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Smart optimization design methods and software for spatial structures derived by parameters

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Abstract

This paper introduces innovative, parameter-driven smart optimization design methods for spatial steel structures, offering an average steel consumption reduction exceeding 8%. Central to these methods is the generation of numerous parametric models for efficient, material-optimized solutions. Current parametric optimization methods, often limited to specific structural forms, face challenges in diverse and complex applications. To address this, two novel or improved multi-parameter smart design implementations are proposed, enhancing the versatility of smart design approaches. These include a comprehensive parameter-driven method for standard spatial grid structures (like three-centered circular reticulated shell structure) and a zoning-based method for arbitrary structures requiring minimal boundary modeling. These methods facilitate rapid, automated model generation for comparative analysis, optimizing material usage and modeling efficiency. Our research team has developed and validated a spatial structure smart design software through practical projects, demonstrating average material savings of exceeding 8% even in mature designs, thus significantly contributing to economic benefits increasing.

Keywords: smart optimization design, parameter design, building material saving, zone-based modeling

1. Introduction

Spatial structures, characterized by their numerous components and diverse and complex shapes, have emerged as a critical area for design optimization. Optimizing the design of spatial structures can effectively reduce the consumption of building materials. Additionally, it has the potential to lower construction costs and enhance economic efficiency. Parametric design optimization of spatial structures, among these optimization efforts, has attracted significant attention from researchers. [1][2]

Parametric design enhances traditional point-and-line modeling by establishing mathematical relationships between points and lines, described with quantifiable parameters. This approach links design elements so that when one changes, others adjust based on predefined mathematical relationships, significantly boosting flexibility and efficiency. The most prevalent parametric design approach in construction combines Rhino curve and surface modeling software with its Grasshopper parametric plugin for complex surface parametric design. Many design teams globally use this approach for large, complex spatial structural projects due to its ability to overcome challenges of time-consuming modeling and modification difficulties. It provides spatial structure optimization with greater degrees of freedom and possibilities.

However, parametric design comes with challenges like a steep learning curve and modeling complexity. To address these, this paper proposes two smart design methods for spatial structures based on parametric design principles: a parameter-driven method for standard spatial grid structures (e.g., three-centered circular reticulated shell structure) and a zoning-based method for arbitrary structures needing minimal boundary modeling. These methods offer advantages such as a lower learning threshold, simplified modeling, and ease in handling complex models compared to traditional methods, making them suitable for various engineering projects. By employing these smart design methods, we can efficiently optimize spatial structure design, significantly reducing building material usage and enhancing economic benefits in the construction industry.

2. The smart design method for spatial structure

The general process of spatial structural design is as follows: (a) Create a geometric model, mainly including nodes and members. (b) Assign physical information to nodes and members. (c) Apply loads and boundary constraints to the structure. (d) Perform analysis and check or optimize members and nodes. This is a method of spatial structural design from micro to macro. In most spatial structural design software, the geometric model is based on points and lines. For complex models, designers need to carry out tedious and difficult modeling work, which not only consumes a lot of time but also makes it difficult to respond to adjustments in design schemes.

To address the challenges, this paper proposes a multi-parameter-driven smart design method for spatial structures. The method includes the following steps: (a) For various spatial structure forms, extract parameters for all geometric models and determine variable parameters and their ranges. (b) Create a load template. The load template is a parameterized method that describes the distribution of loads under various conditions on spatial structures. (c) Create constraint styles. The constraint style is also a parameterized method that describes the distribution of constraints. (d) Based on multiple variable parameters, batch-create spatial structure models and design them. Select the optimal solution based on evaluation criteria (such as material usage). For common spatial structure standard models, it is possible to create geometric models in a fully parameterized way. For non-standard, irregular spatial structures, a zoning-based method is proposed. The following examples illustrate the smart design method described above using models of a spherical shell, a three-centered circular structure, and a complex spatial structure described by a NURBS surface.

2.1. The single-parameter and multi-parameter coupled optimization algorithm

The core idea of the smart design method for spatial structures is to create a large number of models for comparative optimization based on multiple variable parameters. The single-parameter and multi-parameter coupled optimization algorithm is the core algorithm of smart design. Firstly, the influence of a single parameter on the structural performance is analyzed. Then, the importance of each parameter is ranked, and the coupled effects of each parameter are combined for comparison. Finally, the optimization scheme is determined. The optimization control parameters for different structural forms are different, and the values of parameters are different, leading to different steel consumption in the generation of structures. After optimizing each parameter, multi-parameter coupled optimization is conducted to obtain the final optimal model. The algorithm flowchart is shown below.

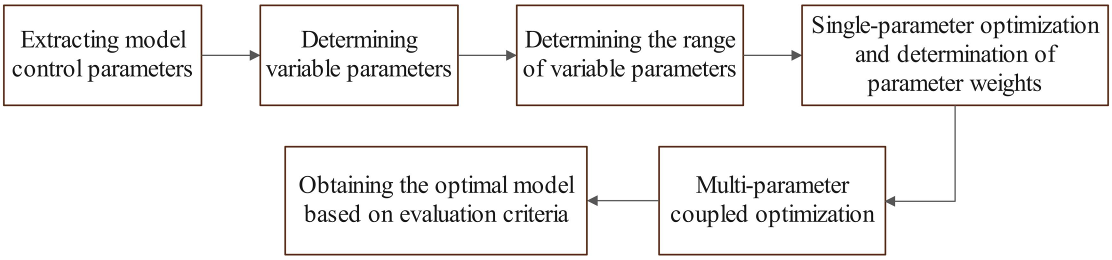
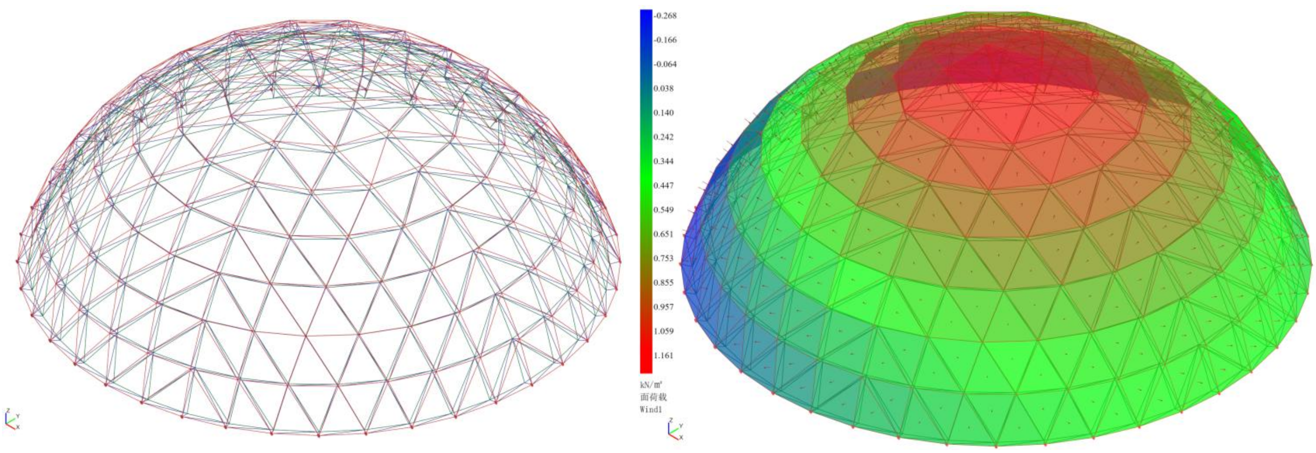


Figure 1: The flow chart of single-parameter and multi-parameter coupled optimization algorithm

The single-parameter optimization algorithm can be performed using exhaustive search, which is suitable for all spatial structure parameterized designs. However, if the multi-parameter coupled optimization uses exhaustive search, it will consume a lot of computing time. Therefore, strategies such as binary search are usually adopted to accelerate the algorithm.

2.2. The smart design method for standard models

The standard models of spatial structures mainly include flat grid, cylindrical shell, spherical shell, etc. These standard models are generated according to specific rules, making it very easy to extract all control parameters of the standard models. Taking the Kuwaiti-type double-layer spherical shell as an example, its shape parameters include the bottom radius, rib division ratio, number of sectors, rise, and thickness, totaling five parameters. Currently, many spatial structural design software can automatically create spherical shell models based on the parameters mentioned above. In contrast to traditional methods, the smart design method proposed in this paper defines the rib division ratio, number of sectors, rise, and thickness as variable parameters and specifies their ranges. The smart design program will batch generate geometric models based on the variable parameters of the spherical shell. Then, based on predefined load templates and constraint styles, the program automatically applies loads and constraints to all models, generating computable spatial structure models. The smart design program automatically compares hundreds or thousands of spatial structure models based on predefined optimization objectives (such as minimizing material usage) and selects the optimal model.

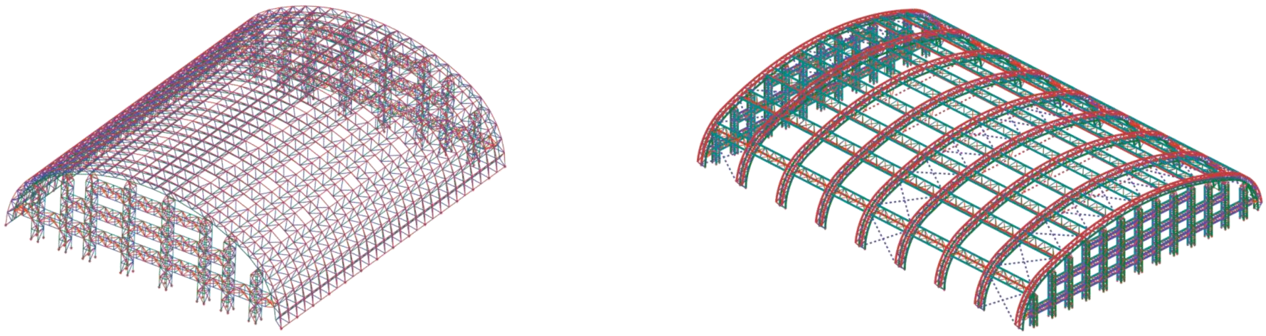


(a). Kuwaiti-type double-layer spherical shell (b). Wind load assigned by load template

Figure 2: Kuwaiti-type double-layer spherical shell and applied load template

2.3. The smart design method for customized models

In addition to the standard models mentioned above, many complex models, although difficult to describe their shapes through simple rules, can still be expressed by using more control parameters than standard models. We refer to these models as customized models, and many complex practical engineering projects can be expressed by multi-parameter customized models. For example, the three-centered circular structure model uses over 30 control parameters, including at least 8 variable parameters. The three-centered circular structure is a spatial grid structure suitable for large-span warehouse structures, mainly including two forms: three-centered circular grid shell and three-centered circular truss, as shown in the figure below. Compared with standard spatial structures such as flat grid frames, cylindrical grid shells, and spherical shells, the geometric shape parameters of the three-centered circular structure are more complex. Describing the three-centered circular structure with parameters and automatically applying loads is more difficult than standard models such as spherical shells. This paper organizes the geometric parameters of the three-centered circular grid shell and truss separately, proposing at least eight variable parameters. The smart design program automatically applies loads and constraints to the overall structural model based on the collected load information and the predefined method of load application. The variable optimization parameters of three-centered circular grid shell structure are mainly including height, thickness, grid count, grid length, arch height, bending moment adjustment coefficient, void ratio and so on. Similarly, the variable optimization parameters of three-centered circular truss structure are including height, thickness, grid count, grid length, arch height, chord length, truss count, bending moment adjustment coefficient and so on. In the third section, the three-centered circular structure will be used as a case study for smart design.

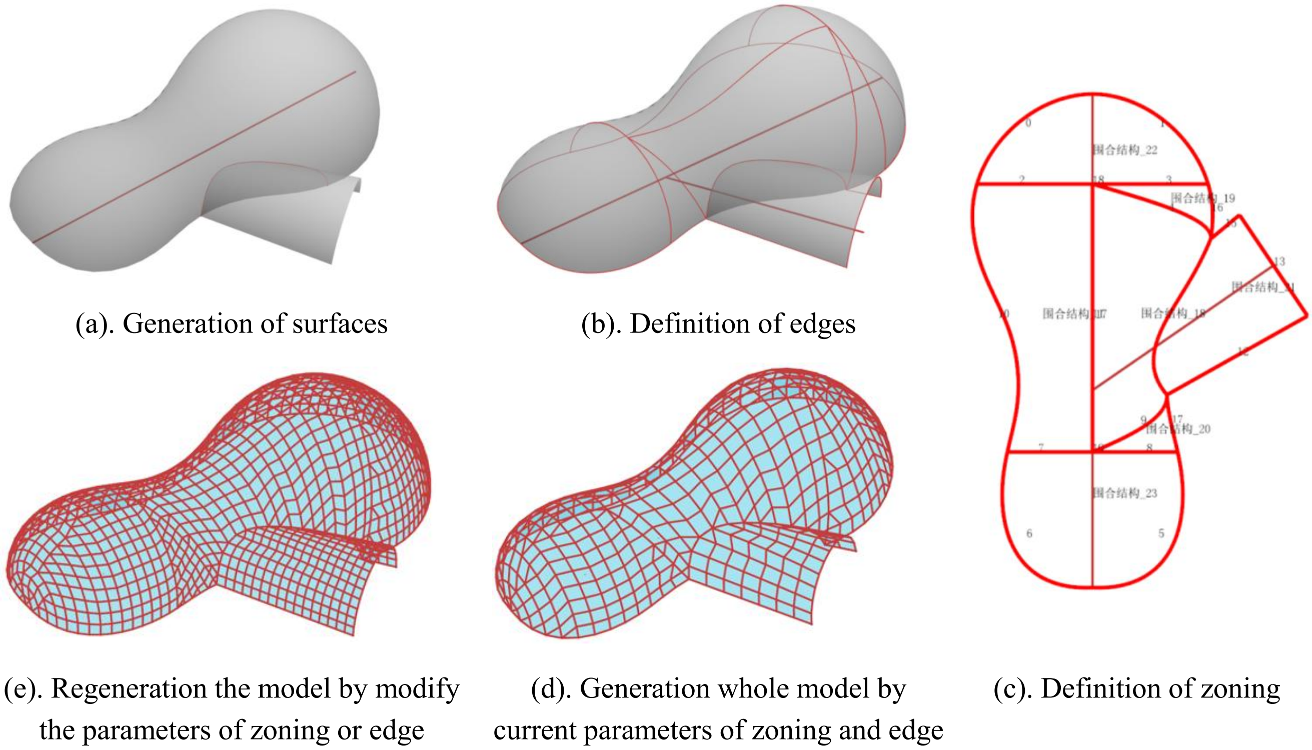


(a). Three-centered circular grid shell structure (b). Three-centered circular truss structure

Figure 3: Three-centered circular grid shell and truss structure

2.4. The zoning-based smart design method for complex surface models

Many spatial structures are created based on complex and irregular surfaces, which are difficult to fully express using multiple parameters. The figure 4 shows a complex surface structure composed of NURBS surfaces and cylinders. Directly partitioning the grid on a complex surface is a very difficult task, and it is challenging to have a universal algorithm to solve the problem of creating high-quality spatial grids on arbitrary surfaces. To solve the problem of modeling spatial grid structures based on such complex surfaces, this paper proposes a zoning-based smart design method for complex surface spatial structures. The design steps are as follows:



(a). Generation of surfaces

(b). Definition of edges

(e). Regeneration the model by modify the parameters of zoning or edge

(d). Generation whole model by current parameters of zoning and edge

(c). Definition of zoning

Figure 4: Zoning-based smart design method for complex surface structures

(a). Automatic generation of smart structural surfaces based on defined geometric elements such as surfaces, surface intersection lines, curves on surfaces, edges, axes, angles, and guide lines using various geometric algorithms.

(b). Divide the whole surfaces by edges into different zoning. The edges are assigned parameters like the number or length of each grid. Furthermore, the step size, minimum number, and maximum number of edge divisions are also be defined.

(c). Determine the grid generation methods and parameters of each zoning. The grid forms, the thickness of grid and other optimization parameters are defined at the same time.

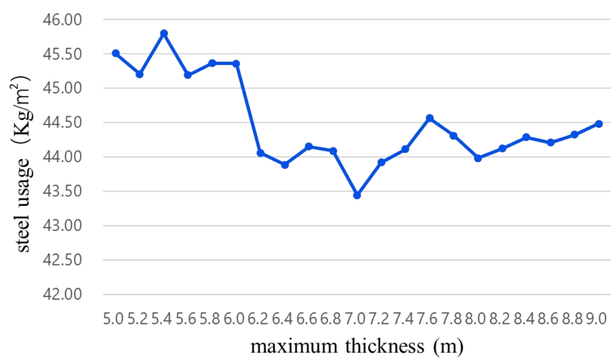
(d). Generate the whole model by current assigned parameters of edges and zoning. Node projection based on surfaces defined in step 1 to determine the direction of the lower chord, followed by the generation of the lower chord smart structure of the pyramid or truss based on different thicknesses (if assigned). The loads and constraints are applied in this step.

(e). It is easy to regenerate the model by simply modify the parameters of zoning or edge. For example, the division count of edges is enlarged so that the grid amount becomes greater.

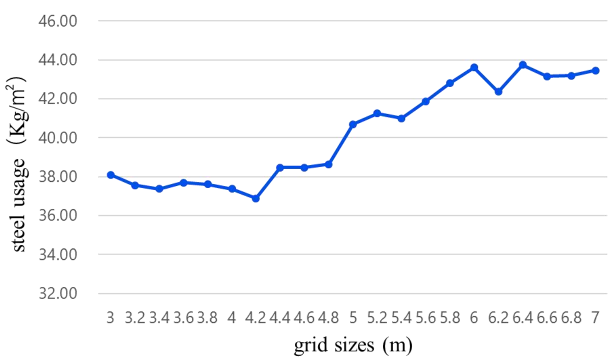
This approach significantly enhances the efficiency and accuracy of modeling large and complex spatial structures, enabling the rapid generation and optimization of batch models. It holds promise for revolutionizing the design process of spatial structures, particularly in scenarios where traditional modeling methods are inadequate.

3. Smart Design Example of Spatial Structures

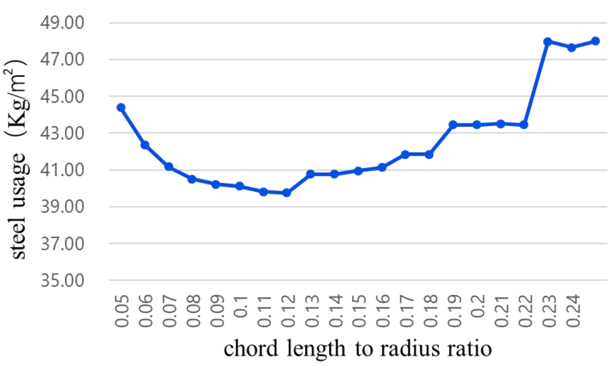
Using a three-centered circular truss structure with a span of 186.5 meters, a length of 251 meters, and a height of approximately 43 meters as an example, this paper demonstrates the smart design method proposed herein. The smart design method first performs single-parameter optimization analysis to determine the impact of each parameter on the structural performance and rank the importance of each parameter. By comparing the coupling effects of each parameter, the optimal solution is determined. The control parameters for single-parameter optimization in this case study include the structural height, arch height coefficient, grid size, truss thickness, chord length-radius ratio, lower chord thickness ratio, void ratio, and the influence of the gable on the number of trusses. In this case study, the structural self-weight coefficient is 1.05, the permanent load of the structure is 0.30 kN/m², the live load is 0.50 kN/m², the snow load is 0.20 kN/m², the basic wind pressure is 0.55 kN/m², the temperature difference is +26.00°C and -24.00°C, the pedestrian walkway permanent load is 1.00 kN/m, the pedestrian walkway live load is 2.00 kN/m, the midspan additional permanent load is 4.50 kN/m, the midspan additional live load is 1.00 kN/m, and 2 pedestrian walkways are arranged along the transverse and longitudinal directions, respectively. The smart design program automatically generates and compares 6768 models totally based on the above design conditions and parameters, which takes approximately 1 hour. This paper uses the large amount of computational data to organize the influence of single-parameter changes on the structural steel consumption, as shown in the figure below.



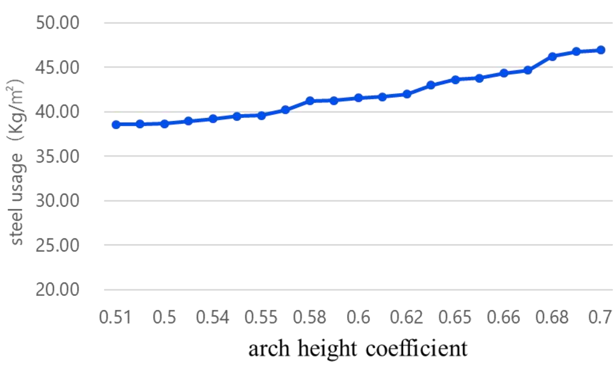
(a). Different maximum thickness corresponding to structural steel usage



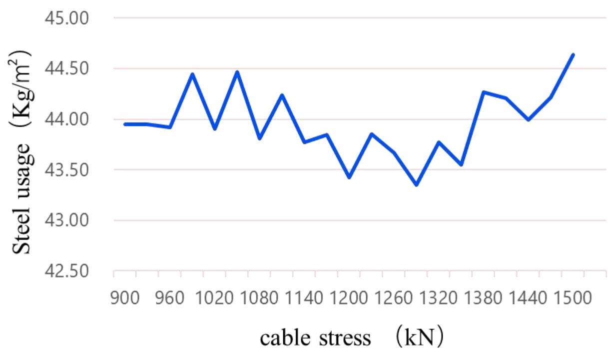
(b). Different grid sizes corresponding to structural steel usage



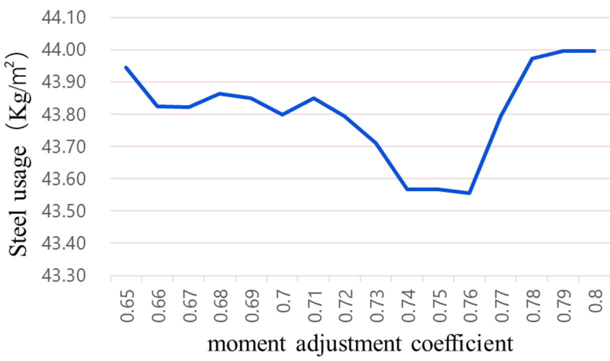
(c). Different chord length to radius ratio corresponding to structural steel usage



(d). Different arch height coefficient corresponding to structural steel usage



(e). Different cable stress corresponding to structural steel usage



(f). Different moment adjustment coefficient corresponding to structural steel usage

Figure 5: The impact of single-parameter variations on the steel usage

Taking the "maximum thickness of the truss" parameter as an example, varying its value can result in more than a 5% difference in steel usage per square meter for a three-centered circular truss structure. Similarly, varying the "grid size" can lead to more than a 5% difference in steel usage per square meter. Through large-scale comparative analysis of overall model calculation results, it can be concluded that the optimal solution reduces the amount of structural steel by up to 12.5% compared to the value obtained empirically. In addition to this case study, the research team has also conducted smart design studies on large-span three-centered circular truss structures of other dimensions. It has been verified that compared to empirically designed solutions, the optimal solutions can achieve an average steel saving of over 8%. Figure 6 illustrates the difference between the empirical design scheme and the smart design scheme. The truss is thinnest at the mid-span and the thickness increases at locations where it transitions to vertical load-bearing characteristics, accompanied by grid densification. The model details in the smart design scheme better conform to the structural stress characteristics.

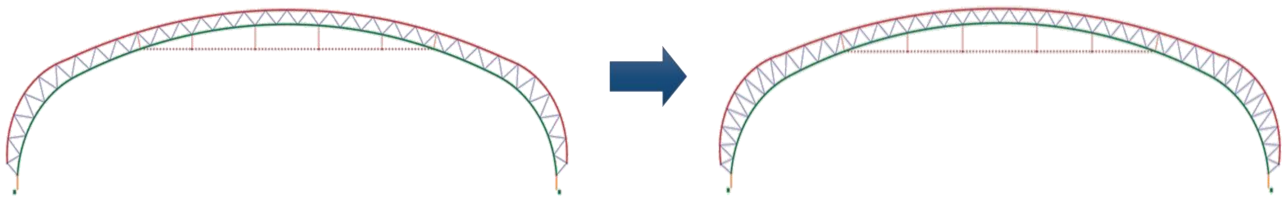


Figure 6: The difference between the empirical design scheme(left) and the smart design scheme(right).

Furthermore, this paper further subdivides the step values of the variable parameters, expanding the total number of models compared from 1000 to 19000. By statistically solving for the optimal steel quantity with different variable parameters' precision, the following figure is obtained. The graph shows that for the same design conditions and optimization range, the higher the interval precision of the variable parameters, the more models are compared, and the less steel is used in the optimal model obtained. The results of smart design are generally superior to empirical design.

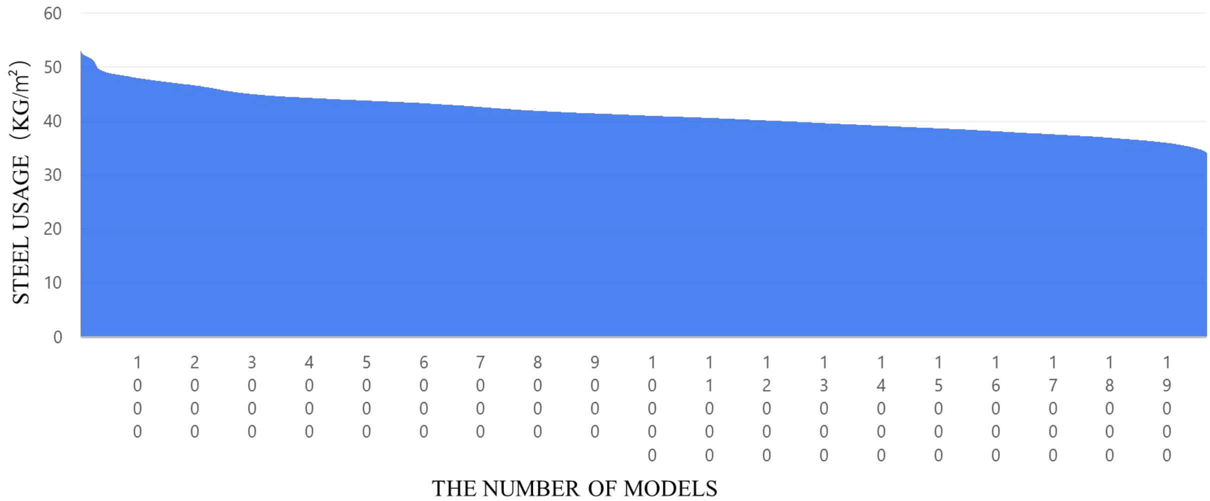


Figure 7: The relationship between the optimal steel usage and the number of models compared in the calculation

4. Smart designer software development

Based on the smart design methods discussed above for spatial structures, our team has developed smart design software for spatial structures, which has achieved significant savings in overall structural material usage. We have incorporated the parameters discussed in the smart optimization design of three-centered circular shell and truss structure into the software. The software adopts a parallel computing architecture, enabling efficient comparison and optimization of large batches of overall structural models. The user interface of three-centered circular shell and truss structure software is shown in figure below.

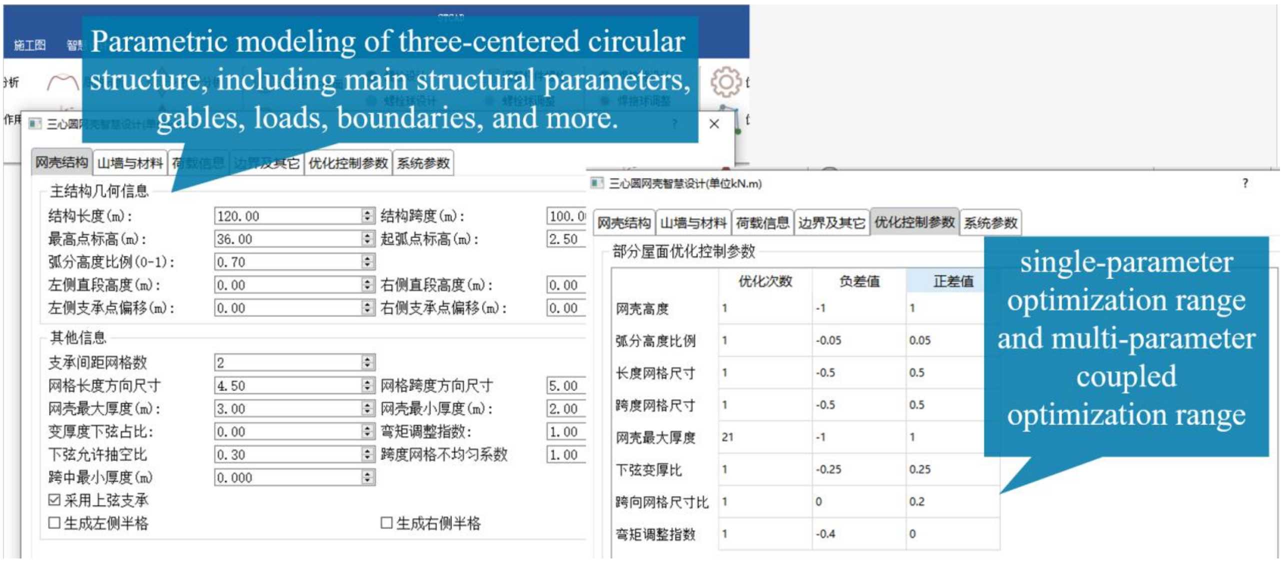
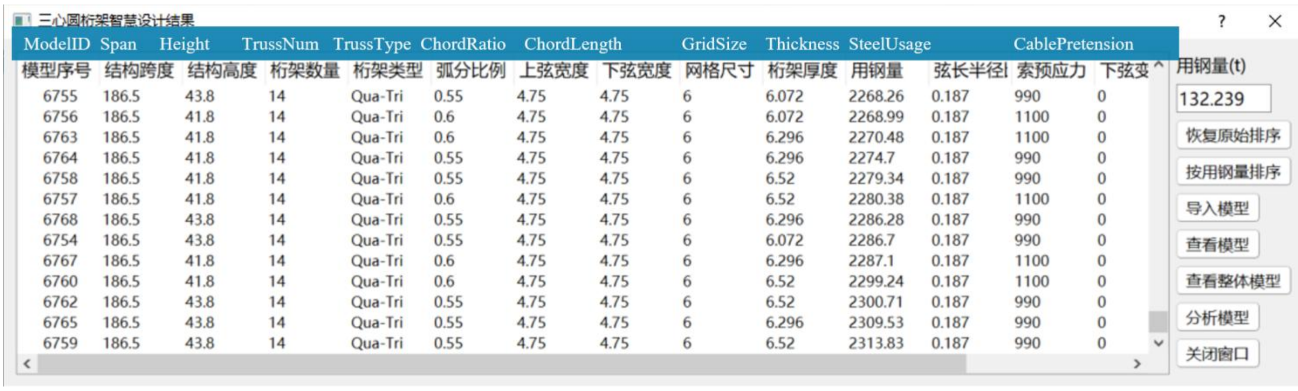


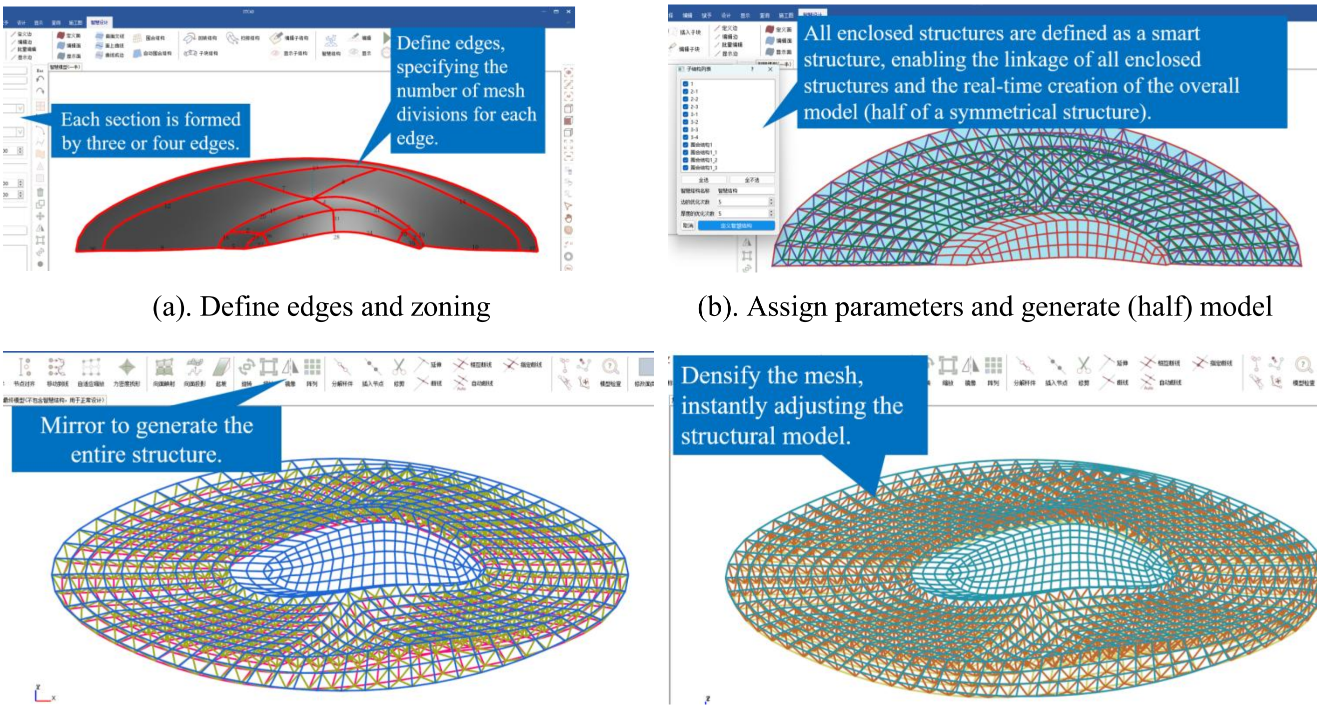
Figure 8: Parameter collection page for three-centered circular structures(Chinese version)



ModelID	Span	Height	TrussNum	TrussType	ChordRatio	ChordLength		GridSize	Thickness	SteelUsage		CablePretension	
模型序号	结构跨度	结构高度	桁架数量	桁架类型	弧分比例	上弦宽度	下弦宽度	网格尺寸	桁架厚度	用钢量	弦长半径	索预应力	下弦变
6755	186.5	43.8	14	Qua-Tri	0.55	4.75	4.75	6	6.072	2268.26	0.187	990	0
6756	186.5	41.8	14	Qua-Tri	0.6	4.75	4.75	6	6.072	2268.99	0.187	1100	0
6763	186.5	41.8	14	Qua-Tri	0.6	4.75	4.75	6	6.296	2270.48	0.187	1100	0
6764	186.5	41.8	14	Qua-Tri	0.55	4.75	4.75	6	6.296	2274.7	0.187	990	0
6758	186.5	41.8	14	Qua-Tri	0.55	4.75	4.75	6	6.52	2279.34	0.187	990	0
6757	186.5	41.8	14	Qua-Tri	0.6	4.75	4.75	6	6.52	2280.38	0.187	1100	0
6768	186.5	43.8	14	Qua-Tri	0.55	4.75	4.75	6	6.296	2286.28	0.187	990	0
6754	186.5	43.8	14	Qua-Tri	0.55	4.75	4.75	6	6.072	2286.7	0.187	990	0
6767	186.5	41.8	14	Qua-Tri	0.6	4.75	4.75	6	6.296	2287.1	0.187	1100	0
6760	186.5	41.8	14	Qua-Tri	0.6	4.75	4.75	6	6.52	2299.24	0.187	1100	0
6762	186.5	43.8	14	Qua-Tri	0.55	4.75	4.75	6	6.52	2300.71	0.187	990	0
6765	186.5	43.8	14	Qua-Tri	0.55	4.75	4.75	6	6.296	2309.53	0.187	990	0
6759	186.5	43.8	14	Qua-Tri	0.55	4.75	4.75	6	6.52	2313.83	0.187	990	0

Figure 9: List of design results for three-centered circular structures(Chinese version)

The zoning-based smart design module has been also developed into the software. Based on practical engineering verification, this smart design method is more efficient and faster in handling complex surface models and coping with changes in design schemes compared to traditional design patterns. The following figure illustrates the smart design process of a non-standard complex curved roof. Several characteristic lines are first defined as edges to partition the curved surface, ensuring relatively uniform grids within each partition. Grid coupling is achieved between the sub-regions through edges. The program automatically generates the overall grid model based on user-defined edge parameters and zoning parameters. By modifying the grid division parameters of edges or zoning, the overall grid model can be updated in real-time.



(a). Define edges and zoning (b). Assign parameters and generate (half) model

(c). mirror half of the model (d). Modifying edge parameters to refine the grid

Figure 10: Zoning-based smart design for a roof with complex curved shapes

5. Conclusion

Addressing the complexities and difficulties associated with modeling in spatial structure optimization design, this paper proposes or improves upon some multi-parameter-driven smart design methods for spatial structures. These methods enable rapid batch modeling and selection of the optimal model, leading to reduced steel consumption. A parameter-driven method for standard spatial grid structures and a smart design approach based on zoning is introduced. These methods facilitate rapid modeling and modification of complex spatial structures, improving efficiency and simplifying the design process.

Collectively, these two smart design methods enhance the feasibility of forward design patterns for spatial structures in practical engineering applications. Validation studies have demonstrated that these smart design methods achieve an efficiency improvement of over 80% compared to traditional modeling methods for complex spatial structures. Furthermore, they result in an average cost reduction of more than 8% compared to traditional design approaches. Their implementation in practical engineering projects can significantly improve design efficiency and cost-effectiveness.

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