in the creation of conceptual models by first year architecture students, the following conclusions were reached:

The qualities that immersive virtual reality has such as immersion, presence, and interaction, added to the easy creation of objects with haptic controls that are achieved with the Google Blocks application allow: (a) To create very quickly and easily multiple responses in the inquiry and search for forms that materialize the main idea. (b) Manipulate, transform, and copy objects in a simple way to test and verify arrangements and composition criteria. (c) Create a very wide diversity of shapes, from simple polyhedral shapes, through curves, to more complex and free shapes with the simple movement of the hands. Moreover, these forms can become more complex with manipulation. (d) To better understand the three-dimensionality of the proposal by the possibility of perceiving the model from different angles, different scales, and different points of the observer. (e) To propose ideas relevant to the place due to the pertinence of creating the model always over the idealized terrain.

On the other hand, the qualities of 3D printing, such as the materialization of almost any three-dimensional shape, low costs and accessibility and automation, as well as its compatibility with the files exported by the IVR application, allow: (f) To reduce the effective time of the student for the manufacture of the model, giving more time to cognitive processes. (g) Achieve a haptic link with the student from the moment of grabbing the printed pieces to assemble the model and arrange them on the cardboard terrain. (g) Perceive the relationships of the volumes to scale, proportion and proximity to make adjustments at the time of presenting the model. (h) Study the interaction of the model with natural light to determine a sun exposure study and the impact of the sun's rays and shadows.

Therefore, from the proposed methodology it is concluded that the complementary introduction of these two disruptive technologies in the processes of ideation and creation of a conceptual model does not alter the cognitive processes of architectural ideation; on the contrary, they provide important advantages that may be the indication of the rupture of some paradigms of the teaching-learning process of architectural design.

The use of other software for artistic creation in conjunction with other digital fabrication techniques is proposed as future research, always looking for innovations in traditional strategies in the methodology of architectural design.

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