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STRUCTURALLY INFORMED ARCHITECTURAL DESIGNS DEFINED BY CATALAN SURFACES – EXAMPLES OF STUDY PROJECTS

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Abstract. In the case of effective structural forms, characterized by a close symbiosis of architectural form and fabric solution, the properties of geometry not only enable the realization of the intention, but remain the main medium of shaping architectural expression in the aesthetic dimension. Moreover, geometric topological forms described by parametric equations provide many opportunities to model structures, also in digital spaces. Paying attention to these aspects was the goal of the academic design task specified in this paper.

Keywords: architecture, Catalan's surfaces, education, geometry, physical model, study projects.

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1. Introduction

Justification for choosing the research topic

Education is a set of activities and processes enabling people to get to know nature, society, and culture, and at the same time to participate in their transformation. The content and forms of education processes are determined by the general learning objectives formulated within the educational concepts of individual university units. The article broaches the subject within the field of engineering and technical sciences, regarding education at the higher level of a technical university in the architectural degree course at the Silesian University of Technology. Since the result of the teaching process should be that students achieve qualifications enabling them to conduct professional activities, teachers conducting project classes use increasingly better, recognized teaching methods. By presenting geometric issues during the first semester of studies, an attempt was made to introduce an element of "playing" with the structure to better understand the principles and rules governing given construction systems by indicating the lines of forces.

Data sources

The primary source of the information required to provide the broadest possible baseline data was a multiple case study based on, among other things, a local audit of a reference facility. All the issues presented in this paper are largely the result of the author's project experience and many years of teaching. The research in the course of the project task presented in the paper was based on Action Research analysis. This iterative, reflective approach allows students and academics to test, document and improve design processes through which creativity and complex problem solving emerge (Babić & Krklješ, 2024). The entire research of this article was preceded by a literature review in accordance with the set of keywords adopted for this topic.

Methodology and scope of activities

The introduction to the teaching cycle of the discussed design exercise aimed to show students the relationship between geometric space concepts and architectural design processes. A comprehensive study would require an analysis of a multidisciplinary theoretical framework. Therefore, certain limitations and specifications were adopted. The main limitation of the scope was the selection of Catalan surface structures. The geometric space under study was framed topologically. The focus was on spatial relationships and invariants, enabling students to generate dynamic, adaptive forms and understand how these can support innovation in digital design environments[1] (Thuy

[1] Recent advances in computational design have revitalized interest in Catalan surfaces. Parametric tools, enable architects to design roof shells and other structures using repetitive modules of Catalan surfaces. These methods link geometric shaping with structural analysis and optimization, allowing for the exploration of various design alternatives and the selection of optimal solutions. The integration of flexible scripts and simulation models facilitates the creation of regular, symmetrical forms that are both visually striking and structurally efficient.

& Thi, 2022). The architectural design process itself was limited to generating and transforming familiar forms. Geometric transformations served as basic tools for exploring spatial and volumetric relationships, often independently of function, in order to inspire new architectural forms (Sebesteny, 2023; Wasilah et al., 2018).

Further limitations mainly concerned the optimisation of shapes and aesthetic criteria in practice. Students were encouraged to be aware of perception as a human experience influencing aesthetic and emotional reception while working on the project. Geometric parameters such as proportions, curvature and spatial relationships have a direct impact on users' emotional and aesthetic responses, which can be measured using subjective and neurocognitive methods (Alp, 2017; Elbaiuomy et al., 2019; González-Pérez et al., 2024; Shemesh et al., 2021).

2. Research background

In 1998, during the 8th International Conference on Engineering Design Graphics and Descriptive Geometry in Texas, USA, Prof. Gary Bertoline proposed a new discipline of study, "Visual Science" (Bertoline, 1998, p. 183). It has three major categories: geometry, spatial cognition, and imaging. The new field of study bound to graphics design and geometry (specifically to descriptive geometry) would become somehow "interdisciplinary" science between engineering and arts.

Teaching practice shows the need for such a discipline, where knowledge of geometric forms and transformations is combined with methods and techniques of visualization and other related fields. Analyses of the relationship between disparate concepts of geometric space and architectural design processes are fascinating issues and are becoming increasingly important in recent construction projects. These design processes are inspired today is inspired by the various possibilities of digital technology and disciplines such as mathematics along with geometry and physics. Computer technologies have changed the representation of design from clear geometric notation to instrumental geometric relationships. We are seeing an ever-increasing interest in the design, calculation and application of architectural structures in the form of a variety of smooth and complex surfaces – the creative use of analytical surfaces, i.e. "surfaces that can be defined by vector, parametric or explicit equations" (Mamieva, 2019, p. 299). This design can be defined as the definition of parameters through which the relationships between the creator's intent and the design response are encoded and clarified. The creative work of the architect in the digital environment is expressed by a multi-criteria decision-making process affecting the simulation and optimization of designs. The visualization of these operations, resulting in a parametric spatial model of an architectural object, is also a virtual determination of the properties of the geometry of the components of its structure. Le Corbusier's famous statement is still valid: everything is geometry.

3. Theoretical framework – to think in architecture, to feel in structure

How structural form relates to architecture leads to the superiority of one form over another to the extent that the optimal form is formed. In fact, the optimality of the form is achieved once there is integration in the form of architecture and structure (Golkar et al., 2021, p. 124).

We perceive architectural form as a combination of shape and matter. Shape implies a reference to the geometric properties of its structure, while form, being dependent on shape, refers directly to aspects of matter and its physical properties. The architects points out that it is important to understand the nature of construction and form itself without reference to function or meaning. Architecture is born with structure and cannot sustain its existence without it. The ability to define the geometric features of objects remains an important and necessary condition for realizing architecture. In the environment of digital model work, in the process of simulating a new type of structure, there is a manipulation of information regarding the complex geometry of the form and its structure. Algorithmic geometry descriptive procedures are generated. Thus, it becomes an iterative, generative and reactive process. Using a specific set of rules encoded in sequences of parametric equations, complex problems are transformed into simple, rational decisions. However, this brings new requirements. This is because designers are expected to have a deeper understanding of geometry, mathematics.

Several hundred analytical surfaces determined by explicit, implicit or parametric equations are currently known, and these are subject to various classification variants. Catalan surfaces are a subset of the class of surfaces generated by straight lines. They are characterized by relative simplicity of construction with simultaneous effectivity of shape in the desired curvilinear architecture. Working with a building object using these surfaces satisfies a variety of forms with features of high aesthetic value. Among the rectilinear surfaces used with great success in architecture we find: cylindroids, conoids, hyperbolic paraboloids. The difference between them results from different paths of movement of the creating surface during its formation. A straight-forming one has simultaneously points in common with three directing ones,[2] with one of them being an improper point.

Considering these three types of Catalan surfaces, it is worth noting the hyperbolic paraboloid. This saddle surface is a two-curvature minimum surface,[3] – an anticlastic surface with negative Gaussian curvature – being stable it

[2] One of these directing is always the improper straight of the directing plane, the other two can be straight or curved. Formers moving while maintaining a position parallel to the said directing plane create a system of oblique straights (for this reason, these surfaces are sometimes called oblique surfaces).

[3] Pierre Simon de Laplace (1749–1827) showed that a minimal surface is a surface whose average curvature at each point of the surface is zero.

Figure 1. Mediopadana Station, Reggio Emilia, Italy (source: author)

is considered extremely rigid. It exhibits so-called membrane action, in which internal forces are effectively transmitted through the surface. Since the early 1950s, there has been a surge of interest in structures made entirely or from fragments of a hyperbolic paraboloid. There are hundreds of them – implemented by prominent architects, recognized as structures with optimal technical and economic parameters, often awarded prizes and ranked high in professional associations and magazines.

The sinuous conoid, on the other hand, was glorified by the famous Spanish architect Antonio Gaudi. Among other things, he used this form in the covering structure of the cheap school for children of the builders of the cathedral in Barcelona. Another world-famous architect of the same origin – Santiago Calatrava, contributed to the spread of a related shape. We can admire the sinuous cylindroid in the structure of the kinetic sculpture Wave, which was installed in 2002 in front of a museum in Dallas.[4] A similar form, but in a horizontal arrangement, can be found in the 2004 project on the site of the Olympic complex in Athens. However, special attention should be paid to the construction of two buildings in which the undulating structure is the basis for the creation of formal and aesthetic expression. In 2001, the construction of the Bodegas and Bebidas Group wineries in the Spanish Laguardia was completed. Meanwhile, in 2014, Mediopadana – the only high-speed rail station on the Milan-Bologna route – was built. It serves as an important transportation hub connecting the city of Reggio Emilia with the rest of the world (Figure 1).

4. The selected reference object

The need for architectural design as art and harmonious shaping of space results from the needs of human nature. The way a given community organizes the space around itself – the structure of the city – is a reflection of its civilizational condition. The art of building is one of the most expressive syntheses of a nation's abilities, one of the most significant elements that distinguish its genius (De Miranda, 1991). Pier Luigi Nervi believed that "construction is also an art in its more technical aspects related to structural stability" (Nervi, 1997, p. 24).

The architect's endeavor in the creative area is to execute and introduce a work of art as a creation designed for non-material, high values (Kosiński, 2009). Creating a new entity of a higher order in the created space by using a solution corresponding to a given situation, role and semantic importance of the object. The choice is not easy – from forms that formally refer to the existing environment, to those that contrast extremely with the surroundings, constituting an autonomous extreme in the choice of the form of an architectural solution. The context is the essence of this choice. French architect Jean Nouvel, winner of the Pritzker Prize in 2008, defines it this way: "When I say context, people think that you want to copy objects around, but often context is contrast, but the surroundings should have the advantage, that is, dialogue. Every time I try to find the missing piece of the puzzle" (https://sztuka-architektury.pl/).

In 2002, the famous Spanish architect Santiago Calatrava[5] undertook to transform the Regio Emilia city's territorial infrastructure project so that it would improve its image and strengthen its position in the urban system to which it belongs and outside the zone of direct influence. The comprehensive master plan was based on three interventions linked by the keyword – connectivity (Piaia & Dussini, 2015). It included bridge structures, highway toll plazas and other infrastructure improvements that would make access to the city easier. The high-speed train station Mediopadana was to become the new gateway to city from the north.

In the first half of the 20th century, Robert Maillart's view was famous – if the geometry of the structure looks correct, then everything is fine (Billington, 2008, p. 368).

[4] The sculpture consists of 129 slender bronze beams of equal proportions connected to a mechanism that sets it in an undulating, sinuous motion. For unusual visual effects, this kinetic structure was seated in a pool of black granite filled with shallow water and is illuminated after dark.

[5] In the case of objects designed by him, one gets the impression that the beauty of form and the logic of construction are equally important to him. Repeatedly drawing inspiration from nature, he creates forms that were not shaped as a result of purely formal procedures, but constitute a logical, justified analogy with a mathematical construction model.

It makes us aware of the need to understand the nature of structure and form itself without reference to function or meaning. In the case of the structural creation of the Mediopadana, Calatrava used the principle of creating rectilinear surfaces – a sinusoidal cylindroid. The structure of a station is characterized by a state of order that gives a feeling of pleasure and visual stability. It is the impression of rationality of form, that everything is in its place in the structure and nothing should be added or subtracted. Each element of the building is in its proper place, and their relationships are subject to the laws of logic.

The integrated structure of the roof and longitudinal facades – northern and southern – consists of white painted steel frame elements. It is 483 m long and has variable width and height. The width varies from 35 m to 50 m, while the roof rises to a height of between 7.5 m and 14.5 m, measured from the level of the inner platforms of the platforms. The periodic change in the position of the portal frame along a sinusoidal curve gives the structure an unusual wave effect. According to the principle of geometric course defined in the project, the shape of the wave differs in individual views. The entrance façade to the station is limited by two waves with the same directional maximum and minimum deviation – with regular, parallel sinusoids in the façade view (Figure 2a). The structure facing the highway has slightly different dynamics of form due to individual shifts of the extreme of this curve – with sinusoids overlapping with respect to the horizontal symmetry line (Figure 2b).


a)


b)

Figure 2. Mediopadana high-speed railway station, Reggio Emilia, Italy: a) view of the front façade; b) from the highway (source: author)


a)


b)

Figure 3. Mediopadana high-speed rail station, Reggio Emilia, Italy: a) front view; b) side view (source: author)

However, it should be noted that the external deflections of the upper sinusoids are larger than those of the lower ones, which definitely had an impact on increasing the level of expression of the form demonstrating the celebration of speed. Boldness and dynamics are the features that characterize this architecture and determine its charm and artistic value. The object surprises with its scale and variety of images. Convex and concave surfaces of the structural form included in multidirectional movement are perceived in perspective by frames of interpenetrating planes. All this multiplies the vastness of a seemingly endless space where the boundary between the outside and the inside is not clear. The use of this structural solution eliminated the impression of massiveness, which is common in buildings of a similar scale, also by seeming to detach the object from the ground. The aesthetic contemplation of the recipients of this architectural work triggers emotions thanks to the astonishing lightness of the slender elements that create, in longitudinal shots, an equivalent composition based on the rhythm and sequence of portal frames (Figure 3a). From the side, the unusual shape is built through contrast, accent, and apparent imbalance of elements that do not fit into the Cartesian grid of verticals and horizontals (Figure 3b).

Several case studies of structurally identical objects and *in situ* research conducted by the author of the article lead to the conclusion that buildings with high-performance structures are cases in which real rationality turns out to be identical with visual rationality. They combine traditional rules with originality – a characteristic that is highly valued in modern value systems.

5. Study project

Every design thinking involves the ability to understand, read and plan operations that will make the designed object evolve in a consciously planned direction. The designer, in the case under study: A student carrying out a design task, operating with numerous resources – a broad knowledge of available forms and knowledge of their properties – can realize his intention in a complete and interesting way.

Cyril Stanley Smith uttered a sentence that became the inspiration for the design task carried out together with first-year students of the Faculty of Architecture of the Silesian University of Technology. "Whatever we perceive, we can understand it only by perceiving its structure and thinking through structural analogy and comparison" (Crapo, 1982, p. 17).

In the issues of shaping defined structural forms in architecture, their morphology – qualitative geometric representation allows a conceptual transition from the original pattern – the prototype of organizing the structure of the form to one in which model formation will take place. Topological objects are subjected to a systematic process of diversification through the addition of elements: giving them different projective properties, then dependency links and – finally – metrical ones. Students followed the same process using the initial lecture material defining the different types of Catalan surfaces. The same preconditions of a design task can, and usually did, result in different solutions. Although the objects created, within each form, differ, this always occurs with structural stability accuracy. However, what is extremely important in the field of architecture, these differences, which could be called deviations from the original pattern, make the separate buildings perceived as individual works of design art.

5.1. Teoretical framework

The optimal situation seems to be one in which an engineer with a strong theoretical foundation in the study of geometric space and architectural design combines classical and contemporary geometric theories, computational methods, optimisation techniques and empirical research on human perception. Only this approach provides a comprehensive understanding of how geometric concepts influence and are influenced by architectural design processes and outcomes (Alp, 2017; Thuy & Thi, 2022).

Academic training is aimed at developing the ability to solve problems rationally, using knowledge of the laws and principles governing the field. Every architectural and structural design must take into account the conditions of the geometry of the structure. The geometric analysis itself concerning only one issue gives the designer rich material for consideration, and the student obtains the right solution through strict geometric reasoning. Acquiring the ability to represent space in drawing form as well as through a properly shaped physical model, on the other hand, is a basic prerequisite for the creative use of the digital techniques that are so common today. "The geometric approach to space is adapted to the intention of the message; may determine the accuracy of the presentation. As history confirms, the choice of the type of mapping is a subjective decision of the architect. However, in order for the expression in an architectural image to have full impact, the geometric approach must be written in an appropriate form" (Misiągiewicz, 2023, p. 265). As shown in the article, one of them is "the difficult art of building models, which does not consist solely in reducing reality. This art is subject to its own laws, and the presentation of the structure of the object is only its pretext" (Gajewski, 2001, p. 89). Based on the described design study and didactic experience, we note undeniably that the construction of architectural models generates many benefits – a better understanding of the spatial structure, ideas, function and form of the object. It pursues the highest goal of mental development of students of the Faculty of Architecture, which is to develop the sense of coordinating various activities – construction, composition and aesthetic proportions.

5.2. Specification – forms of representation

Renzo Piano, in a lecture given on June 17, 1998, on the occasion of his Pritzker Prize, said these significant words: "Architecture is an art. It uses technological advances to build emotion, and it does so in its own language" (Jodidio, 2014, p. 6). In order for these emotions to "speak" there is a need to use the language of writing.

The basic ways of recording an architectural idea are the media for transmission, for communication between the designer and the viewer. However, they all serve to clarify a certain mental model that is created in the mind and that is realized in an architectural work. Undoubtedly, in order to ensure a fairly broad reception and understanding of the project, several methods of recording architectural space must be used simultaneously. Their interpenetration and complementarity affects the quality of the architect's work and translates directly into the value of his works.

As a matter of fact, there are six ways of capturing any design concept. The first one is aimed to describe assumptions of the project and the underlying idea. The next one is a planar drawing displaying an organization of the space of the object, which is composed of projections and sections (orthogonal projection). There also exists a spatial drawing which comprises axonometry and perspective (parallel and central projection) with the use of which we display an organization of internal and external space in relationships with the environment as well as the scale of the human. „These ways of portraying the space assure that the architectural representation becomes more tangible through some theoretical background reflecting upon the physical reality of the construct. These are some forms of *mimesis* – a graphic mimicking of the existing entity and expressions, a rigorous way of describing information about a shape or dimension of the object..." (Misiągiewicz, 2023, p. 265). One could mention here about a description in a form of a movie – in this case the space is augmented by a factor of time. The next way of description is a digital model in which the form is generated with the aid of a suitable algorithms. In 21st century architecture, attention is focused on parametric design, in which the digital model becomes a single source of information that can be generated, controlled and managed by the designer. And finally, a physical model that contains a completely different aspect than those mentioned earlier, namely it shows the method of construction combined with the physical touch of matter.

Two-dimensional representation – drawing

The role of drawing in the architect's education process and its importance for the creative workshop was and is unquestionable. Starting from hand-drawn, illustrative, proportional representations of solids, projections, sections, elevations, to technical or purely instructional drawings, drawing is the basic code of the relationship between the architect's mind and hand. "If the ultimate goal of architecture is to build, it is drawing which starts this initiative, and at the same time informs about constructing – it is in fact a record which determines spatial

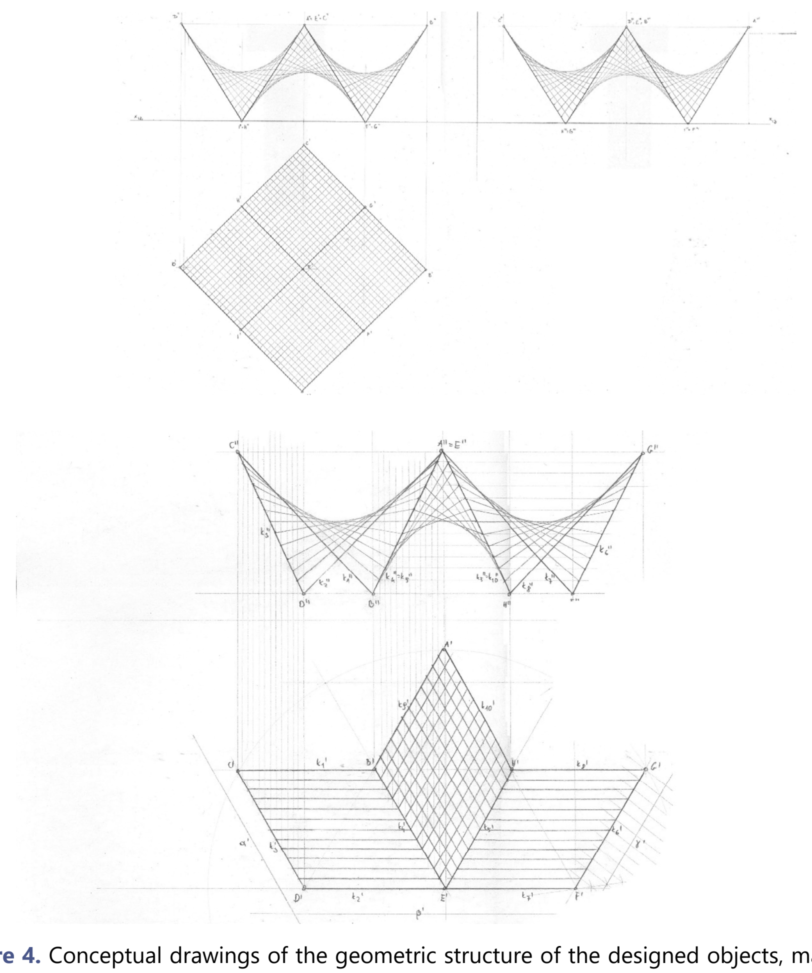

Figure 4. Conceptual drawings of the geometric structure of the designed objects, made by first-semester Students of the Faculty of Architecture, Silesian University of Technology (source: author)

and visual correlations and maps them in geometric and graphic terms. [...] The architectural presentation, theoretical principles of geometry allow visual transfer, which is an accurate representation of things" (Misiągiewicz, 2023, p. 265). Geometric projection conventions, based on metric rules and the formal definition of architecture form essential elements of the transfer. Such projections suggest: orthogonal, axonometric and perspective views, which in drawing design are daily used) (Figure 4).

Three-dimensional representation – physical model

Models – miniatures have for centuries acted as a medium of information in the contact between the designer and the investor or potential clients. Professional groups associated with the construction industry are proficient in the world of two-dimensional representations of three-dimensional space, while audiences outside this circle may have some trouble putting together projections, sections and views into a single form of an object. The spatial-physical model being the kind of record that shows the aspect of the way of construction is understood by all. It has many features in common with the target object, which makes it possible to carry out a relatively reliable verification and valorization of the solution used. It is a well-known common belief that what can be modeled can also be built. Therefore we can conclude that the model is a certain prototype of the physical construct.

The indisputable value of the model is the existing touch of the matter from which it is created. As a real product of a future object, it evokes the need to touch it, to examine its structure and shape. This is probably

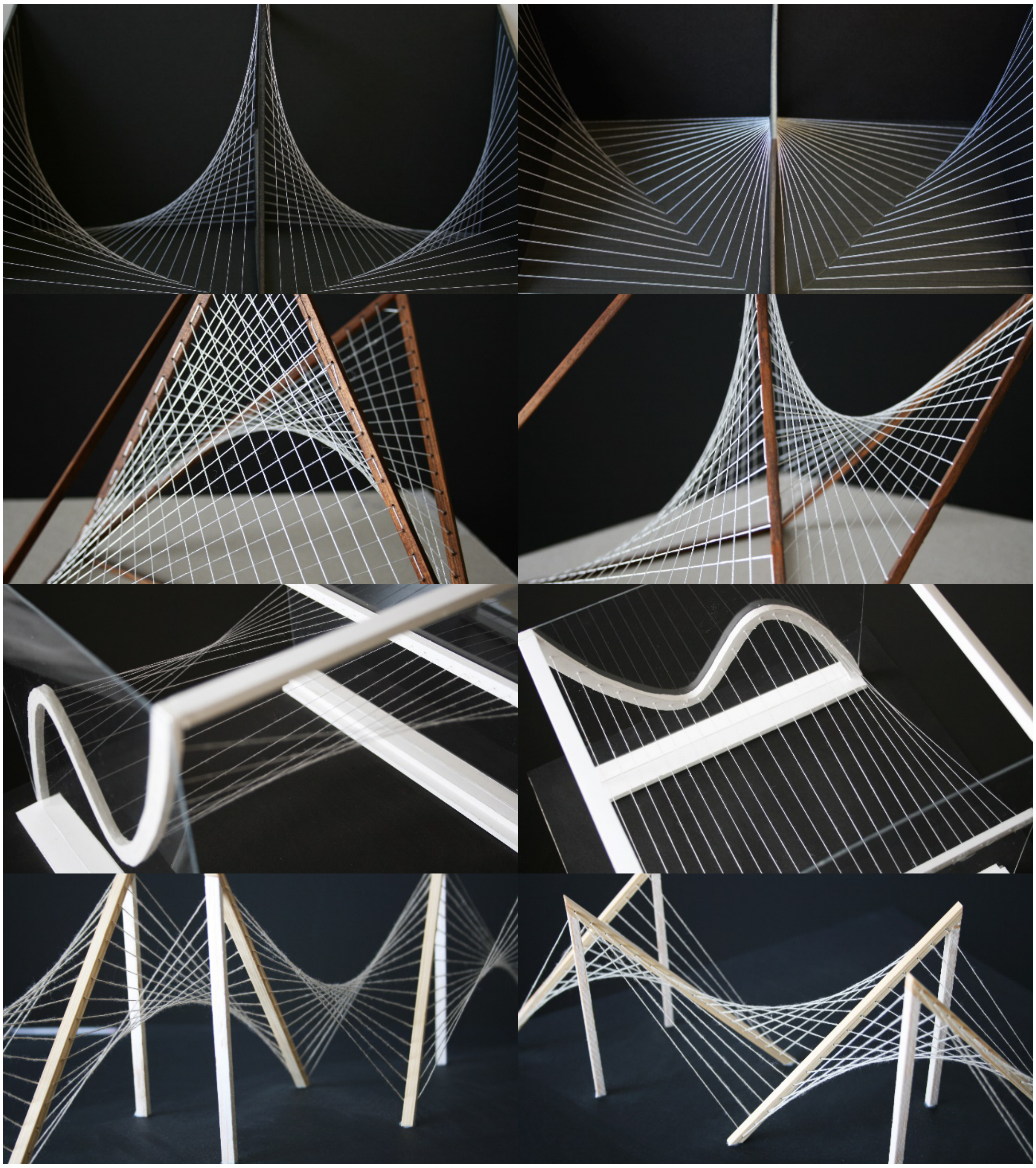

Figure 5. Models of architectural objects in which Catalan surfaces were applied, made by first-semester Students of the Faculty of Architecture (source: author)

because a model, especially one that faithfully reflects reality, activates the viewer – the client or investor being more comprehensible to him than a record in the form of drawing documentation or a virtual image made in synthetic digital space.[6] The physical model always constitutes an attractive alternative to connect with the client and as such it enjoys his/hers interest. As a summary of the project, it could be a useful element in the promotion process.

The physical model offers the potential builder the opportunity to evaluate the overall shape, proportion and form of the building. The technology of its construction using materials with specific physical properties reflects the laws of statics acting on the structure. Of course, the material commonly used in student practice, i.e. balsa, cardboard, plexiglass, styrodur, etc., has different properties than the material used in the project. Nevertheless the project completed for some tangible material teaches the students a responsibility to make a decision about choosing a suitable material to realize the project (Figure 5).

6. Conclusions

Enhanced spatial understanding and geometric reasoning

Physical and digital models serve as essential tools for developing spatial literacy and geometric thinking. Engaging with models allows students to visualize and manipulate three-dimensional forms, deepening their comprehension of spatial relationships and geometric principles fundamental to architectural design (Leopold & Zhurava, 2020; Rinaudo et al., 2023). The process of model-making, also when combined with digital tools like 3D printers and laser cutters, fosters a direct, haptic connection with space, supporting the theoretical claim that hands-on geometric reasoning is crucial for creative problem-solving in architecture (Leopold & Zhurava, 2020; Patra et al., 2020; Rinaudo et al., 2023).

Linking model-making to theoretical framework

The act of building models is not merely a reduction of reality but a complex exercise governed by its own set of rules, echoing the theoretical perspective that geometric approaches must be intentionally structured to communicate architectural ideas effectively (Rinaudo et al., 2023). Physical models, in particular, provide a unique form of spatial engagement, allowing students to explore and internalize the structure, function, and form of architectural objects in ways that digital models alone cannot fully replicate (Leopold & Zhurava, 2020; Patra et al., 2020). This supports the framework's assertion that spatial representation – through drawing, modeling, and digital visualization – is foundational importance for the creative use of contemporary digital techniques (Leopold & Zhurava, 2020).

Educational benefits and cognitive development

Model-making activities were found to improve students' ability to coordinate construction, composition, and aesthetic judgment, fulfilling the highest educational goal of fostering integrated cognitive development in architecture students (Leopold & Zhurava, 2020; Rinaudo et al., 2023). The interdisciplinary use of geometry as both a language and a tool for observation, analysis, and dissemination further reinforces the theoretical framework's emphasis on the centrality of geometric reasoning in architectural education (Rinaudo et al., 2023).

The results confirm that integrating physical and digital model-making into architectural education directly supports the development of spatial understanding, geometric reasoning, and creative problem-solving, as outlined in the theoretical framework.

[6] The computer, being a tool in the hands of the creator, may, but should not, limit the design process to the framework of the capabilities of individual programs and to the level of mastery of the graphical interface and available functions.

Disclosure statement

No potential conflict of interest was reported by the author.

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