Optimisation Study of Building Structure Design Scheme based on K-means Clustering Algorithm

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Abstract. In the construction project, the building structure, as the main part of the building, plays the role of the main load-bearing skeleton, but due to the lack of scientific design scheme, it leads to the problems of high building cost, poor quality, high carbon emission, etc. In this paper, starting from the structural design specification in the field of construction and combining with the actual situation of building construction, we propose an optimization path of building structure design scheme based on K-means clustering algorithm, which obtains the scientific material distribution by clustering analysis of structural materials according to the indexes of price, quality, and carbon emission, so as to help the structural designers to design the structural scheme with low cost, good quality, and low carbon and environmental protection. It helps structural designers to design low-cost, high-quality and low-carbon emission structural solutions. Taking the application of K-menas clustering algorithm for cost control of hybrid building structural design as an example, the feasibility, scientificity and efficiency of K-means clustering algorithm in the cost optimisation of structural design scheme are verified. It is shown that: (1) K-means clustering algorithm has good feasibility at the level of building structure optimisation. (2) Compared with the traditional multi-objective optimisation method, the K-means algorithm solves the cost optimisation with fewer steps, simpler principles, faster speed and lower technical threshold. (3) The successful application of K-means algorithm in structural cost optimisation proves its feasibility in structural quality and carbon emission optimisation. For example, the quality of materials can be assigned corresponding weight indicators based on composition, physical properties, chemical properties, etc., and the K-means algorithm can be used to analyse the indicators by clustering and classify the materials into different quality levels. Carbon emission can be assigned according to the carbon content of the material, effective service life and other values and cluster analysis, the material will be different grades, to assist structural designers to control carbon emissions. This research method greatly improves the efficiency of building structure design, and is expected to solve the existing problems of structural design solutions and promote the development of green buildings.

Keywords: Building structures; K-means; multi-objective optimisation; green buildings.

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1 Introduction

With the establishment of the strategic objectives of carbon peak and carbon neutral, the construction industry actively promotes the green and low-carbon transformation of the industry and develops energy-saving and low-carbon buildings[1]. As the load-bearing skeleton of the building, the building structure is the main part of the building, which has a broad research prospect in saving resources, reducing costs and reducing carbon emissions. At present, some scholars have made in-depth research on the optimisation of building structure design. Li Peihao improved the particle swarm algorithm and applied it to the optimisation of truss structure, and concluded that the improved particle swarm algorithm has a positive effect in the optimisation of truss structure[2].Alexandra Baicoianu proposed a new type of genetic algorithm based on mathematical planning to improve the efficiency of structural design under the condition of satisfying multiple design constraints of buildings [3].Zhang Shihai used the K-means clustering algorithm to cluster and analyse the attributes of the built high-rise building structure such as aspect ratio and site category to derive the attribute distribution of the high-rise structure, which provides an index reference for the subsequent structural engineers to design the high-rise building[4].Shao Xiaogan establishes a mathematical model with quality as the objective function for the discrete optimisation problem of building structures and uses an improved genetic algorithm for optimisation to solve the single-objective optimisation model[5].

The research results achieved by the above scholars in building structure are indisputable and undoubted, but there are some limitations, such as the structural optimisation of particle swarm algorithm is only for the truss structure, without in-depth study of the main structure of the building, which is somewhat special; K-means clustering algorithm only analyses the attribute index of the high-rise building structure, and lacks of clustering application of the middle and low-rise building structure; the quality optimisation of structure is easily trapped in local optimum and the algorithm is complicated. Genetic algorithm to solve the quality optimisation problem of the structure, easy to fall into the local optimum and complex algorithm. Therefore, this paper proposes a new method for building structure optimisation - K-means clustering algorithm. Through this algorithm, the cost, quality, carbon emission and other objectives of the main structure of each type of building (low, medium, high, ultra-high buildings) are optimised and analysed, and a low-cost, high-quality, low-carbon emission main structure design scheme is derived, which breaks the constraints of the traditional structural optimisation, improves the efficiency of the structural design, and carries out the structural optimisation and resource allocation in a more scientific way. The theme idea of structural multi-objective optimisation based on K-means clustering algorithm is as follows:By discussing the application of K-means clustering algorithm in structural cost optimisation and extending it to similar optimisation objectives, such as structural quality and carbon emissions. Overall, the K-means clustering algorithm is used to cluster the unit price of the materials constituting the structure, to divide a material into multiple price levels for the structural designer's reference, and to build a lower-cost structural solution to achieve cost optimisation in building structural design.

2 Methods

This paper summarises the current problems in the design and construction of building structures and puts forward targeted measures to solve them by studying the relevant literature on building structure design solutions. In the study of structural design solutions of high cost, poor quality, low stability and other pain points, the use of reverse thinking will be "pain points" into "goals", so that how to solve the pain points of building structural design solutions into a number of control objectives of the optimization problem. However, unlike the traditional method, this paper uses K-means clustering algorithm to solve the multi-objective optimisation in structural design, and through the clustering analysis and processing of material price, quality and carbon emission, the accurate material categories are derived, which can assist the structural designers in designing the economic, safe and green structural solutions for the buildings.

2.1 K-means clustering algorithm

K-means clustering algorithm (K-means algorithm) is a classical unsupervised iterative algorithm which as the name suggests can cluster data into K clusters. The algorithm is based on division in clustering algorithm, so that each point in the space belongs to the centre of the cluster closest to it, and the position of the centre of mass is continuously updated through iteration until the optimal clustering result occurs[6-7]. The specific steps of its implementation are shown below:

Step1) Select K points as cluster centres for initial aggregation (non-sample points can also be selected);

Step2) Calculate the Euclidean distance from each sample point in the space to the cluster centres of K clusters, respectively, and look for the closest cluster cluster centre to the point in turn, and divide it into the corresponding clusters;

Step3) After step 2, the dataset is divided into K clusters, and recalculate the centre of each cluster, and identify it as the new "cluster centre";

Step4) Repeat the iteration steps 2-3 until the cluster centre does not change anymore, then the iteration is terminated;

Step5) After the termination of the iteration, each sample point belongs to a cluster and the algorithm ends.

2.2 Problem optimisation of K-means clustering algorithm

K-means clustering algorithm is a commonly used unsupervised learning algorithm with the advantages of simple principle, low technical threshold, fast convergence speed, and applicability to large-scale datasets, but there are some problems in the use of the algorithm, such as K-means algorithm K-value selection, i.e., the data will be divided into several major classes, due to the human judgement to make the choice, resulting in its final clustering results have a subjectivity[8]. Secondly, the algorithm is easy to fall into the local optimal solution in the iteration process, which in turn affects the global nature of the clustering results. Finally, the K-means clustering algorithm is extremely sensitive to outliers and noise, which can lead to the problem of too large a threshold.

The author has come up with the following solutions by reviewing the related literature:(1)Use the elbow rule to find out the data clustering K-cluster value.(2)Perform multiple random initialisations before the algorithm starts.(3)Perform missing values, outliers and dimensionality reduction on the data[9].

2.3 Application of K-means clustering algorithm in structural design objective optimisation

In the design of building structure involves many materials, including concrete, masonry, steel, mortar, wood, etc. The main research line of this paper is shown in Figure 1, which aims to solve the problem of concrete, steel and mortar in cost optimization by using K-means clustering algorithm. Specifically, through the K-means clustering algorithm on the unit price of concrete, steel, mortar clustering analysis, the method to achieve the basis of the construction materials below are equipped with a variety of different specifications, different prices of materials, such as concrete can be divided into C20, C25, C30 and other levels [10]. The use of K-means clustering algorithm on the structure of the materials contained in the unit price of clustering analysis of the price of each material category, structural engineers can be based on the price of each material classified categories for the combination of design, so that the final design of the structure of the lowest price program. Similarly, this cost optimization method can also be extended to structural quality, carbon emission, etc. Therefore, the structural engineer can quickly design an economic, green and safe building structure according to the clustering results of the cost of each material, quality and carbon emission.

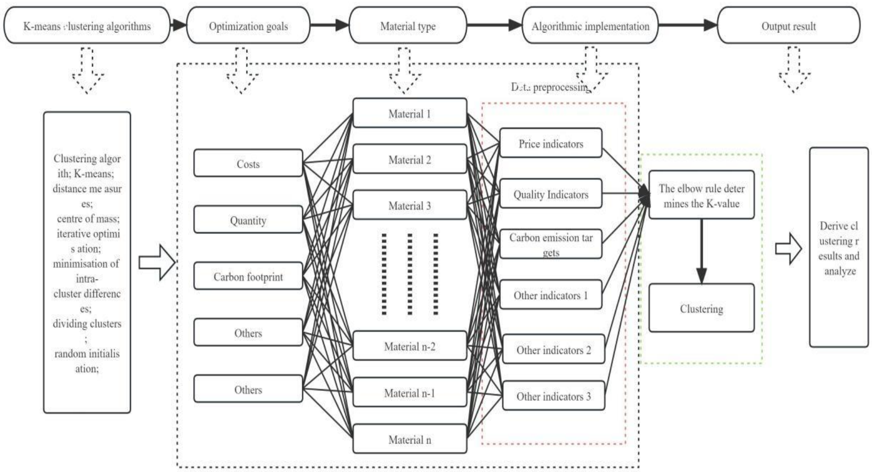


Fig. 1. Technical route of K-means clustering algorithm in structural goal optimisation application

3 Data sources

In order to make the application of K-means clustering algorithm in structural optimisation mentioned above more feasible, scientific and persuasive, the author summarises the main materials included in designing a set of building structural plan by integrating the information, including reinforcing steel, concrete (sand, stone, cement), masonry materials, timber, bamboo, glass, and new types of materials, etc[11-12]. In order to show the application of K-means clustering algorithm in structural optimisation in more detail, this paper mainly focuses on the optimisation of the cost of concrete, steel reinforcement, cement mortar, etc., and then uses this as a basis to argue the feasibility of other materials, quality objectives, and carbon emission objectives. Considering that the data is a direct determinant of the clustering results, in order to ensure the quality of the data the author obtains the unit price of each type of material (excluding tax) from the 2020 price list of labour, materials and machinery benches released on the official website of Shandong Provincial Housing and Urban-Rural Development Department and carries out preliminary data processing.

3.1 Data processing and analysis

For the concrete, steel reinforcement, cement mortar unit price data obtained from the official website of Shandong Provincial Housing and Urban-Rural Development Department using Excel software to find the average, maximum, minimum and other indicators, to carry out a preliminary data analysis, as shown in Table 1.

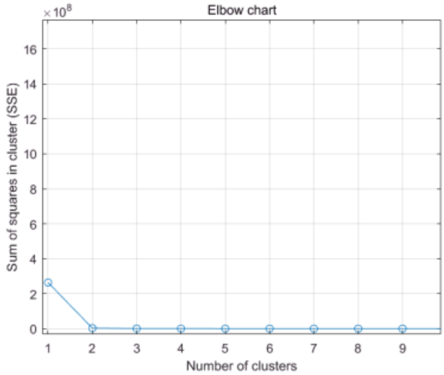
Table 1. Statistical data sheet on material prices

	Concrete	**Steel reinforcing bar**	**Cement mortar**
Average	528.23	2919.59	1578.86
Max	1420.35	4424.78	39285.97
Min	60.35	3.62	19.42

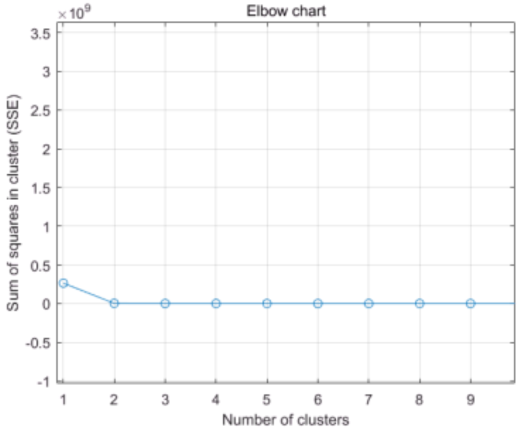
From Table 1, it can be seen that the price of each material fluctuates greatly, which more affirms the correctness and scientificity of the K-means clustering algorithm for the price of a single material clustering division.

3.2 Clustering of Material Prices and Analysis of Results

3.2.1.Clustering. Determination of K-value using elbow rule for preprocessed concrete, reinforcing steel, and cement mortar data solves the problem of subjectivity in the selection of K-value in the algorithm, and the elbow plots of concrete, reinforcing steel, and cement mortar are shown in Figure. 2 as (a), (b), and (c), respectively.



(a)



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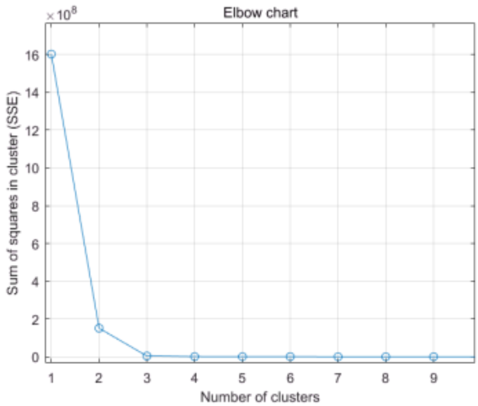
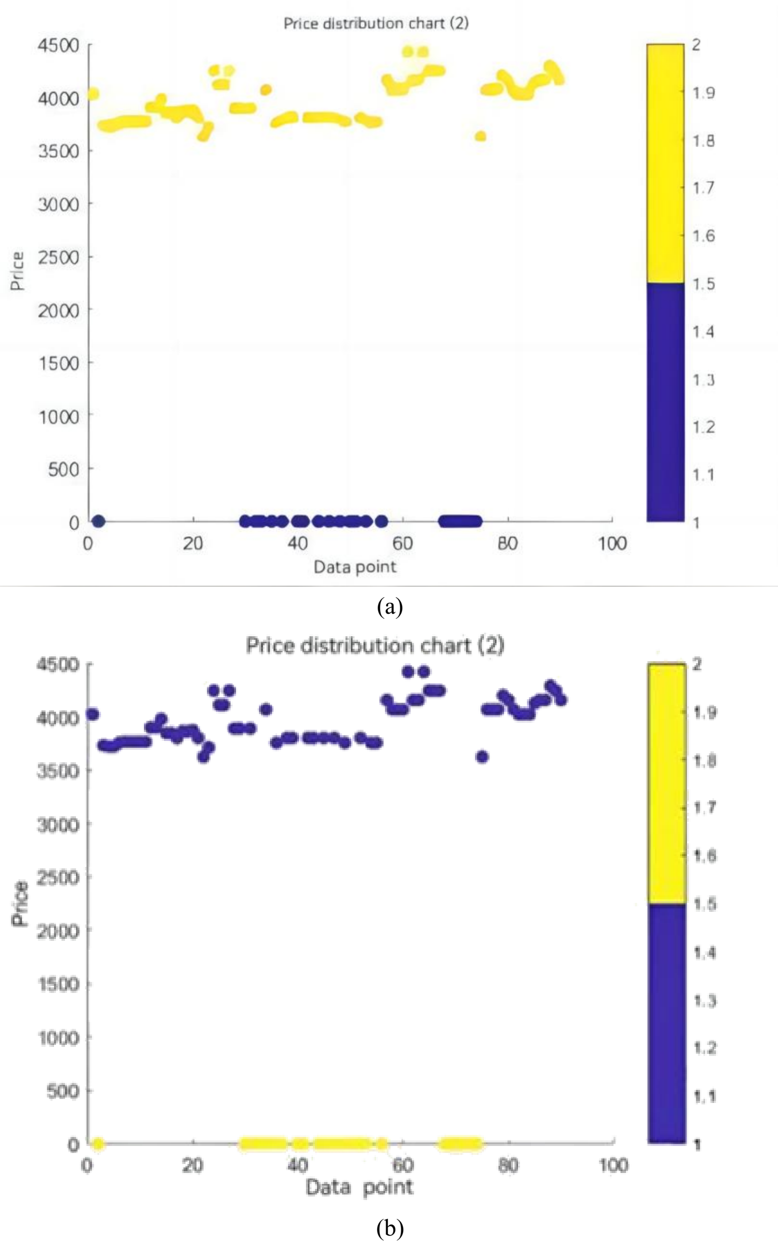


(c)

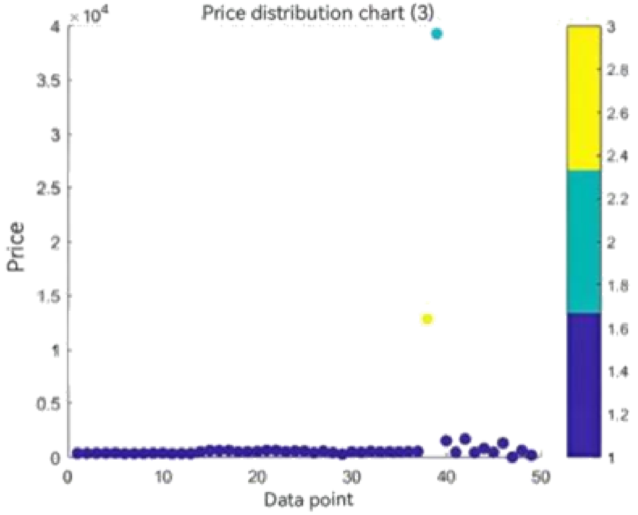
Fig. 2. Elbow diagram of concrete, reinforcement and cement mortar

Combined with the elbow diagram of concrete, steel reinforcement and cement mortar shown in Fig. 2, it can be determined that the unit price of concrete and steel reinforcement have a value of K of 2, and cement mortar K = 3. Based on the K-means algorithm solution step through Matlab to produce the distribution of material prices, as shown in Figure. 3, in which (a), (b), and (c) corresponds to the concrete, steel reinforcement, and cement mortar.



(a)

(b)



(c)

Fig. 3. Clustering results for concrete, steel reinforcement, cement mortar

Clustering the data using IBM SPSS software on the basis of the material price clustering results graph shown in Figure 3, the price clustering results can be derived more concisely, as shown in Table 2.

Table 2. Clustering results of concrete, steel reinforcement and cement mortar

Concrete		Steel reinforcing bar		Cement mortar	
form	**name**	**form**	**name**	**form**	**name**
Category 1	C15 cast-in-place concrete rubble <20	Category 1	rebar HPB300 φ6.5	Category 1	Special epoxy mortar 1:0.07:2.4
	C20 cast-in-place concrete rubble <20		rebar HRB335>φ25		Mixed sand pellets M5.0
	C25 cast-in-place concrete rubble <20		rebar HRB500＞φ10		Mixed sand pellets M7.5
	⋮		⋮		⋮
	C35 ready-mixed impermeable con-crete		Prestressing rebar three φ16	Category 2	Cement mortar M20.0
	C15 fine stone concrete		Pre-tensioned prestressing steel (integrated)		Masonry cement mortar M5.0
CCategory 2	Asphalt medium granular asphalt concrete	Category 2	Rebar φ14		Masonry cement mortar M7.5
	Asphalt Fine Grain		Cold rolled		Ready-mixed

Asphalt Concrete	twisted rebar φ12		expanded cement mortar
Asphalt Fine Grain Asphalt Concrete	Rebar φ22		Ready-mixed expanded cement mortar 1:1
Asphalt Coarse Grain Asphalt Concrete	Socket reinforcement φ5~10		Ready-mixed masonry mortar (dry mix) DM M5
Asphalt granular asphalt concrete	Ribbed steel bar φ10-12		Special acid-resistant mortar 1:2
Asphalt-modified asphalt concrete	Reinforcing steel processing parts φ40	Category 3	Special epoxy resin primer 1:0.07:0.15

In concrete category 1, in addition to the parts listed in Table 2, there are commercial concrete, ready-mixed concrete, C15 concrete, etc.; reinforcing steel category 1 in addition to some of the reinforcing steel in the table, but also contains different diameters of steel, steel HRB400 dozen of kinds of reinforcing steel, hoop reinforcement, etc.; cement mortar category 2, also includes ready-mixed mixed mortar, dry hard cement mortar, ready-mixed mortar and so on dozens of kinds.

3.2.2.Analysis of clustering results. The K-means clustering algorithm divides the broad category of concrete into two categories based on the price of the material, i.e., one for high price and one for low price. When the structural design requires the use of concrete, the structural designer can select one or more differently priced concretes from a high-priced analogy or a low-priced category under the premise of meeting the design requirements. It should be noted that the price difference of concrete in the same category is very small, and the price difference of different analogues is large, so the structural designers can quickly pick out a reasonably priced combination of concrete to achieve the purpose of controlling the cost of concrete use.Reinforcing bars are also processed by K-means algorithm are classified into two categories and value significance can be assigned to these two categories such as category 1 for high price tier and category 2 for economic tier. As with concrete, structural designers can select reinforcing bars from both price categories and combine them to optimise structural costs, provided the design requirements are met. Similarly, the K-means clustering algorithm divides the cement mortar into three tiers; category 1 is the high price tier, category 2 is the average price tier and category 3 is the economic tier. Structural designers can combine reasonably priced mortars based on the clustering results to achieve the goal of controlling the mortar's share of structural costs.

Above, the K-means clustering algorithm has achieved remarkable results in dealing with the cost control of concrete, steel reinforcement and cement mortar, proving the feasibility of achieving structural cost control based on the clustering treatment of material prices, and showing the readers a new approach to the optimisation of the cost of building structures. Now, based on the successful application of K-means clustering algorithm, this concept is extended to structural quality and carbon emission optimisation. At the level of structural quality, the structural materials are assigned corresponding weight indicators based on their usage characteristics, constituents, and parts of use, which are used as variables for subsequent clustering, e.g., concrete can be assigned a quality level based on the size of the embedded crushed stone blocks. At the level of structural carbon emission control, the carbon emission level can be assigned according to the carbon content and effective service life of the material as the object of data processing by K-means clustering algorithm.

Taking concrete as an example, it introduces how to apply the material cost, quality, and carbon emission results output from the K-means clustering algorithm. When the structure needs concrete, the structural designers can consider and select the concrete material according to the cost, quality, and carbon emission clustering results, when choosing the concrete with low price, they need to see whether the quality and carbon emission are suitable, and finally, they can arrive at a combination of low-cost, high-quality, and low-carbon emission concrete through multiple comparisons. Considering the slow speed of comparing the clustering results, statistical software can be used to solve this problem.

In summary, the clustering process and analysis of structural material cost, quality, and carbon emission by K-means algorithm can assist structural designers in designing economic, high quality, green, and safe building structure solutions.

4 Conclusion

This study takes the official construction material prices in Shandong Province as an example, and through the K-means clustering algorithm, some of the materials involved in the building structure are demonstrated and explored with regard to the cost control problem, and the conclusions are shown as follows:

(1)Through the successful application of K-means clustering algorithm on structural cost optimisation, concrete, steel reinforcement and cement mortar are divided into 2, 2 and 3 classes, which provides a basis for structural designers to quickly optimise the structural cost, and achieves the purpose of controlling the structural cost, and proves that the K-means clustering algorithm has a high feasibility in solving the structural objective optimisation problem.

(2)The use of K-means algorithm to solve the cost, quality and carbon emission optimisation problems of building structures has fewer steps than the traditional multi-objective optimisation methods, the principle is simple, the speed is faster, and the professional and technical level of the solver is less demanding, which is suitable for the staff in the construction industry.

(3)Based on the successful application of K-means clustering algorithm in structural cost optimisation, it can be extended to the optimisation of structural quality, carbon emission and other objectives. At the level of structural quality and carbon emission, the grade indexes of material quality and carbon emission can be assigned according to the composition, use part, characteristics, carbon content, and effective service life of the materials, and the K-means algorithm can be used to process the indexes to produce the clustering results. Structural designers can combine the clustering results of material cost, quality and carbon emissions to come up with low-cost, high-quality and low-carbon structural material solutions.

This paper proposes a new path to solve the multi-objective optimisation of building structural design, through the K-means clustering algorithm, the cost, quality and carbon emission of structural materials are clustered separately and analysed, which results in the distribution of the same material with different cost, quality and carbon emission levels, and helps the structural designers to efficiently design the economic, high-quality and green structural solutions.Based on the research in this paper, the author believes that by pioneering the application of K-means clustering algorithm in the structural optimisation as well as the construction process, a new engine of construction development can be found to better help the construction industry flourish. However, the research in this paper still has the following shortcomings:

(4)Only concrete, steel reinforcement and cement mortar are selected as the research objects in structural cost optimisation, which has some limitations.

(5)The paper only makes a detailed argument for structural cost optimisation, and does not explain the detailed application of K-means algorithm in quality, carbon emissions and other issues, but only provides a new way of thinking and theoretical guidance. In conclusion, the K-means clustering algorithm has a good prospect of use in dealing with the optimisation of cost, quality, carbon emission and other objectives of building structure design, but it still needs researchers to invest energy in in-depth study to better cope with the shortcomings.

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