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RESEARCH

# Geometry and Construction Optimization: An example using Felix Candela's Church of St. Joseph the Craftsman in Mexico

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## Abstract

This paper presents a contemporary architectural working method that encompasses digitalization and parameterization of existing buildings and optimization of new buildings designed with ruled surfaces. The method uses parametric modeling and computational structural analysis in order to simplify contemporary building processes. As an example of the application of these techniques, in this paper they are applied to Felix Candela's Church of St. Joseph the Craftsman, a design which features hyperbolic paraboloids that are considered difficult to design, calculate and build. The optimization method introduced in this paper seeks to explore different possibilities for designing and modifying buildings designed using non-standard geometry allowing them to be built out of simplified elements but also keep construction and visual properties of their shape. This method is also useful for students and young engineers to expand their skills in structural analysis, parametric modeling and optimization methods with contemporary tools.

**Keywords** Construction optimization · Geometry · Ruled surfaces · Digital fabrication · Felix Candela

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## Introduction

To talk about architecture without using the word “form” may now seem inconceivable (Forty 2013). Much of the architecture of the twentieth century is characterized by its experimentation with the use of geometric shapes in building design. Reinforced concrete is one of the most used materials for building these designs. Not only because it has the ability to cover large areas, but also because it enables physical continuity of the shape. However, in shell structures with non-standard geometry, the complexity of the geometry, the large continuous surface area and material use, demands certain phases in the building process that are costly in order to get the best final results. These include: the cost of wooden formwork, the time for concrete to stabilize and how to get the right shell shape (Jovanović et al. 2014).

Topology optimization can be described as a family of computational methods aimed at finding optimal structural layouts and configurations (Aage et al. 2014). There are a range of methods for this optimization including solid isotropic microstructures with penalty (SIMP) methods (Mariano et al. 2009), heuristic methods of topology design and the homogenization method (Bendsøe and Kikuchi 1988). The method also depends on the type of object. For example, for optimization of higher buildings there are manufacturing type constraints, in particular pattern gradation and repetition, in the context of building layout optimization (Stromberg et al. 2011). For optimal reduction of material the Evolutionary Structural Optimization (ESO) method for developing conceptual forms of complex structures can be used also (Xie et al. 2005). Although, it is powerful tool, the important steps must be chosen in order to have the best overview of the effects of optimization. Developments in technology have brought new programs which enable us to optimize, design parametrically and rationalize shapes and elements of construction, therefore making them more efficient, while still taking care of the aesthetic component of the final product (Stavrć and Wiltsche 2015). Furthemore, the structural behavior of shells is developed essentially due to their form. Some researchers deal with small modifications in the geometry of the form without modifying their initial aesthetic configuration too much (Cavieres et al. 2011). In contrast, this paper uses discretization of the shape, for construction simplification, while keeping the visual effect of the hyperbolic paraboloid (HP).

The aim of this paper is to demonstrate a method for using geometry properties for optimization and to place constructive elements in the optimal positions. The method supports appropriate material choice, structural system selection and the development of additional elements of the façade. The method supports the examination of these properties of both new and existing construction, including a consideration of mass, stress in elements, necessary process of building, architectural properties. It allows for defining analyzed parameters of both models in the form of percentages for comparison and the analysis of geometrical properties of elements for potential digital prefabrication (Tomas and Marti 2010a).

The case study used to demonstrate the method is the Church of St. Joseph the Craftsman in Mexico, designed by architect Felix Candela and built in

1959 (Wortman and Tuncer 2017). The method is undertaken using Rhinoceros with plug-ins Grasshopper, Karamba, Silvereye and FEMAP with NX Nastran. Using the method we present the geometry and construction optimization of the new contemporary variation or model of the case study building. The main characteristics of this building, which are changed to create the new contemporary model, are the execution cost and performance process. Although it will be defined in detail in the next section, the principle of shortened workflow can be seen in this scheme (Fig. 1). In the workflow the operations are lined up by order. The first three are dealing with definitions of geometry, parametrization, construction elements, material, support and loads. Operation 4 is a calculation of defined construction (using plug-in Karamba) and operation number 5 is minimizing deformation in function of number "N" (using plug-in Sivereye). Operation 6 is checking the other geometrical and construction characteristics. If they are in an acceptable range of numbers (length and number of elements, mass) and satisfy visual criteria (shape) for the process of prefabrication, then the number "N" from step 5 is the final solution. Otherwise, the next number "N" is taken and the operation 6 is repeated. The loop from 6 to 6′ will be repeated until we satisfy conditions from the operation 6, in which case the number "N" will be defined in the final step 7.

## Geometry and Construction Optimization

A level of complexity arising from the application of topology optimization procedures is the geometric rationalization of results required for translating optimized rods into buildable geometry (Aage et al. 2014). Past research suggests that massive constructive systems, depending on the stress placement, can be turned into a spatial grid, arch or beam system (Radivojević and Kostić 2011). In order to define the precise dimensions of Candela's building, we were able to use Radivojević and Kostić's (2011) drawings (Fig. 2) while geometrical methods helped us determine approximate dimensions of the starting HP.

The geometry of the Church of St. Joseph the Craftsman is formed out of two identical HPs (Moreyra Garlock and Billington 2010), obtained by using a spatial

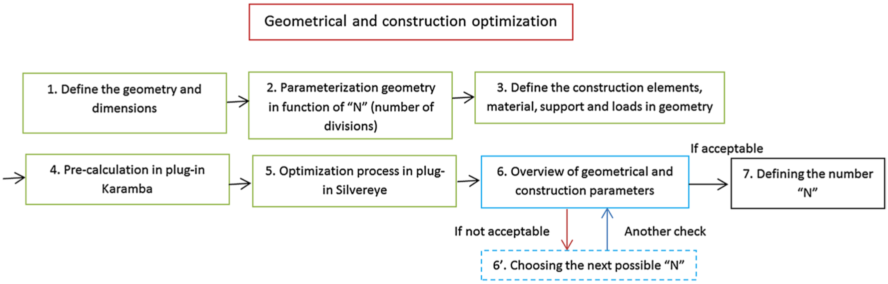


**Fig. 1** Workflow for designing and optimization of a new model

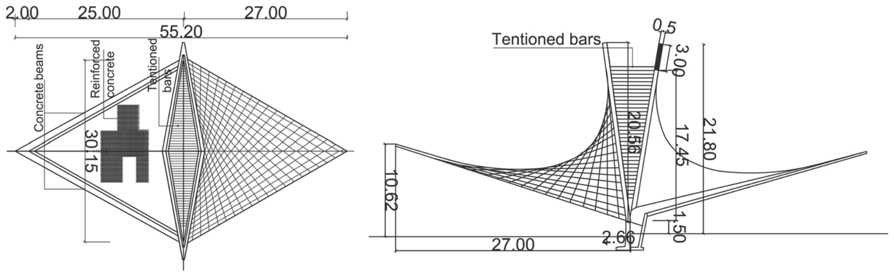


**Fig. 2** Plan and front view of the Church of St. Joseph the Craftsman in Mexico (Source: Radivojević and Kostić 2011)

quadrangle. The space between two HPs is formed for daylight illumination (Fig. 3). The other four remaining sides are used as glass walls with thin columns.

Typically, the three observation levels micro, meso and macro are distinguished in reinforced concrete construction. A new idea is to transfer this principle to shell construction. It is not absolutely necessary to construct the entire load-bearing structure on the macro level through one shell, but rather to understand the shell as part of an overall structure on the meso scale. For example, ceiling structures can be composed of individual shell elements, which in turn act as a beam (Faber 1965). To accomplish this it is necessary to think about the elements of the construction and their connections, which are the main properties. Geometry optimization of the shell can be done through shell tessellation with many algorithms (Hegger et al. 2018). Using geometry properties this type of optimization is possible on the double curved surface of the HP form between two straight lines (generatrices of both systems); thus, Candela achieved economy of construction by avoiding use of curved panels for his formwork in construction (Moreyra Garlock and Billington 2010).

To digitize the building's shape, it is necessary to analyze its dimensions and geometry first. This building is an example of ruled surface where we can use its characteristics for optimization of its geometry. In this case, geometry optimization is defined by using discretization of the geometry by planarization of the continuous, double curved form of the HP, with triangular panels. The goal is to keep a similar visual effect of the HP form, achieve good construction

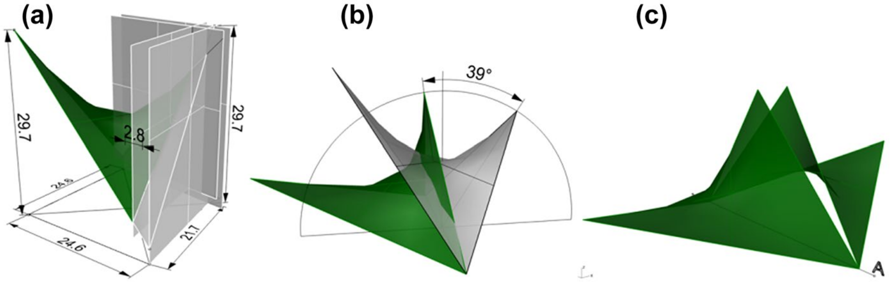


**Fig. 3** Rhinoceros drawings with approximate dimensions which demonstrate the geometry of Candela's design

properties and at the same time facilitate the process of building with prefabricated elements.

The whole geometry of the building is then defined in Grasshopper. The idea is then to modify a new HP surface using its straight generatrices. Parameterization is defined by number “N” which represents the number of divisions of HP directrices (guidelines) on equal parts in order to get straight lines (Krasić 2012). These creates the basis of the grid, for both systems of generatrices are the main rods in the construction (Fig. 4). The second step is to find the average point coordinates of every special quadrilateral and connect them with all four points. These are the second type of rods called diagonals. Triangle modules represent the planar panels, which are not susceptible to bending during construction (grid) deformation in order to form stable structural geometry. The third type of rods which connect two HPs are ties.

Then pre-calculation of the new construction design is necessary, because even though the geometry optimization represents discretization geometrical features of the shape in order to facilitate the assembling of building elements, they are also part of the construction system and all construction properties have to be satisfied. The pre-calculation process is using Karamba where we are able to define: *cross-section of elements, loads, thickness of the panels, material and support.* For material, steel type S355 is chosen, not only because of its mechanical properties, but also because of the shape of the elements and their connections. These loads are taken into account in the decision: *mass of the construction and weight of triangular panels.* For determining support three degrees of freedom (rotation around all three axis) were defined, in marked blue points (Fig. 4).

We then calculated mass and deformation of the new design and using Grasshopper all properties of construction are directly related to the number of division “N”. Changing that value all characteristics (except cross sections) are simultaneously changing as well. For every selected value “N” the Karamba calculations are represented in Table 1.

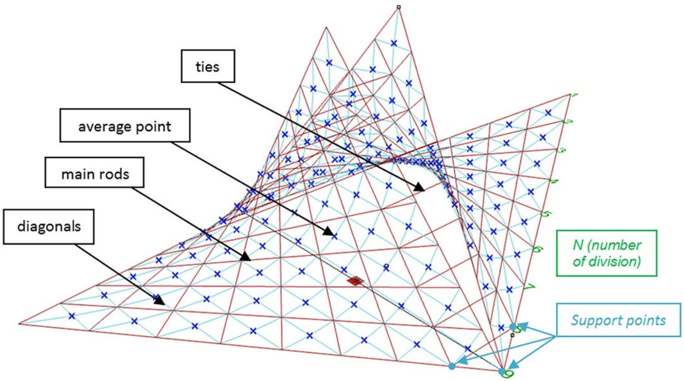


**Fig. 4** Grasshopper drawing of the position of all elements of the new model

**Table 1** Geometry and construction properties of the new HP in function of number “N”

| N (number of division) | 4 | 6 | 8 | 10 |
|---|---|---|---|---|
| Mass | 19,449 kg | 27,810 kg | 36,173 kg | 44,538 kg |
| Deformation (m) | 0.263 | 0.185 | 0.158 | 0.154 |
| Min–maximum length of rods (m) | 3.30–13.80 | 2.20–9.20 | 1.64–6.9 | 1.31–6.22 |
| Number of elements | 183 | 396 | 688 | 1060 |
| Shape of geometry | Polygonal | Polygonal | Continuous | Continuous |

The next step is to define the number “N”, which is directly related to geometrical properties of construction elements including *number and length of elements (geometrical features) and mass and deformation (construction features)*. These are all intended to be minimized for the assembling process and level of stress in elements. In order to see relations between construction properties and number “N”, the process of optimization is done in Silvereye. The goal is to find the number “N” (input parameter) for minimal values of deformation (fitness value) of the construction system. As mentioned, geometry and construction optimization are co-dependant so we compare the two most important properties of geometry and construction optimization (Fig. 5).

From Fig. 5 we can see that the value of deformation varies from N = 1–4 because of the placement of the supports, length and cross-section of the elements. After stabilization maximal deformation dramatically decreases when the value of number N > 4 and then slowly rises after N = 11. Nevertheless, divisions more then 10 aren’t analyzed further because of the large number of elements and their connections. If changes in the original shape are made in order to place planar elements, the lower boundary of the discretization must be defined in order to preserve the fluid continuity of the geometry as much as possible, as it presents the whole architectural beauty of the shape. The similarity between curve and polygonal line depends of scale and individual perception, so it is up to the designer to select the satisfactory discretization. Authors decided that options 4 and 6 are eliminated as the line from

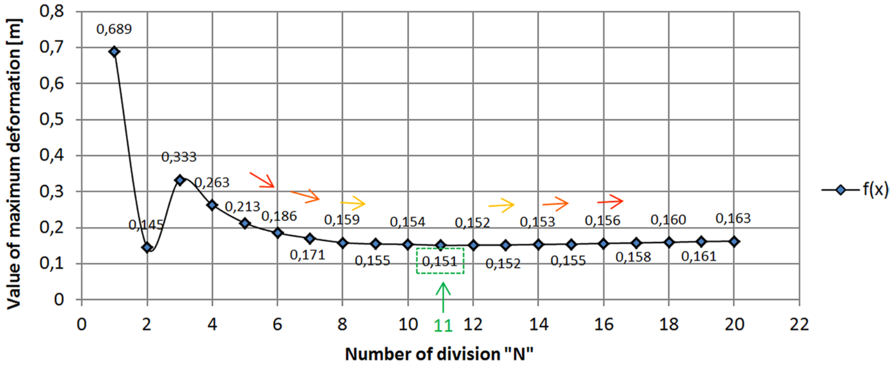


**Fig. 5** Interdependence of number of division and maximum deformation in the new HP model

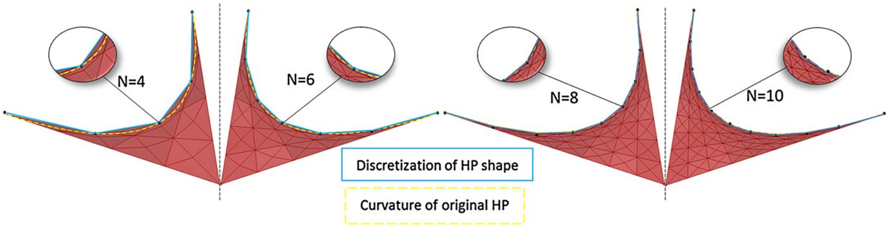


**Fig. 6** Grasshopper drawing of the shape of discretized geometry with planar panels with different "N" value

the "discretization of the original HP" shape which is achieved with division points of generatrices (blue full line) does not follow/overlap the "curvature of the original HP" (yellow dashed line). Therefore, it does not create the same effect and satisfy the visual criteria (Fig. 6).

In the end, we focus on the number and length of the elements. Even though they are inversely proportional, it can be noticed that for N = 10, length of the elements does not decrease much when compared to N = 8, but the number of elements is drastically higher. The last characteristic is mass, which is increasing with every number „N". After overviewing all parameters it can be concluded that chosen number for division is 8.

## Calculation of Structural Properties of Both Models Using Femap with NX Nastran

### Structural Properties of the Existing Building

Candela produced structures of astonishing elegance and efficiency thanks to his intuition and experience (Moreyra Garlock and Billington 2010). Even though it was an advanced approach at the time, its execution was not easy and demanded a series of precise engineering phases. As such, complications may appear in these structures as in the example of the Chapel of Lomas de Cuernavaca at Palmira in Mexico where, during the building process, the part of the structure suddenly collapsed while scaffolding was being removed. Such accident are due to problems of construction (too young concrete, scaffolding removed defectively, existence of local defects) (Tomas and Marti 2010b). That is one of the reasons that motivated us to explore a different solution. Structural system of the existing object is defined with HP shells which rely on four beams (3.0 × 0.5 m) and are connected with number of ties and supported on the ground by two large eccentric foundations. On other four sides the reinforced console beams are also supported by the same foundations. Due to all the experiments he achieved to make shell that is only 0.04 m thick (Moreyra Garlock and Billington 2010) (Fig. 7). This construction is already

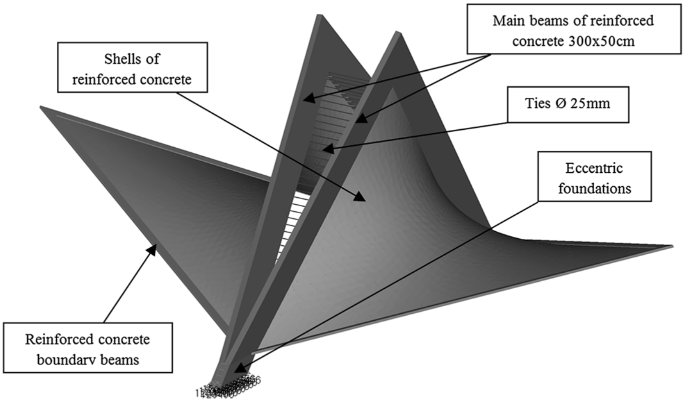


**Fig. 7** Rhinoceros drawing of the existing Church of St. Joseph the Craftsman with main constructive elements annotated

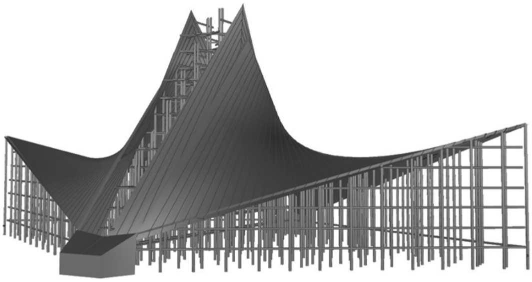
effectively optimized and is one of the most advanced buildings, not only in terms of construction system, but also building technology in that time.

The chosen geometry and material require physical continuity, which makes the process of building complicated and lenghty. It also requires a lot of precision especially during placing the formwork (Fig. 8). Structural calculations for the existing building are done with all the stated elements using FEMAP with NX Nastran. It is important to define mass and maximum deformation in the system with reinforced concrete to be able to compare the results with the calculations of the new designed building.

When analyzing stress distribution we found that maximum intensity is located in the spikes of the shell as well as connections of shells and main beams, as expected for this system. Maximum stress is 12.64 MPa as it can be seen in Fig. 9.

Figure 10 shows total translation which is located at the spikes of both shells; the maximum amount is 0.244 m. The mass of the whole construction of the existing object is 565.805 t. The structure is analyzed with geometric nonlinear theory and linear behavior of the concrete. Conditions are formed for the basic load case, which includes only self-weight of the structure. Deformation on Fig. 10 is enlarged three times.

**Fig. 8** Rhinoceros drawing of the formwork that was used for the building process of the Church of St. Joseph the Craftsman (adapted from: Smith et al. 1967)



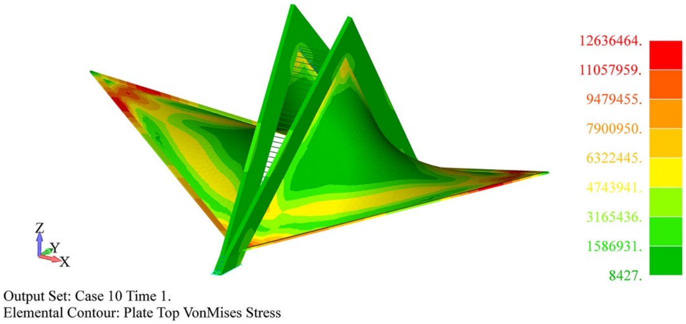


**Fig. 9** Stress distribution in the existing object—max: 12.64 MPa (FEMAP with NX Nastran)

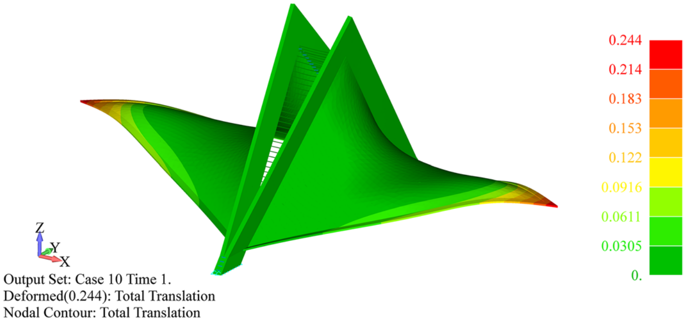


**Fig. 10** Total translation in the existing object—max: 0.244 m (FEMAP with NX Nastran)

## Structural Properties of the New Model

The authors wanted to analyze results of the calculation for the new model in the same program as they used for the built Church. All of the inputs (*position of elements, material, load and support*) are defined to be the same as in previous Karamba calculation (Fig. 11).

Points marked “123” in Fig. 11 present supports with three degrees of freedom (rotation around all three axes). Cross sections are tubular and their diameter is different for every type of element: *main rods* (*168.3 mm*), *diagonals* (*133 mm*) *and ties* (*88.9 mm*). Moreover, because of the buckling in the longest ties at the bottom, they are replaced with simple beams, which will serve only for glass panel’s position.

After the definition of all elements, connections, materials, loads and supports, the results of the stress distribution are shown in Fig. 12. Maximum stress is located on the connections of rods and it is max = 62.72 MPa.

Figure 13 presents the model of total translation, where the location of the maximum level of deformation is in the same place as it is in the existing

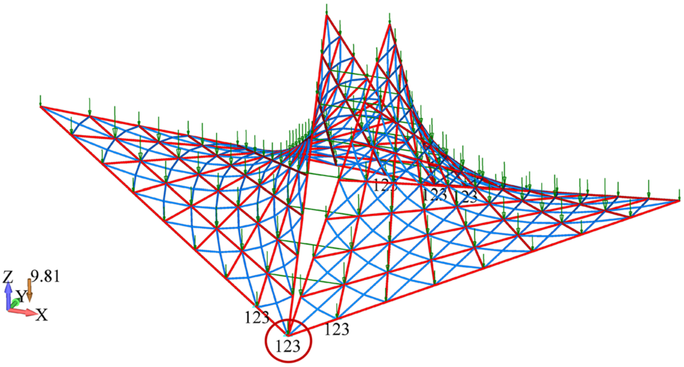


**Fig. 11** Elements and loads of the new model (FEMAP with NX Nastran)

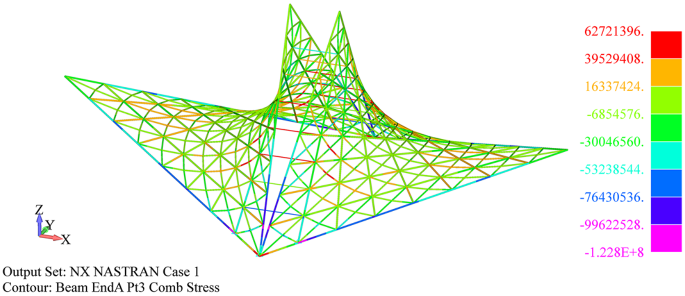


**Fig. 12** Stress distribution of the new model—max: 62.72 MPa (FEMAP with NX Nastran)

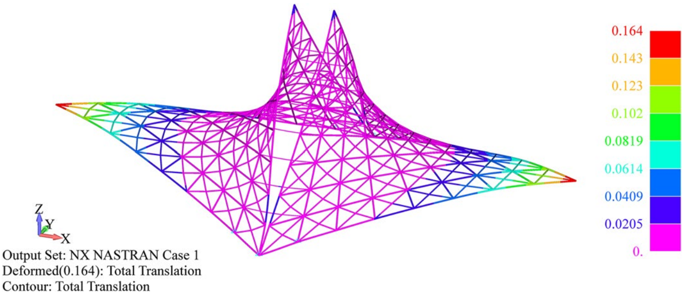


**Fig. 13** Total translation of the new model—max: 0.164 m (FEMAP with NX Nastran)

building. This value is shown in the contour view and it is max = 0.164 m. Total mass of the object is 36.039 t. This value is less than stated previously, because of the reduction of cross sections during the design, but the value of deformation has not varied a lot.

## Comparison of Construction Properties of the New and the Existing Building

The comparison of the construction properties of the new and existing or referenced building is shown in the Fig. 14 according to the previous analysis in the paper. There are two charts with mass and deformation characteristics presented in percentages.

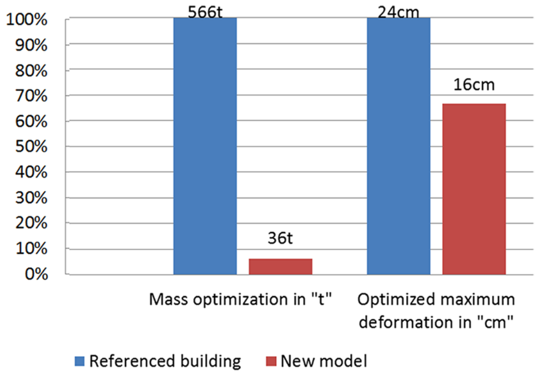
The first chart defines the percentage of mass of the new and referenced construction, where it can be seen that the choice of different material and construction elements can reduce mass by *about 16 times*. The second chart presents analysis of maximum deformations, where the new construction has *around 66%* of maximum deformation of the existing construction. This comparison demonstrates the level of control of the methods used throughout the previous process. Moreover it shows that wide range of possibilities of different analyses in contemporary technology can be effective on these shapes.

The use of optimization techniques in the design process of structures widens the field of use of computers and allows the user to obtain optimum designs for stated design conditions. There are other researches that are achieving optimization due to transformation of the entire geometry (dimensions, thickness, curvature), while preserving aesthetic appearance similar to that initially planned by the designer (Tomas and Marti 2010a). In future research the combination of these two methods could be explored.

## Digital Fabrication of Elements

After analysis of the construction and geometry, optimizing and finding element's number and positions, elements are placed in the construction system (Fig. 15). Optimal design of rods offers, by comparison, a path for closer integration between optimization and fabrication, and it is therefore arguable that they should take a more prominent role in the investigations of the field (Aage et al. 2014).

**Fig. 14** Percentage of mass and maximum deformation



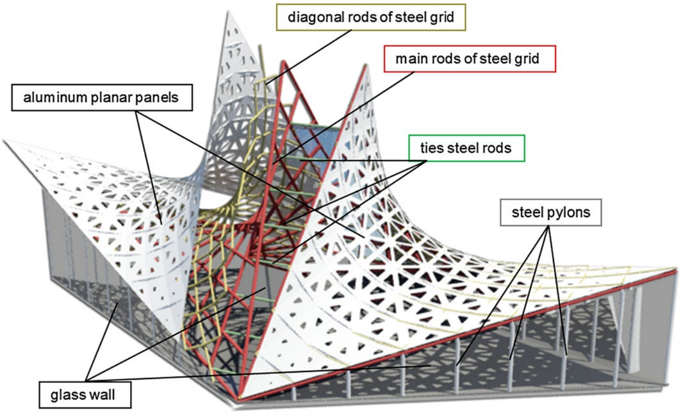


**Fig. 15** Scheme of all elements of the new model construction as well as facade expression (Rhinoceros)

Using technology the next step is to digitalize elements for potential fabrication. This is an indicator of the geometrical properties of the elements.

Firstly, we can define types of rods in the construction. Rods are divided in five groups regarding their length which is from 1.4 to 6.9 m. Figure 16 demonstrates how every group of elements is distributed through the model. Table 2 shows specifications of every group length and the number of elements as well as the percentage of elements that the group covers in the whole structure. It can be concluded that most of the elements are from 1.64 to 4.65 m long and only around 6% are from 5.08 to 6.90 m. All of the 5th group rods are ties. The total number of rod elements is 688. This geometrical configuration is beneficial as the main rods, which have the biggest percentage of stress, are the shortest and the longest ties have only tension.

The second phase is prefabrication and division of panel's area. The groups are formed depending on the surface area of the panels. This analysis can show the curvature of the surface, as the zone with the smaller panels has bigger curvature

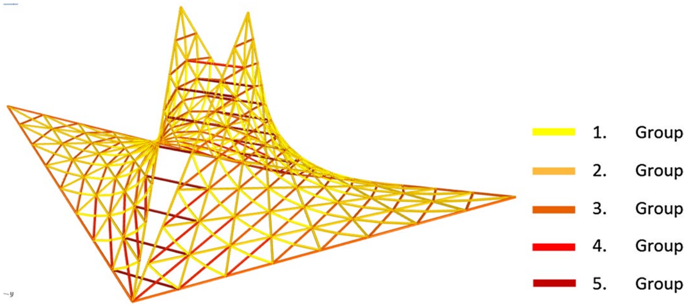


**Fig. 16** Grasshopper drawing of five groups of elements divided by length

**Table 2** Group's specification of rod elements of the new model

| | 1st Group | 2nd Group | 3rd Group | 4th Group | 5th Group |
|---|---|---|---|---|---|
| Length of the rods (m) | $L = 1.64 - 2.15$ | $L = 2.36 - 3.57$ | $L = 3.74 - 4.65$ | $L = 5.08 - 6.22$ | $L = 6.32 - 6.90$ |
| Number of the rods in group | $n = 198$ | $n = 314$ | $n = 136$ | $n = 26$ | $n = 14$ |
| Percentage of rods in every group (%) | ≈ 29 | ≈ 46 | ≈ 19 | ≈ 4 | ≈ 2 |

than the area of the bigger and identical panels. When adding all numbers from Table 3 the total number of panels is 512.

The most curved part of the surface is the middle of the HP where the first group is. The difference in the surface areas in every group varies. In the first group it is 0.19 $m^2$, then it rises to 0.38 $m^2$ in the second, third and fourth group and finally the fifth group has four identical panels (Fig. 17). Most of the panels are from the first three groups (90.61%). According to the surface area of the panels it can be concluded that the distribution during the process of building will not be complicated, as the panels are from 1.54 to 3.26 $m^2$.

Every panel is attached to three intersection points of the rods. Weight is also not the issue during assembling, as its amount is around 10 $kg/m^2$. Composite aluminum panels are fireproof, water resistant, with excellent heat and accoustic insulation. Some of the aesthetic values are (1) surface flatness and smoothness, (2) superior weather, corrosion and pollutant resistance, (3) even coating, (4) super peeling strength, (5) impact resistance, (6) lightweight and easy to process and maintain. As they can be custom made, and all dimensions are specified, it is possible to make prefabrication precise (Lee et al. 2018).

Finally, it can be noted that in many topology optimization procedures, certain regularization is necessary in order to control the physical size of structural members appearing in the new design (Aage et al. 2014). Although these dimension values apply only to this example, this process is not only defining overall properties about construction, but helping in practical digitalization of the elements as well. It facilitates organization in the whole structure and gives better input when it comes to construction process. Figure 18 shows the final result of the new building's design. Given the change in the construction system it is possible to cover the spatial grid with lightweight aluminum panels with openings which can provide more daylight in the Church. There is a lot of freedom in design options. The planarization of the panels enables placing glass in place of the panel's openings.

One deficiency of the building process concerns the precise spatial placement of the rods and their connections. It is planned to start from the support placement, and then to be tied with matching rods. It will be necessary to finish the middle of the object first in the shape of cantilever going to the ends. In future work such issues have to be thought through in more detail. For example, when it comes to the production process one of the priorities is to create a safe waterproof shield for the building, therefore, the shell element's connections must be designed as continuous.

**Table 3** Group's specification of the panels of the new model

| | 1st Group | 2nd Group | 3rd Group | 4th Group | 5th Group |
|---|---|---|---|---|---|
| Area of the panels ($m^2$) | A = 1.54 – 1.73 | A = 1.80 – 2.18 | A = 2.20 – 2.57 | A = 2.63 – 3.01 | A = 3.26 |
| Number of the panels in group | n = 104 | n = 204 | n = 156 | n = 44 | n = 4 |
| Percentage of the panels in every group (%) | ≈ 20 | ≈ 40 | ≈ 30 | ≈ 9 | ≈ 1 |

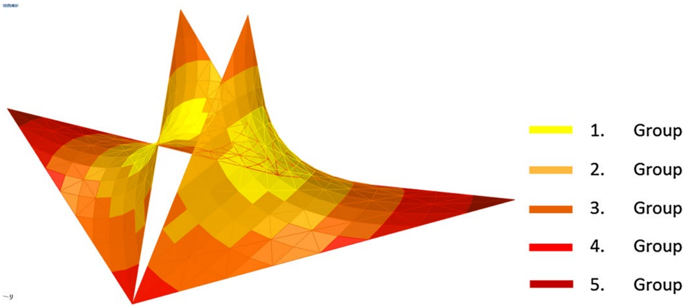


**Fig. 17** Grasshopper drawing of five groups of panels divided by area

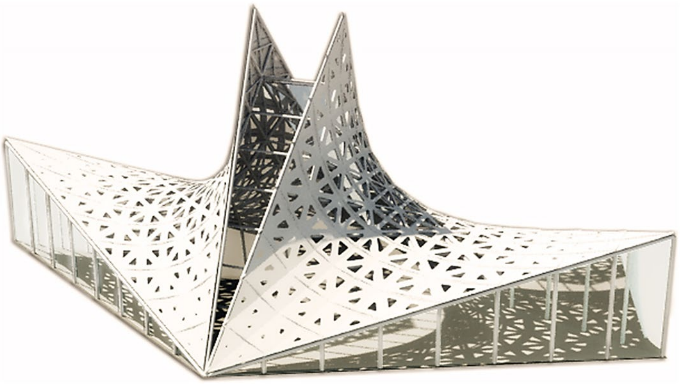


**Fig. 18** Final model of the new building

## Conclusions

New developments in technology have spread across all the areas of expertise in architecture and civil engineering, making new technology and processes available in the building process. Complex geometric shapes can now be achieved using prefabricated elements and the visual identity of the final object can also be preserved at the same time.

The geometry optimization method described in this paper helps in defining the element's *shape, position and dimensions* in order to analyze its construction properties. Both are co-dependant, as geometric properties have influence on some of the construction characteristics and vice versa. Together they form elements which can be precisely analyzed for the process of fabrication. This process is one of the main benefits of efficient building. Now, not only will the process be quicker and less expensive, but also less risky when it comes to the process of building.

This paper presents an analysis of a case study building, taking Candela's built object as a good example of HP shape design, and offers a contemporary solution with different materials and changes in the constructive system which can make the building process much easier. Candela's significant structures were all of HP forms (Moreyra Garlock and Billington 2010). This research shows methods which can modify this approach to contemporary designing, optimizing the construction and geometry in ruled surfaces geometry with strictly defined dimensions. However, it is not possible to use this method for more free-form and complex geometries as the starting point. Construction properties, such as mass and deformation, of the new and referenced HP shape are compared in order to verify the right methods. In addition it is important to see in which ways are contemporary programs and technology upgrading the process of modelling, digital fabrication (Tomas and Marti 2010b) and optimization. The process is not only important for existing objects such as Candela's Chapel, but also for new design works.

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