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*Professional paper*

# APPLICATION OF GEOMETRY IN ARCHITECTURE, FOCUSING ON METAL CONSTRUCTIONS

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**Abstract**

Geometry in architecture refers the art of designing and construction of buildings and structures based on different mathematical shapes and forms. It involves the application of geometric principles to create aesthetic, functional, and structural designs. This paper aims to present the importance of geometry in the design of architectural and other metal structures. The rationalization methods used is discrete geometry, structured mesh analysis, and numerical optimization. The paper includes several practical cases, which have faced various problems in the production process of metal constructions intended for use in architectural buildings and other structures, and how they have been solve. Furthermore, there is included an algorithm for optimizing the material in the cutting process so there is as little waste as possible, analyzing also the role of digital software.

*Keywords:* Architecture, metal constructions, discrete *geometry, optimization, digital software.*

## 1. Introduction

The geometry in architecture has been a foundation for the creation of form, being the primary language that determines spatial arrangement, structural order, and visual representation. It has molded not just the realities of building for millennia but also the aspirations of societies - especially the artistic impulses of those with wealth and power. In the more recent decades, developments in the field of technology, material behavior, and digital fabrication have led to a huge expansion of what is possible in geometry for design, in particular when it comes to designing free form structures and complex metalwork.

Freeform architecture, which is defined as non-rectilinear, non-standard, smooth and free form design features, has become a new frontier of design beyond normal design practice. Metal, being a highly versatile material, provides strength, flexibility and precision to achieve such demanding geometry. However, transforming a mathematically complex surface into a realizable, manufactural, and cost-effective metal structure, is about much more than just an artistic vision, it involves a profound mathematical understanding and real-world optimization methods.

This paper investigates the fundamental relation between geometry and metal construction, and the way in which mathematical techniques and procedures can help to overcome the challenges of spanning complex design with the intent to realization. In particular, the work focusses on the methods from discrete geometry, for mesh structuring and rationalization and the use of numerical optimization techniques. Rationalization becomes crucial for this type of metal construction, driven by the fabrication limitations, material properties and cost for solutions design. Additionally, using our professional experience, we present a few case studies drawn from real world, where problems related to the production and installation of metal structures were effectively solved by using geometrical reasoning. One area, which was targeted for practical benefit, was an algorithm that allows optimizing the usage of material when cut, which

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results in substantially less waste. The contribution of digital tools, as well as the software environments, that enable these processes is also discussed. The aforementioned involve various kinds of computer technology such as parametric design, computational design, and simulation software, which make possible to analyze and optimize complicated forms in a high accuracy level and less time-consuming way.

With theoretical inputs and some practical examples, the paper shows not only the geometry to be an inspiration for the architectural form, but it becomes essential tool for treatment of real engineering problems, mainly in the severe industry branch – metal construction.

## 2. Application of geometry in architecture

In recent years, the architectural geometry community has increasingly turned its attention to the complex challenges presented by discrete freeform structures. While continuous geometry has long been a subject of architectural interest, the transition to discrete representations - particularly in the context of fabrication, structural optimization, and material efficiency - has opened a new frontier of inquiry. Discretization is not merely a geometric simplification; it is a crucial step toward making ambitious architectural forms realizable with current technologies and materials, especially in metal and glass construction. Despite the growing number of applications, many fundamental questions remain open. Issues such as the aesthetic arrangement of meshes, the planarity of faces, and the optimization of nodes in supporting structures are far from trivial. These problems are further complicated by the need to balance design intent, material constraints, structural logic, and fabrication feasibility. As such, discrete geometry in architecture represents not just a technical necessity, but also a rich design space that demands new methods, tools, and interdisciplinary collaboration. As researchers engaged in this evolving field, we see significant potential for innovation in both theory and practice. The intersection of computational geometry, digital fabrication, and architectural design offers fertile ground for new discoveries that could shape the future of how complex forms are conceived and constructed. Far from being a solved problem, the rationalization and optimization of discrete freeform structures remains a vibrant and essential area of research. Freeform buildings and construction are an exciting development in the design and construction of buildings, based on dynamic, fluid like forms to replace the more conventional rectilinear buildings. Freeform architecture, in contrast to rectilinear architecture (where most structures are based on rectangles or squares and their combinations), uses curves and other shapes that are irregular in appearance. The result is a series of visually stunning, sometimes organic images that challenge all preconceptions of built architecture.

**Figure 2.1** Metal construction for factory “Metal Group”, in Gjilan, Kosovo (2024)

**Figure 2.2** Metal construction for a factory in Kumanovo, North Macedonia (2024)

The progression of freeform architecture is significantly driven by advancements in digital design tools, such as parametric modeling and computational geometry. These innovations have equipped architects with the ability to effortlessly model complex forms, thereby enhancing the creative and technical possibilities within the field. Equally as essential are advancements in material science and construction techniques, which allow for the realization of custom elements, often made from steel, glass or composites. Design free forms are often inspired by nature, the freeform can take on the curve of a landscape line, the sinuosity of a biological form, or the flow of water, etc. This organic sense not only determines the aesthetics, but it also brings architecture closer to the environment. More than looks, freeform design disrupts familiar ideas of space, form and function. It unlocks the possibilities of experiential design, producing spaces that feel dynamic, expansive, and alive. In the process, it is still stretching the boundaries of what can be achieved in terms of architectural ingenuity.

*2.1 Gaussian curvature:* For a structure to be statistically stable, it needs to be in equilibrium with the external forces it is subjected to. With the help of modern computer programs, different kinds of numerical methods can be used for form finding. One type of these are the geometric stiffness methods, which are material independent. A particular example of this is the Force Density Method, which is based on the ratio of force to length. When discretizing free form surfaces, studying curvature behavior is essential. One way of measuring is by Gaussian curvature, which is a scalar that is the product of minimum and maximum curvatures, which are perpendicular to each other. It is expressed at every point in the surface the same as the formula below:

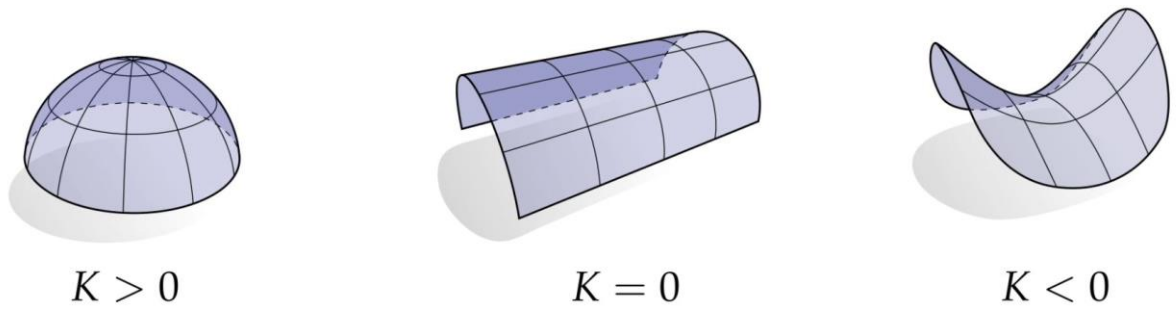


**Figure 2.1** Interpreting the Gaussian curvature's value

The sign of a Gaussian curvature is of importance when mapping panels on a surface, particularly for hexagonal grids.

*2.2 Meshes and other methods of surface realization*

A mesh is a structured network of polygons used to approximate complex surfaces for analysis and fabrication. Each piece of the mesh (called a face) is connected to edges and vertices (corners), creating a network-like structure. Meshes are essential tools when working with freeform surfaces, especially in metal constructions, because they allow designers to translate smooth, mathematically defined forms into physical elements that can be built.

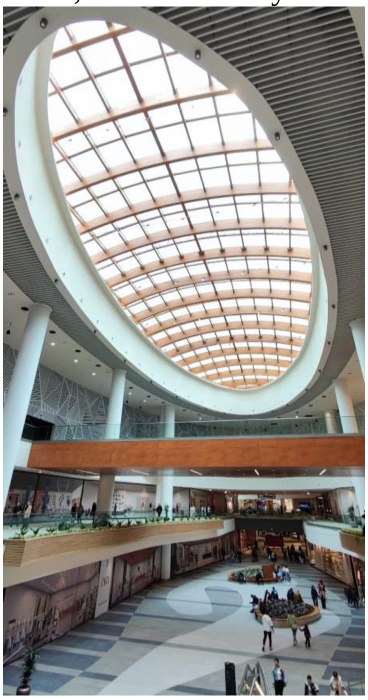

**Figure 2.2.1** Quadrilateral mesh in Prishtina Mall (2022), Kosova

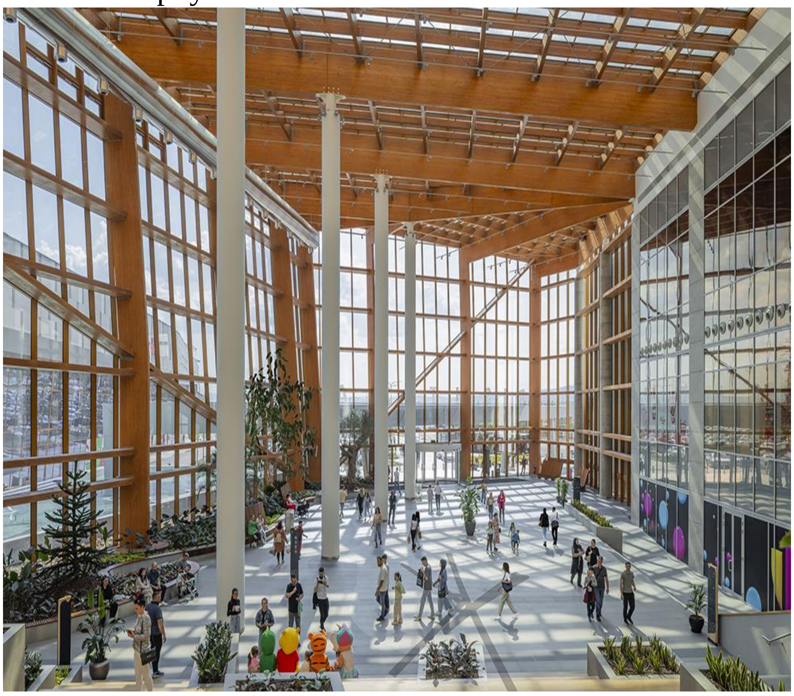

**Figure 2.2.2** Combined meshes (triangle and quadrilateral) in Prishtina Mall (2022), Kosova

To realize freeform surfaces, a common way is by dividing it into segments, known as discretization. The discretization methods vary in number of element face edges, node complexity, etc. Planar elements are often preferred since the production costs generally are lower, due to curved elements, often, they require a unique mold to be created for each element. We will cover here triangular, quadrilateral, and hexagonal meshes. Obviously, any of the meshes has its advantages and disadvantages from the other one.

**Table 2.2** Comparison table of different meshes

| Mesh Type | Advantages | Disadvantages |
|---|---|---|
| Triangular Mesh | - Fits any surface, even with high curvature<br>- Structurally very stable<br>- Simple algorithms available | - Fabrication complexity at joints<br>- Panels often non-planar<br>- Visual roughness without dense meshing |
| Quadrilateral Mesh | - Easier fabrication with flat panels<br>- Better for regular surfaces<br>- Smoother visual appearance | - Harder to mesh very complex surfaces<br>- Requires careful optimization to avoid distortion |
| Hexagonal Mesh | - Aesthetic appearance<br>- High efficiency in material usage for some designs<br>- Good for lightweight structures | - Difficult to fully cover arbitrary surfaces without irregularities<br>- Complex joints |

As we can see from the Table 2.2, triangular meshes may be easier to deal with from the perspective of representing a given surface S. But, that is not always the case, because in a triangle mesh, typically six beams meet in a node. Based on experience with triangular meshes, the per-area-cost is higher than with quadrilateral meshes. Generally, one has less steel, more glass, meaning less weight. On the other hand, at a hexagonal mesh only three beams are joined at each node, resulting in lower manufacturing costs. A definitive answer of which mesh is of better usage could not be given, it all depends from the project.

Therefore, we often see a combination of different geometrical shapes. This is also because it is not always possible to cover all the space with a single geometrical shape, as it is also showcased in *Figure 2.2.2*

It should be also mentioned that there is the so-called T-junctions, where two faces meet the same edge of another face. T-junctions in meshes are not desirable, but modeling softwares, like CAD for example, may generate them in large amounts.

## *2.3 Optimization problems*

In the design of complex architectural forms - especially freeform surfaces - shape optimization has become an indispensable tool for bridging the gap between conceptual geometry and buildable structure. Shape optimization refers to the process of systematically adjusting the geometry of a surface or structure to fulfill multiple performance criteria. These criteria may include reducing material waste, ensuring structural efficiency, simplifying fabrication, or enhancing the visual quality of the form. Unlike purely aesthetic modeling, optimization is goal-oriented and relies heavily on mathematical formulations and numerical methods to evaluate and improve the design based on defined constraints.

One of the key challenges lies in managing the degrees of freedom of the surface: how much a shape can be modified while still satisfying the design intent and architectural constraints. For example, if a surface must consist only of planar panels (for ease of metal fabrication), then the

optimization process must adjust the geometry in such a way that each panel becomes as planar as possible without distorting the overall appearance. Similarly, node positions in a supporting steel structure must often be optimized to avoid complex or costly connections.
This process is inherently multidisciplinary, as it combines knowledge from computational geometry, structural engineering, material science, and digital fabrication. Optimization often happens iteratively, where geometry is tested, modified, and refined based on real-world limitations such as bending tolerances, or available fabrication technologies. Ultimately, shape optimization does not replace architectural creativity but complements it. It enables architects and engineers to explore more ambitious forms while maintaining control over performance, cost, and constructability. As computational tools continue to advance, optimization techniques are becoming more accessible and integrated into the early stages of design, allowing for more intelligent, data-informed decisions in the realization of complex architectural geometries.
A vital role is in the material cutting process, which is critical for efficient use of sheet metal and profiles in fabrication. In such cases, algorithms are used to determine the best way to nest individual panel shapes onto standard-sized sheets and profiles with minimal waste. This process, often called 2D nesting optimization, uses computational techniques such as simulated annealing, genetic algorithms, or greedy heuristics to explore thousands of layout permutations and select the one that maximizes material usage. The result is a substantial reduction in material cost and environmental impact, making the project more sustainable and economically viable.

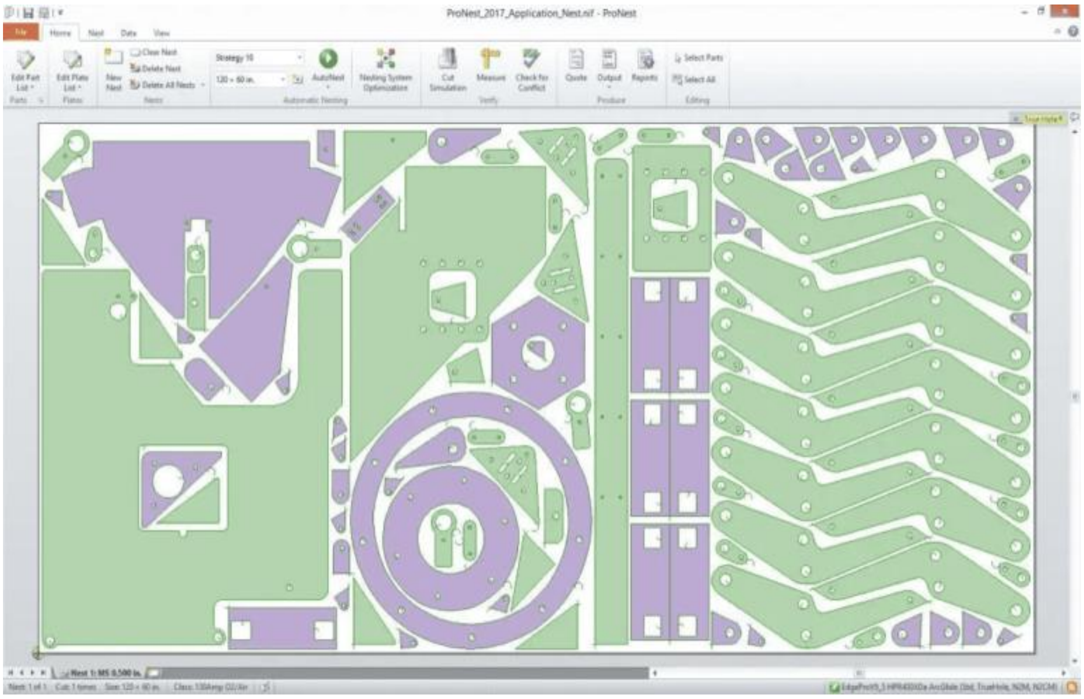

**Figure 2.3.1** Example of nesting metal parts in a software.

Some issues we’ve faced in optimizing the material is for example when we had this project for producing 3200 meters of railings, with 1183 different assemblies. The railings were bended with a radius of 130 with 90°, but we didn’t had the capability to bend it in the desired radius. So we had to buy pieces of curved pipes with radius 130 (which we could find only in radius 125) and weld them with the other parts (2982 pieces of curved pipes were needed in total). Now the issue here is that the optimization I had was for radius 130, and since now I’m changing the radius to 125, I had to reoptimize all of the project, which was a lot of work that could take weeks. What we did was to substract the circumference of the curves with radius 130 from radius 125, and that way we would find how much less material we would need to order (check figure 2.3.2).

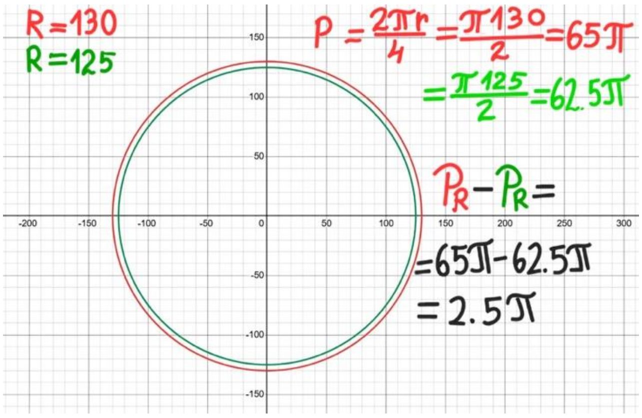


**Figure 2.3.2** Calculating the circumference difference between the two radiuses.

So now that we know the circumference difference between the two radiuses (130 and 125), which is approximately 7.854 mm, we can easily find out how much less material we need, by multiplying the total number of curved parts needed with the circumference difference, which is approximately 23,421 mm.

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