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Virtual reconstruction and geometric analysis of Félix Candela's inverted umbrellas for The Villahermosa Cathedral

The paper presents the virtual reconstruction and analysis of the project for the Cathedral of Villahermosa in Tabasco (Mexico), designed by Félix Candela in 1960 in collaboration with Jorge Creel and Juan José Díaz. With 9-meter cantilevers supported by a single column and a height of more than 35 meters, the inverted umbrellas designed for the Cathedral would have been the tallest ever built by Candela using this structural system.
The project presents a variation of the traditional hyperbolic-paraboloid (hypar) umbrellas widely used by Candela in Mexico during the 50s and 60s. A parabolic discontinuity is introduced in each fragment of the surfaces, resulting in a structure formed by eight different hypars. This is not the first project where Candela used this type of variation, however, by modifying the direction of the generators and increasing the height of the hypars, it was possible to improve the curvature of the structure and reduce the deflections that appeared in previous constructions.
The virtual reconstruction of the project has been developed using a procedural non-destructive 3D model. The algorithm enables to modify the geometry and introduce different iterations in Grasshopper and Houdini. It has been linked with Unreal Engine, allowing to render the final project and its variations in real time and exporting the scenes to Virtual Reality. The procedure avoids the need of exporting multiple iterations -as they can be generated inside the render engine- as well as the loss of precision associated when converting NURBS to polygonal meshes in curved surfaces, using a discretization process.

Keywords:
Félix Candela; Virtual Reality; Architectural Geometry; Historical Structures; Hyperbolic Paraboloid

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1. INTRODUCTION

During the 50s and 60s Félix Candela built more than 800 projects using the geometry of the inverted umbrellas (del Blanco & García, 2017). Candela considered these structural forms as his greatest contribution to architecture, due to its low cost and high performance (de Garay, 1994).
With a single support and four symmetrical fragments of hyperbolic paraboloids (hypars), it was possible to cover more than 200 square meters. The thickness of the hypars was generally 4 cm, resulting in one of the most efficient structures in the history of architecture. The formworks were its main drawback, making it a more expensive construction (Basterra, 1998).
As Ove Arup wrote (Arup, 1963), Mexico was the only country at that time were Candela could have accomplished such a massive amount of constructions using thin concrete shells. Candela's persistence allowed him to build these structures in the United States and Europe, using more sophisticated construction systems. However, despite his attempts to systematize the construction of umbrellas outside of Mexico, they were only built in few occasions.
The antecedent to the geometry of the inverted umbrella is found in the scheme of F. Aimond in 1936. Candela experimented with multiple variations of the traditional inverted umbrellas without finding a more efficient solution than the original one. One of these variations leaded Candela to introduce folds in the thin shells, trying to improve its structural behavior (Billington, 2010). The umbrellas for The Villahermosa Cathedral used this variation (fig. 1), duplicating the amount of required hypars.

Fig. 1 - Virtual reconstruction of The Villahermosa Cathedral, front view. Mixed techniques with custom shaders. Image of the author.

2. THE VILLAHERMOSA CATHEDRAL AND THE DUPLICATION OF HYPARS IN THE INVERTED UMBRELLAS

In 1960 Félix Candela, Jorge Creel and Juan José Díaz designed the project for The Villahermosa Cathedral. The inverted umbrellas gain a monumental scale for this project, moving away from the economic efficiency of the traditional umbrellas.
The umbrellas designed for the Cathedral surpassed the 35 meters in height with 9-meter cantilevers supported by a single pillar. They would have been the tallest inverted umbrellas ever built by Candela using this structural system, becoming a milestone in his career (fig. 2).
The project hasn´t received much attention. Up until today there is only one drawing published of the Cathedral (fig. 3), although the archives of the Avery and Fine Arts Library at Columbia University (Candela, Félix; Pérez Piñero, 1984) also preserve a photography of the model. It was originally published in the book: "Candela, the shell builder" (Faber, 1963), accompanied by a descriptive paragraph:

> High over the tropical marshes of Villahermosa will float the roof of its new cathedral. Its umbrellas in juxtaposition, square and hexagonal, with two different heights and spans, will perch on warped pillars of slender dimension. Upon entering the cathedral, the spectators will be atracted by the windowsless shells as they overlap in vertical retreat (Faber, 1963).

The book was written by Colin Faber using a selection of projects provided by Candela. During the 80s, Félix Candela donated to the Columbia University most of his documentation, including the archives of his company Cubiertas Ala (del Cueto, 2010).
Owing to the large dimensions of the cantilevers, the geometry of the umbrellas for the Cathedral presents a variation of the classical structure of Candela, including a parabolic discontinuity in each of the fragments of the hypar. As a result, the structure is generated by duplicating the amount of hypars in the umbrella.

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This variation of the inverted umbrella was used by Candela four years before for the construction of the Jamaica Wholesale Market in Mexico City (1956), a structure which presented the same length of 9-meters cantilevers. He was forced to reduce the curvature of the hypars because of the restrictions in the height of the building. The overall rise between the supports and the roof was only 3 meters. The deflections generated in the project for the Market were excessive and Candela considered that they had surpassed the "limits" of the structure (Cassinello, 2010).

In an attempt to increase the stiffness of the structure, Candela introduced a parabolic discontinuity from the support to the corners of the hypar, increasing the number of hypars from 4 to 8. This fold was supposed to improve the structural behavior of the classical umbrella, however, a recent structural analysis (Wang, et al., 2020) proved that the discontinuity generates larger deflections and stresses.

The Market was in perfect conditions until the 1985 big earthquake in Mexico City, which leaded to its demolition.

In 1956 Candela collaborated with another exiled spanish architect, Josep Lluis Sert, to design the inverted umbrellas for the Presidential Palace of Havana in Cuba. The geometry of the umbrellas was similar to the Jamaica Market, using square umbrellas with eight hypars. With the same 3-meters rise from the supports till the superior edges of the roof, the umbrellas for the Presidential Palace only had 4-meter cantilevers. The project was never built, but the big increment in the curvature of the hypars should have provided enough stiffness to the structure.

It was four years later, in 1960, when Candela designed what would have been the tallest inverted umbrellas for The Villahermosa Cathedral. At that time Candela had already built hundreds of inverted umbrellas, and he was aware that by increasing the curvature of the hypars it would be possible to augment the length of the cantilevers without compromising the structure.

In order to meet the monumental scale of the structure, the inverted umbrellas had more than 35-meters height. It presented two different geometries,

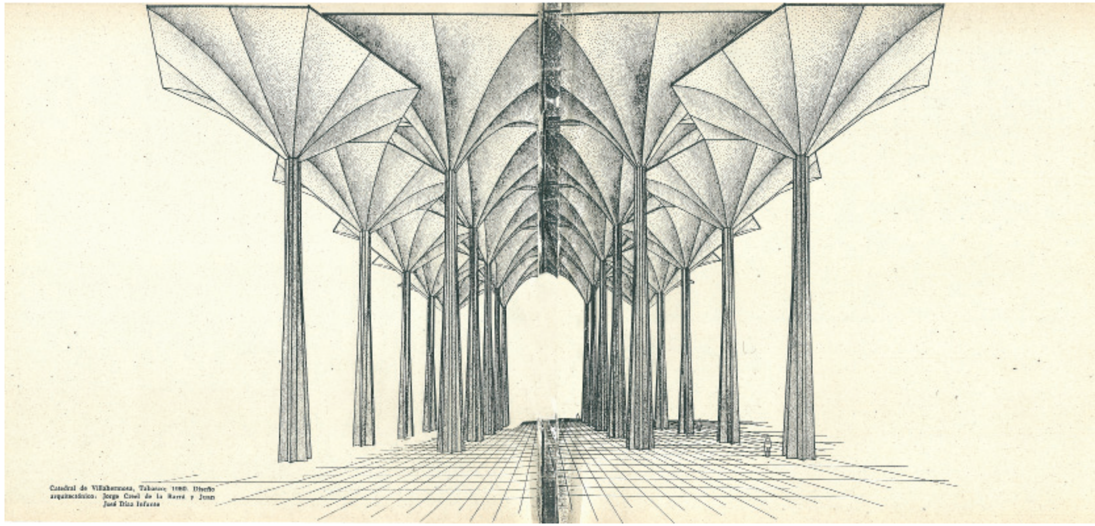

Fig. 2 - Original documentation of the Cathedral. Published in *Candela the shell builder* (Faber, 1963)

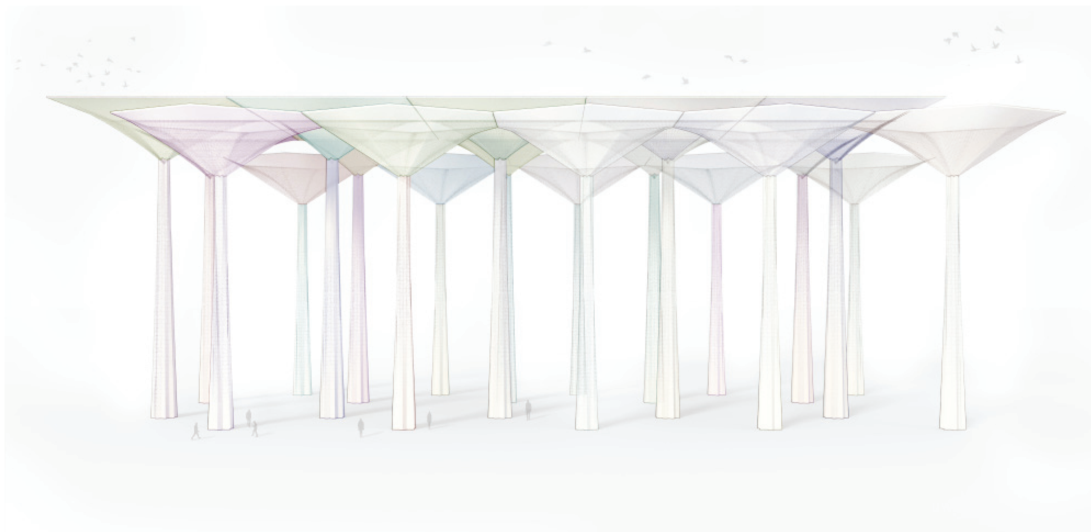

Fig. 3 - Virtual reconstruction of The Villahermosa Cathedral, exterior left view. Mixed techniques. Image of the author.

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a square and a hexagonal umbrella, both of them with a span of 18 meters. They had the same span as the problematic market in Jamaica. However, for this project the umbrellas had a rise of 8,5 meters for the square umbrellas (from the support till the roof) and 7 meters for the hexagonal ones.
The Cathedral was never built and Candela reused the geometry of these umbrellas for a humbler design: The Candelaria Metro Station in Mexico (fig. 4). This project has been fundamental to propose hypotheses for the virtual reconstruction of the Cathedral. the same span as the problematic market in Jamaica. However, for this project the umbrellas had a rise of 8,5 meters for the square umbrellas (from the support till the roof) and 7 meters for the hexagonal ones.
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The inclusion of a parabolic discontinuity in the surface of the hypars for the inverted umbrellas was not used again by Candela in any mayor project. The reason could be the decrement of the economic efficiency that this variation supposed, or maybe Candela realized that his initial hypothesis of introducing folds in the surface of the hypars wasn´t improving its structural behavior.
In 1983 Candela designed with Fernando Higueras, César Manrique and Ramón-Laca a non-built project for the San Javier Airport in Murcia (Spain), using inverted umbrellas with 12-meter cantilevers (del Blanco & García, 2018). It is the largest span designed by Candela with this structure, and he relied in the traditional and efficient four hypar solution. At this time Candela had stopped building thin concrete shells, and the airport could be considered as his latest major project using inverted umbrellas. In order to achieve a span of 24 meters with a single umbrella, the thickness of the structure was increased to 5 centimeters. It is also important to note that there is a difference of more than 30 years since the construction of the first inverted umbrella (García & Ríos, 2016).

3. METHODOLOGY

The lack of a complete documentation leaded to implement a perspective restitution from the original drawing of the project. Using the projection principles of the descriptive geometry, it was possible to obtain the metrical proportions and measures of the Cathedral.
The perspective restitution allowed to generate a three-dimensional procedural reconstruction using NURBS. The algorithms were implemented in the applications Grasshopper and Houdini, using Python and VEX languages respectively. In order to export the information to a virtual reality system, NURBS were transformed into meshes. Usually there is a loss of precision in this process when we are working with curved surfaces.
To avoid that loss of quality, the geometry of the umbrellas was defined from the generators of the surface. As a doubly ruled surface, any hyperbolic paraboloid presents two families of straight lines, which will be used as the generators and directrix curves of the inverted umbrella. The intersection of every pair of straight lines that belong to both families generates 4 vertexes. By defining a quadrilateral mesh from those vertexes, we can get a polygonal mesh with no loss of precision from the initial NURBS. The parabolic discontinuity is defined as a mirror plane between the different fragments of the hypars, as it cannot be represented as a smooth curve while working with meshes.
The 3D model can be used to extract new documentation of the project, including the necessary plans for a rigorous analysis of the Cathedral.
For the virtual representation, Catmull-Clark subdivision algorithm have been used to obtain a smooth surface from the meshes, avoiding the appearance of hard edges along the surface. In order to have a higher artistic control in the final processed images, the computer-generated images have been altered with custom shaders and freehand drawing.

Fig. 4 - Candelaria Metro Station in 1967. Archives of the Collective Transport System, Mexico City Metro.

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4. GEOMETRY

4.1 COMPOSITION

The Villahermosa Cathedral emulates the composition of the traditional western cathedrals, achieving a monumental interior space. The project is formed by twenty inverted umbrellas placed in four rows, generating a central nave and two lateral aisles with smaller dimensions and height. There is no transept (fig. 5).

There are two variations of the traditional inverted umbrellas. The central umbrellas present a square perimeter with 18-meters side, equaling the span that Candela reached in The Jamaica Market (1956). They are formed by 8 fragments of hypar. The hexagonal umbrellas are aligned in the perimeter. They present an apothem of 9 meters, resulting in the same 18 meters from side to side. Following a similar subdivision, they are formed by 12 fragments of hypar.

However, the hexagonal umbrellas are 4,5 meters lower, producing a difference in height which is used for the juxtaposition of the umbrellas. That variation allows the light to enter directly in the central nave, generating a rich composition of thick shadows. The nave is 18-meters width, while the lateral aisles are reduced to 11 meters. The edges of the square umbrellas are displaced 2 meters from the axes of the hexagonal umbrellas' supports. The reason could be to favor the entry of more light, but specifically to avoid the intersection of the hexagonal and square umbrellas (fig. 6 and 7).

The modulation of the project allows that along the longitudinal axis the distance between the supports is always the same (18 meters), juxtaposing the umbrellas one after the other. A marked and homogeneous rhythm appears in which the perimeter umbrellas are interspersed with those of the central nave, thus breaking the scheme of the traditional cathedrals. In the transverse direction the umbrellas overlap, making it difficult to recognize the modules.

The spatial units are perfectly defined in the central nave, delimited by squares formed by joining the supports (fig. 5). From the inside, the roof of

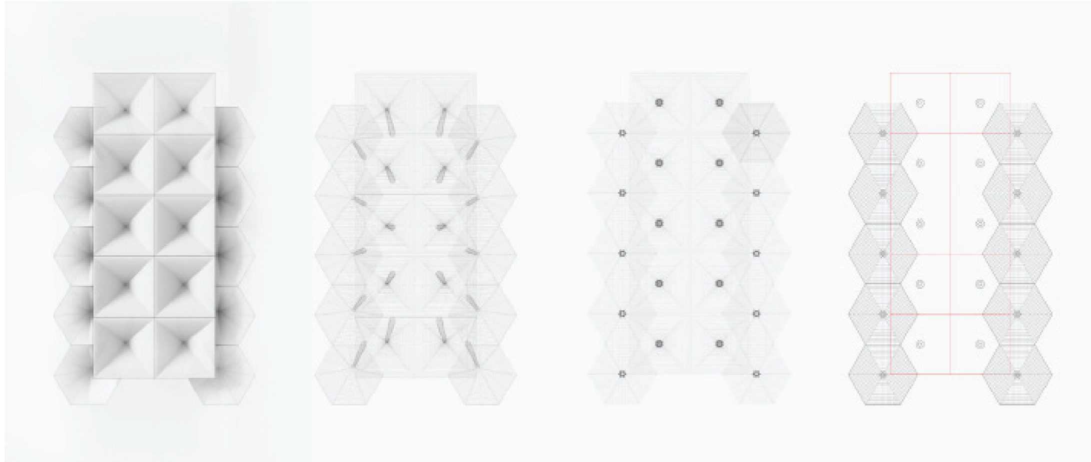

Fig. 5 - Top views of the inverted umbrellas, columns and generators of the hypars. Image of the author.

Fig. 6 - Front view. The axis of the exterior supports are displaced 2 meters to avoid the intersection of the umbrellas. Image of the author.

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Fig. 7 - Left view. The 4.5 meters of difference in height of the umbrellas generate a non-hermetic windowless roof. Image of the author.

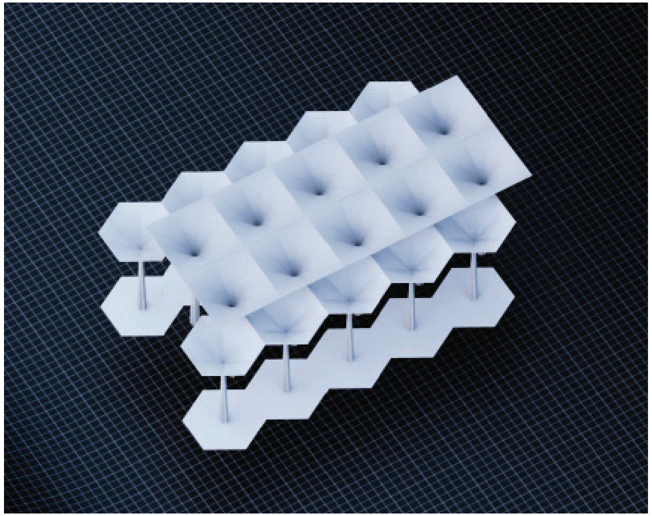

Fig. 8 - Axonometric view of the Cathedral. Image of the author.

the central nave is perceived as ribbed vaults (fig. 1), where the ribs have been replaced by the folds that show the intersection of the different fragments of hypar. In the lateral aisles the spatial units are dissolved, the pillars are only aligned in one direction, and the roof is formed by overlapping umbrellas that do not close hermetically.
There is a clear directionality in the Cathedral. However, the three longitudinal axis do not mark the directions of circulation because of the lack of a physical limit that could prevent the transit of people. Pedestrians could move freely around the supports. The limit of the project is defined by the line of supports and the cantilevers of the roof, which generate a transitional space with the exterior (fig. 8).

4.2 INVERTED UMBRELLA

After the reconstruction, a geometric analysis of the structure has been completed, allowing to identify the main differences with other inverted umbrellas designed by Candela and to pose hypothesis about the decisions of the pragmatic architect.
The traditional inverted umbrellas designed by Candela are generated by four symmetrical hyperbolic-paraboloids supported by one single pillar, generally using a thickness of 4 centimeters. The umbrellas of the Cathedral follow the previously described variations. A parabolic discontinuity is introduced in the bisectors of the surface -the diagonals of the square and the apothems of the hexagon- duplicating the amount of fragments of hyperbolic paraboloids used in the standard solution.
At first sight it seems that Candela used the same variation in the geometry for the square umbrellas in the Cathedral that in the previous projects. However, after the reconstruction and the analysis of the geometry, we can find an important difference.
In order to increase the curvature of the surfaces, Candela performed two operations. The first was the obvious one: increasing the rise of the hypars. The second variation in the geometry is hidden in the drawing, it consisted in modifying the direction of one of the families of the generators of the hypars (fig. 9).

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It is important to note that the intersection of a hypar with any plane that contains its axis or is parallel to it, will generate a two dimensional parabola.

The four fragments of hypar of the traditional umbrella are included in a warped quadrilateral with four straight edges. It has 3 vertices at the same height. The fragments for the square variation in the Jamaica Market or the Presidential Palace present two straight sides and a parabolic one, as a result of the parabolic discontinuity. It is possible to achieve this geometry by simply changing the height of one of the three vertices. The intersection of the hypar with a surface that contains both, the axis of the hypar and its bisector, would generate the desired parabola. That surface is the symmetrical plane that contains the parabolic discontinuity (fig. 9).

The fragments of hypar of the Cathedral present only one straight edge and two parabolic ones. By continuously increasing the length of the first family of the generators, the resulting fragment couldn´t be inserted in a square perimeter. The intersection of the surface with the symmetrical planes that contain the folds would result in two parabolas. This solution allowed Candela to add additional curvature to the structure and generate more pronounced folds at the intersection of the different fragments of hypar (fig. 10).

This variation can be achieved in different ways, as we could as well modify the direction of the first and second family of generators. The original drawing of the Cathedral doesn´t show the straight lines of the generators of the hypar, a very important information that Candela used to include in the drawings of other projects. As a consequence, it is not possible to know which of the options Candela used. The formal result would be almost identical. The hypothesis presented in the reconstruction seems to be the most feasible, since modifying both families of generators would affect the geometry of the formwork (fig. 11).

The hexagonal umbrella variation presents 12 fragments of hypar, presenting an important difference with the square version. Each fragment has two straight edges and a parabolic one. The

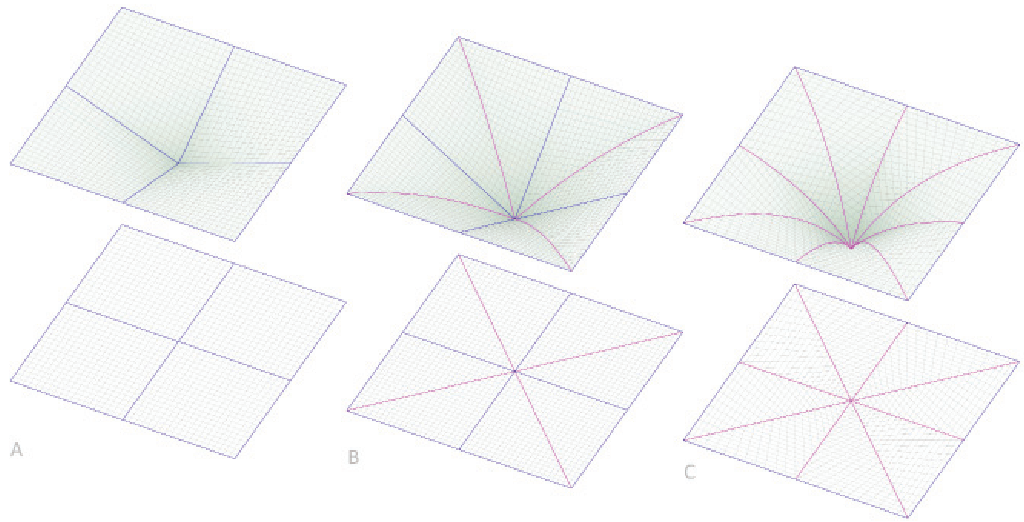
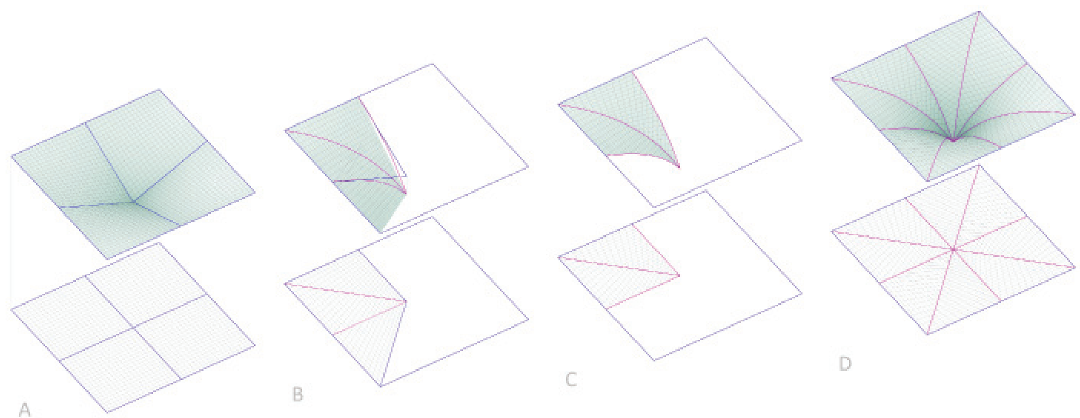


Fig. 9 - Variations of the inverted umbrella, axonometric and top projections. The grey lines represent the generators of the hypars, the blue lines the straight edges and the magenta lines the parabolic edges. A) Traditional inverted umbrella, each hypar has 4 straight edges. B) Subdivision used in the Jamaica Market. Each hypar has two straight edges and a parabolic one. The generators of the hypars are parallel to the straight edges C) Variation of the Cathedral. Each hypar has one straight edge and two parabolic ones. One of the direction of the generators of the hypars is modified. Image of the author.

Fig. 10 - Variation from the traditional umbrella to the one used in the Cathedral. The grey lines represent the generators of the hypars, the blue lines the straight edges and the magenta lines the parabolic edges. Image of the author.



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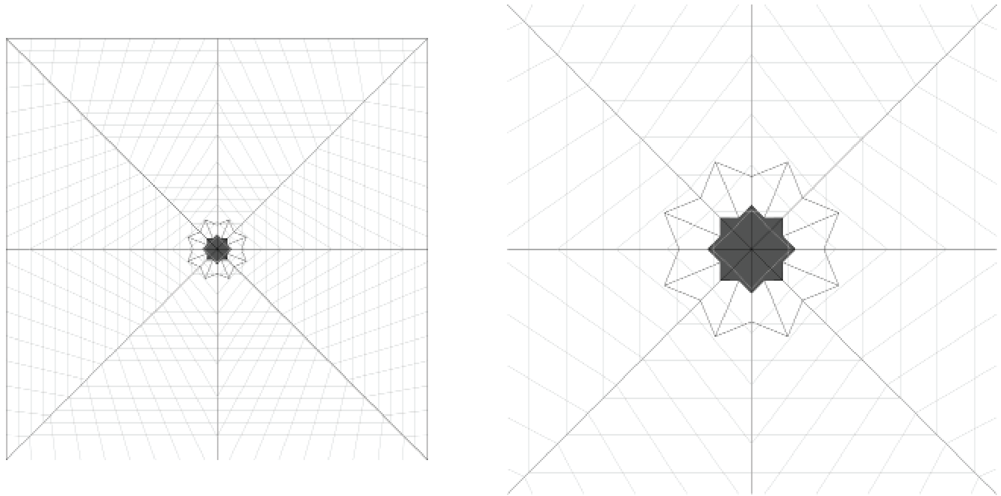
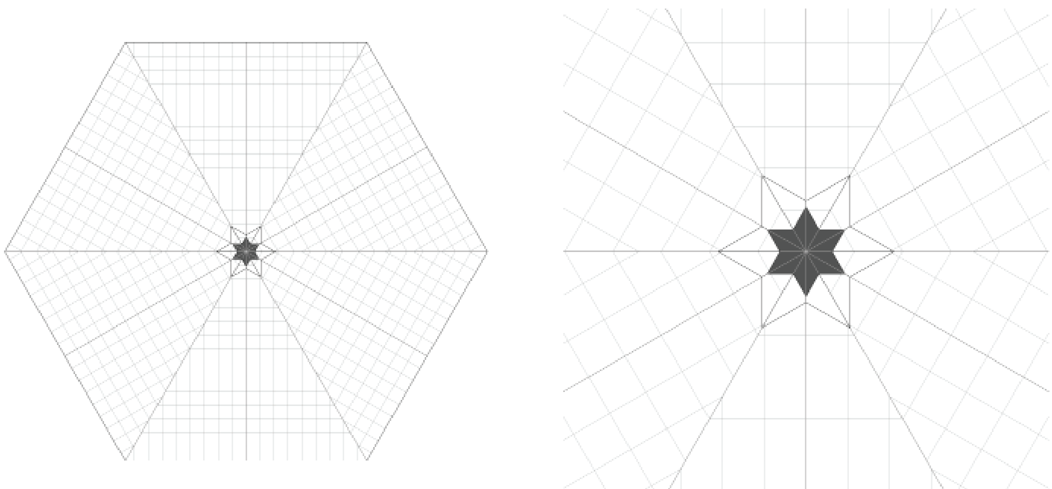


Fig. 11 -The generators' direction of the hypars are modified to increase the curvature of the shell. The edges of the hypar are not parallel to the generators, so the folds of the shell are parabolic. The eight folds correspond with the concave parts of the eight-pointed star support. Image of the author.

Fig. 12 - Hexagonal umbrella. The generators of the hypars are parallel to the straight edges. The twelve folds of the umbrella (six parabolic and six straight edges) correspond with the six-pointed star support. Image of the author.



segmentation follows a similar procedure than the umbrellas for the Jamaica Market. Candela avoided modifying the direction of the generators. The reason could be that in the hexagonal umbrella there are already six parabolic discontinuities generating strong folds, which correspond with the six-star shape of its support (fig. 12).

In the project for the Candelaria Metro Station (1967), where Candela used a similar geometry to solve the umbrellas, each fragment of hypar present two straight edges and a parabolic one. The geometric configuration for the square umbrellas in the Cathedral with two parabolic edges was unique and was not used in later projects.

The dimensions of the square umbrellas were 8.5 meters of height with 18 meters for each side. In the case of the hexagonal umbrellas, they had a height of 7 meters, a distance of 18 meters from side to side, a diameter of 20.785 meters.

4.3 SUPPORTS

The large dimensions of the supports contribute to the monumental scale of the Cathedral. The slender but wide pillars present hard edges that would have generated a high contrast of light and shadows (fig. 13).

The horizontal section of the warped pillars generates a polygonal star which varies as it ascends. The concave part transforms into convex to accommodate for the edges of the hypars of the umbrellas. The hexagonal umbrellas use a six-pointed star support, while the square umbrellas use an octagonal one (fig. 14).

The numbers are not arbitrary, as they correspond with the number of parabolic edges of the umbrellas. The surfaces of the supports are formed by twelve and sixteen hypars respectively.

The solution for the connection between the supports and the umbrellas is slightly different. For the square umbrellas, the eight parabolic folds that mark the intersection of the hypars, connect with the convex side of the supports. However, in the case of the hexagonal umbrellas, both the convex and concave parts of the support are used to connect with the straight and parabolic folds of the umbrella respectively.

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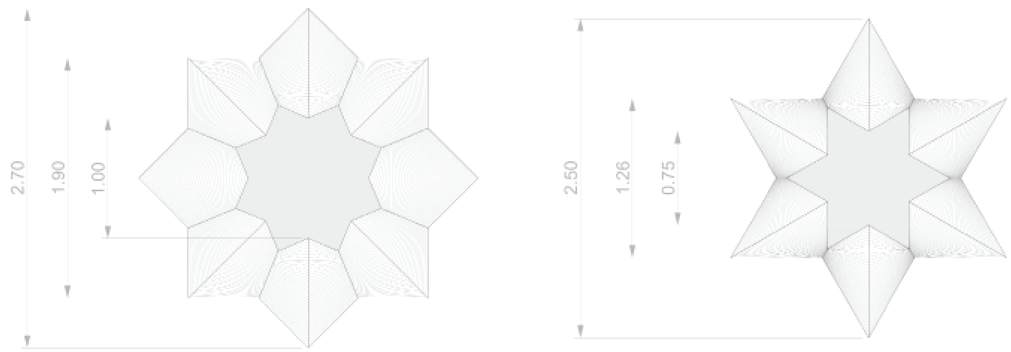
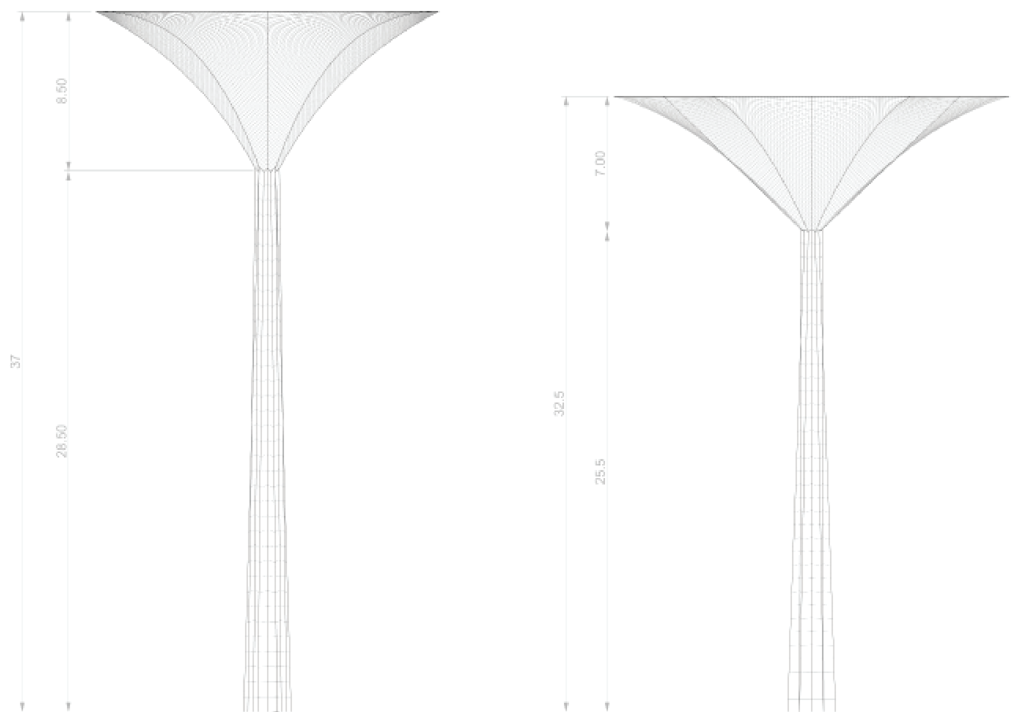
Fig. 13 - Simulation of the shadows generated by the sunlight. The pillars are 2.5 and 2.7 meters wide. Image of the author.





The only reference for the measures of the Cathedral is the original perspective drawing presented by Colin Faber. As a consequence, small measures such as the section of the pillars cannot be taken with total precision. With that in mind, we present a very approximate solution that corresponds with the drawing.
The dimensions of the hexagonal star supports are 2.5 and 1.5 meters at the bottom and 1.3 and 0.75 meters on top. With 25.5 meters in height, they would rise the hexagonal umbrellas to a total of 32.5 meters.
In the case of the octagonal star supports, they have 2.7 and 2 meters at the bottom and 1.25 and 1 meter at the top. They are 28.5 meters tall, with a total height of 37 meters with the square umbrella (fig. 15).

5. REAL TIME RENDERING AND VIRTUAL REALITY INMERSIVE EXPERIENCE

The virtual project was generated using Grasshopper and Houdini, defining a procedure rather than using the traditional 3D modelling tools. Both applications allow a parametric approach which enables the introduction of different iterations, doing simulations or FEM analysis. However, all these capacities would be lost once the model is baked or exported as a 3D mesh to be used in other specialized applications.
The first step was to define the main variables for the parametric model of the umbrellas. The height, the span and the number of sides of the roof control the overall geometry of the umbrella, allowing to generate different variations. The direction of the generators controls the curvature of

Fig. 14 - Polyhedral supports for the square (left) and hexagonal (right) umbrellas. The straight lines indicate the generators of the hypars.
Fig. 15 - The two variations of the inverted umbrellas. The straight lines indicate the direction of the generators of the hypars of the supports and the umbrellas. Images of the author.

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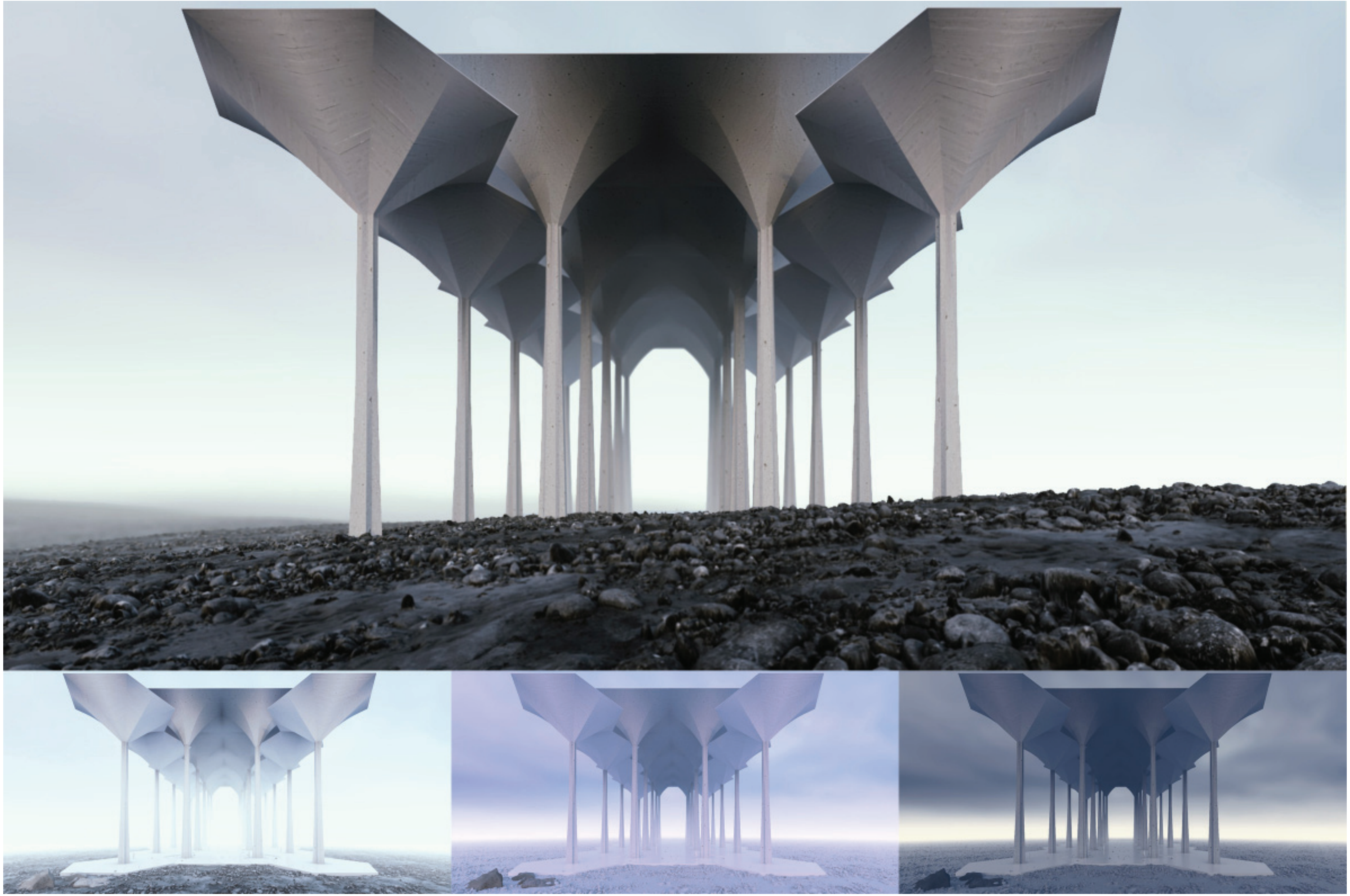

Fig. 16 - Virtual reality scenes of the Cathedral. The render engine is linked with the parameterized model, so any modification to the geometry is possible from the engine. Different environments or atmospheric effects are programmed to be chosen from the scene. Image of the author.

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the surface, as well as the type of curves at the edges of each fragment of hypar (straight lines or parabolic intersections). Finally, the density of the generators defines the smoothness of the different surfaces. As mentioned before, in order to avoid a loss of precision in the conversion from NURBS to meshes, the surfaces were discretized into smaller patches defined from 4 vertices that form a quadrilateral. The size of these quadrilaterals depends on the amount of generators. After the conversion to meshes, they will preserve the topology of the original surfaces.
Exporting different iterations of the algorithm would imply generating multiple heavy 3D files which would have required the production of various scenes in the render engine. In order to avoid this process and to maintain the procedural capabilities of the parametric model from the render engine, we used the Houdini-Engine plugin (Side Effects, 2015). Houdini-Engine allowed to link the external render engine with the original virtual model, so its properties are preserved and can be modified in the immersive experience.
The optimization of a model plays an important role when rendering in Real Time, especially if it is going to be used for Virtual Reality (Schulze, et al. 2021). For this reason, only two inverted umbrellas were really generated (fig. 15). The rest of the umbrellas are instances of the originals reproduced in the render engine, reducing the computational requirements for the virtual reality scene (fig. 16). The surfaces were clustered into smoothing groups, allowing to reduce the density of generators of the hypars, and in turn, lowering the polygonal count of the meshes and the number of required "draw calls" from the engine (Garcia, 2021).
The final scene was reproduced inside Unreal Engine 5, a powerful game engine that allowed to render the scenes in real-time. Using this workflow, the files do not need to be rendered and baked as a whole. Every frame of the scene is constantly updated and allows to use external inputs, so every experience from the users could be different (fig. 17).
The system utilized is similar to the "Virtual

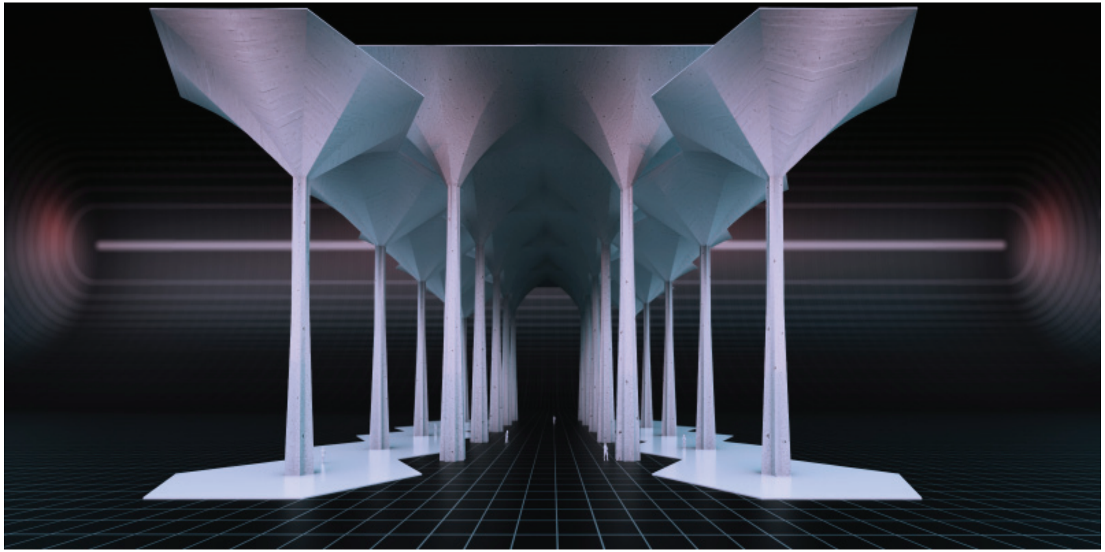

Fig. 17 - Real time postproduction is performed from the engine, without the need of exporting sequences to other specialized software.
Fig. 18 - The surfaces that surround the model can be mapped to recreate different environments as in the previous figures. The resulting scenes require low computational power to be executed. Images of the author.

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Production" used in films (Fields, 2021), without the associated limitations and complexity of combining real footage with virtual elements. The project is surrounded in all directions by surfaces that can be mapped, represented in black (fig. 18). The only real 3D models are the Cathedral and the people to populate it. The use of additional 3D objects has been avoided so the scene can be reproduced in computers with low specifications or mobile devices.
The users can interact with the Cathedral and visit the project using a virtual reality system. The new RTX technology developed by Nvidia enables real time rendering using "Ray-tracing" not only for the virtual reality experience, but to render images instantly without the associated waiting times of the offline render engines. The introduction of the new technologies "lumen and nanite" (Karis, Brian; et al., 2021) enhance the real time experience. Using a single Nvidia RTX 2080 Ti, the engine rendered at 120 frames per seconds (fps) consistently at a resolution of 1440p. It means that it takes 8,33 milliseconds to render one frame, a significant difference with the traditional rendering methods. It is important to note that the maximum amount of fps was capped at 120 to avoid unnecessary use of resources.
There was an important time delay when reproducing the scene from mobile devices without RTX, as well as making the system unstable. To improve its performance, the "Ray-tracing" rendering method was replaced by "Rasterization", which led to eliminate dynamic lighting in favor of static lighting, using baked maps to store the lighting information. The original materials included displacement textures to add fine details, which were replaced with normal maps. Using a Mali-G71 MP20 GPU (integrated GPU from Samsung S8), the system could render the scene above 30 fps consistently with a resolution of 1080p. The different backgrounds and atmospheric effects didn't have an important impact in the performance, since they are projected images or videos. To enhance the user experience, the scene is pre-programmed with different lighting set-ups, environments, atmospheric effects and materials (fig. 19), which can be modified by the users inside the interactive experience by simply pressing buttons. Other advanced options to modify the geometry of the linked surfaces, personalized lighting, image post-processing, altering the geometry of the surfaces that receive the projections (to modify the terrains for example) or other aspects to improve the performance of the scene can only be accessed from the editor of the engine.
The narrative is not predefined, there is not a linear path and each user can personalize his experience. The content becomes dynamic, as opposed to a pre-recorded video of the scene.

6. CONCLUSIONS

The project for the Cathedral of Villahermosa defines a milestone in the career of Félix Candela. The architects achieved a monumental scale sacrificing the economic efficiency for which the umbrellas were originally designed.
The variation of the umbrellas for the Cathedral are the tallest ever designed by the architect, with 8.5 meters in the roof and more than 35 meters of height. The 9-meter cantilevers match the largest span built by Candela using the umbrellas. By

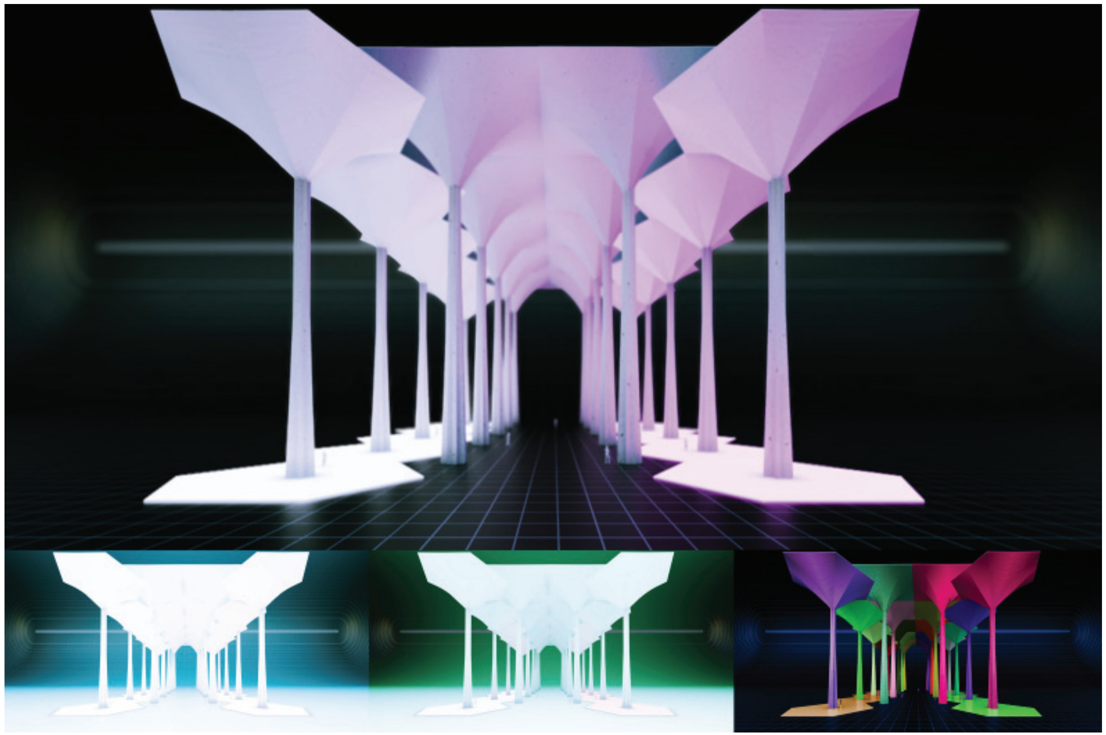

Fig. 19 - Users can choose from different lighting set-ups from the real time engine. Users with technical knowledge could create a custom lighting. Each inverted umbrella has a different identification number which allows the modification of its geometry and materials. Images of the author.

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increasing the curvature and experimenting with the geometry of the hypars he tried to improve the structural behavior, although the folds in the surface didn´t have the expected results. Only the non-built project for the airport in Murcia (Higueras, 1983) surpasses the length of the cantilevers with 12 meters. The airport, one of the latest projects designed by Candela, used the traditional four hypar inverted umbrella, opening up a new question about the convictions of Candela in the efficiency of folds for inverted umbrellas.
The introduction of the folds in the surface of the hypars complicates the construction process of the inverted umbrellas, which was one of the key aspects in the massive production of thin concrete shells in Mexico. The geometric variations of these umbrellas distance them from the economic and constructive efficiency of the original umbrellas.
Working with procedural algorithms instead of traditional 3D models have proved to be useful using this methodology. It has solved the needs to generate various models for different solutions, allowed to use NURBS and meshes with variable resolutions, as well as the possibility to modify the geometry of the project without relying on multiple heavy 3D models. Connecting the files with a render engine avoiding the loss of the parametric properties of the model is of great value, expanding the possibilities of the immersive experiences. We can use a similar procedure to generate digital fabricated models or to implement a finite element analysis of the structure. In both cases we need to work with discrete geometry inputs such as meshes or polylines.
Despite the singularity of the Cathedral in the design of inverted umbrellas, the project hasn´t received enough attention. The virtual reconstruction of the Cathedral enables the production of new and precise documentation as well as recreating the project using a virtual reality system. The files are ready for future research in the fields of generative optimization, structural analysis or digital fabrication.

REFERENCES

Arup, O. (1963). Foreword by Ove Arup Preface Introduction in: *Candela, the Shell builder*. London: Architectural Press.

Basterra Otero, A. (1998). *Las estructuras arquitectónicas de Félix Candela: una revisión actual*. ETSAV, Valladolid.

Billington, D. P., & Moreyra Garlock, M. E. (2010). Structural Art and the Example of Félix Candela. *Journal of Structural Engineering*, 136(4). https://ascelibrary.org/doi/10.1061/%28ASCE%29ST.1943-541X.0000144

Block, P., Kilian, A., & Pottmann, H. (2015). Steering of form - New integrative approaches to architectural design and modeling. *CAD Computer Aided Design*, Vol. 61. https://www.sciencedirect.com/science/article/abs/pii/S0010448514000712?via%3Dihub

Candela, Félix. (1954). *The shell as space encloser*. MIT, United States.

Candela, Félix; (1954). Warped Surfaces. In MIT Massachusetts Institute of Technology (Ed.), *Conference on Thin Concrete Shells*. Massachusetts.

Candela, Félix; Pérez Piñero, E. (1984). *Félix Candela architectural records and papers, 1950-1984*. Avery Drawings & Archives Collections. https://findingaids.library.columbia.edu/ead/nnc-a/ldpd_3464748

Cassinello, P. (2010). *Félix Candela centenario 2010* (Fundación). Fundación Juanello Turriano.

de Garai, Graciella (1994). Interview with the architect Félix Candela carried out at his home in Riley, North Carolina. Sound file.

del Blanco García, F., & García Ríos, I. (2018). Fernando Higueras y Félix Candela en un retorno a la geometría de paraguas invertidos. Análisis y reconstitución gráfica del aeropuerto de Murcia, 1983. *EGA Expresión Gráfica Arquitectónica*, 23(32), 232-243. https://polipapers.upv.es/index.php/EGA/article/view/9813

del Blanco García, F., & García Ríos, I. (2017). Las cúpulas de Félix Candela. Análisis y reconstitución de las instalaciones deportivas de la Universidad Brown, 1965-1972. *EGA Expresión Gráfica Arquitectónica*, 22(29), 228-239. https://polipapers.upv.es/index.php/EGA/article/view/7358

del Blanco García, F., & Perez Lupi, L. (2018). Métodos paramétricos de reconstrucción virtual de superficies parabólico hiperbólicas en la arquitectura de Félix Candela. *EGE Revista de Expresión Gráfica en la Edificación*, 0(10), 18-26. https://polipapers.upv.es/index.php/ege/article/view/12437

del Cueto Ruiz-Funes, J. I. (2010). *Félix Candela 1910-2010*. Valencia: IVAM, SECC.

Draper, P., Garlock, M. E. M., & Billington, D. P. (2010). Structural optimization of Félix Candela's hypar umbrella shells. *Journal of the International Association for Shell and Spatial Structures*, 51(163).

Faber, C. (1963). *Candela, the Shell builder*. London: Architectural Press.

Fields, L. (2021). ILM Presents: The Visual Effects & Virtual Production of "The Mandalorian." *Siggraph 2021*.

García, F. L. D. B., & Ríos, I. G. (2016). De las estructuras laminares a las estructuras metálicas en la arquitectura de Félix Candela. Análisis y reconstitución de la sala de exposiciones para el concurso del Palacio Olímpico de los Deportes, México 1968. *Rita Revista Indexada de Textos Academicos*, 5, 98–105. http://ojs.redfundamentos.com/index.php/rita/article/view/106/106

Garcia, K. (2021). Advances in Real-Time Rendering in Games. *Siggraph 2021*.

Garlock, Maria E. M.; Billington, D. (2008). *Felix Candela: Engineer, Builder, Structural Artist* (Princeton University Art Museum; New Haven Yale University Press, Ed.).

Higueras, F. (1983). *Memoria del proyecto para el aeropuerto de Murcia*. Archivo Higueras del Colegio de Arquitectos de Cataluña.

Karis, Brian; Stubbe, Rune; Wihlidal, G. (2021). Nanite. A deep dive. *Siggraph 2021*.

Pottmann, H. (2010). Architectural geometry as design knowledge. *Architectural Design*, 80(4). https://onlinelibrary.wiley.com/doi/10.1002/ad.1109

Schulze, J. et al. (2021). Immersive visualization for science research, art and education. *Siggraph 2021*.

Tang, C., Sun, X., Gomes, A., Wallner, J., & Pottmann, H. (2015). Form-finding with polyhedral meshes made simple. *ACM SIGGRAPH 2015 Posters, SIGGRAPH 2015*. https://dl.acm.org/doi/10.1145/2787626.2787631

Wang, S., Levine, A., Garlock, M., Contreras-Jiménez, J. A., & Jorquera-Lucerga, J. J. (2020). Structural evaluation of Félix Candela's 8-sided hyperbolic paraboloidal umbrellas. *Engineering Structures*, 222. https://www.sciencedirect.com/science/article/abs/pii/S0141029619341434?via%3Dihub

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