The Role of Multi-criteria Decision Techniques for Sustainable Construction of Chinese Residential Buildings

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Abstract

The increasing urbanization in China has created a high demand for housing and other infrastructure. Meeting this demand has huge resource implications with potentially harmful effects on the environment. A sustainable approach to construction is therefore a way forward to ensure that the competing needs for housing, economic development and protection of the environment can be achieved. This paper reports on the early stages of a research into sustainable construction in China. The aim is to explore how multi-decision techniques can be used to assess the sustainability of different structural systems (e.g. load-bearing bricks, concrete and steel frame construction) for residential building construction. The concept of sustainable construction is defined and various criteria for achieving it are identified. A review of various multi-criteria decision techniques is provided and a conceptual framework for an evaluation system for assessing different structural systems in the context of the residential building process in China is proposed. It is expected that this framework will provided the basis for a more detailed study to validate and test its effectiveness in making credible decisions on the choice of building systems for sustainable construction in China. The paper concludes with an outline of how this detailed research will be conducted.

Keywords: sustainable construction, multi-criteria decision, residential building

1. Introduction

The increasing world population and the shortage of adequate housing create a huge demand for future residential building with an expectable demand for sustainable solutions. This situation is more obvious in China, where urbanisation increased from 18% to 43% between 1978 and 2005 (Wu, 2007), and with the urban population expected to reach 926 million by 2025 (Living Steel, 2010). Taking the two biggest cities for example, Shanghai requires an additional 1.3 million square metres of new residential housing annually to house

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its swelling population and Beijing has more construction than in the entire European continent. Against this background, the Chinese construction industry has developed very quickly and it accounts for a large share of the energy consumption, waste generation, and use of natural resources. Over the last 20 years, the process of Chinese urbanization has followed a pattern of the high input and consumption. However, limited resources and the capacity of the environment cannot support the rapid economic and social development if the traditional model of development continues (Li, 2008).

The construction process in China has seen a major change from a more state-driven process before the Open Door Policy in 1978 to a more market-oriented system since then (Chan et al, 1999). The key players in a typical process include the Preparatory Office (PO) (or project bidding agency), Design Institute (DI), Contractor and Construction supervision unit (CSU) (Chan et al. 1999). The PO is a temporary organisation which manages the project and "is responsible for all the necessary functions other than those performed by the design institute and contractor" (Chan et al. 1999). The DI (equivalent to Architect/Engineer functions) is responsible for preparing conceptual and detailed designs; the contractor carries out the building works but not responsible for procuring materials (the PO is responsible for this); and the CSU supervises construction as an independent third party (Chan et al. 1999).

The residential building construction process in China is broadly similar to that in Western countries. However, due to a heavy reliance on labour-intensive processes, it is less efficient and the generation of waste is generally higher; and the pace of development doesn't usually keep up with advances in technology. The separation of design and construction (i.e. the DI and Contractor functions described above) also leads to a lower design service level. The consumption of raw materials such as steel, cement, concrete and timber are relatively higher. In aspects of construction management, the lack of comprehensive information management systems leads to a relatively less efficient process, especially with respect to frame structure construction. The reliance of labour-intensive processes for frame construction on site often leads to increased costs, poor quality, longer duration of projects and safety issues which have a negative impact on worker's health and the building environment. The need for sustainable construction in frame building systems is therefore apparent.

The frame building system used in Chinese residential buildings is mainly comprised of three alternatives, which are steel, concrete, and load-bearing bricks. Other materials such as stone, bamboo are also used (Qu et al. 2012) but to a lesser extent in the industrialised housing sector. It is necessary to make credible decisions on the choice of suitable frame structure in building systems development, both for the sake of protecting the environment and for rapidly supplying the high-quality housing demanded by society. How to choose the most suitable frame structure building system in a rapid urbanization process is a multi-criteria problem. The objective of this paper is therefore to explore how multi-decision techniques can be used to assess the sustainability of different structural systems (e.g. load-bearing bricks, concrete and steel frame construction) for residential building construction. The concept of sustainable construction is defined and various criteria for achieving it are identified. A review of various multi-criteria decision techniques is provided and a conceptual framework for an evaluation system for assessing different structural systems in the context of the residential building process in China is proposed. Preliminary data from a survey of typical projects in China will be used to test the conceptual framework. The paper concludes with recommendations for future research.

2. Sustainable construction

There has been a growing movement towards sustainability since the latter half of the twentieth century, leading to the development of various concepts of sustainable construction. Sustainable construction is part of the larger concept of "sustainable development". One of the earlier definitions of sustainable development (as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" - Bruntland, 1987), has led to many other conceptions of sustainability and sustainable construction.

Similar terms that apply to the sustainability of buildings include: "eco-building", "sustainable building" and "green building" (Adler, 2011). Sustainable construction has a rich content which include resource efficiency (energy, integrated design, third-party commissioning, enhanced security), construction and demolition practices, recycling, environmental sensitivity (learning from the locals, site selection and development), water and landscape, sewage treatment, designing for people and productivity (building design and materials, maintenance, more natural indoor environment, quality lighting, individual environmental control) (Atkinson et al, 2009). Sustainable construction applies not just to the building product, but to the construction process, construction strategies, building and infrastructure design and orientation, project management, maintenance and so on. It can therefore refer to: all decisions and actions during the design and construction of buildings, which are designed to ensure that both the process and outcomes of construction over the lifecycle of a building are sustainable (i.e. have net positive benefits with respect to the social, economic and environmental aspects of sustainability).

Sustainable construction with respect to frame building system can be generalized from some sustainable construction evaluation concepts (Cinquemani and Prior, 2011). The most important and globally used environmental assessment methods were investigated and a generic model for the development of an effective environmental assessment method intended for the establishment of environmental sustainability, was developed by Alyami,.and Rezgui (2012). With respect to China, the Ministry of Housing and Urban–Rural Development has established the evaluation criteria for green building (CNS, 2006). Five criteria for sustainable construction of residential frame building systems can be identified from this government study. Firstly, it should be concerned about the frame construction sites and assess the issues arising from the building's construction and management on man, environment and land. Secondly, it should be concerned about water efficiency during the frame construction stage and assess the water use efficiency of the building process. Thirdly, it should be concerned about energy and atmosphere and assess the energy use in the frame construction, the sustainable use and management of electricity, coolants, and the extent of the use of renewable energy. Fourthly, it should be concerned about materials, resources and assess the frame building materials used, their sourcing, the proportion of recycled materials in them, ease of their recycling, sourcing from sustainable forests that protect man and the environment. Fifthly, it should be concerned about the efficient and effective management of the cost, quality, duration, safe and benefit for technology development demands. (CNS, 2006

In the context of China, which is facing rapid urbanization and industrialization, sustainable construction in relation to frame building systems should include other variables in addition to those mentioned above. Because the new urban population need their living space urgently and the government's finances are relatively limited, some balance should be attained with respect to environmental protection, social benefits and economic benefits. Specifically, sustainable construction related with the frame building system in China should also consider: less material consumption, less energy consumption, less land use, less water consumption, pollution control, construction cost control, construction duration control, housing supplying efficiency, benefit to housing industry technology development, benefit for living culture. The selection of the most suitable frame building system during the urbanization should therefore be in accordance with sustainable construction principles.

3. Multi-criteria decision techniques

Multi-criteria decision techniques have increasingly been applied in many kinds of research. This is especially the case in sustainable development, due to the multi-dimensionality of sustainability, with respect social, environmental and economic considerations.

Multi-criteria decision techniques are mainly divided into three categories which are: elementary techniques, unique synthesizing criteria techniques and outranking techniques (Wang, 2009). The elementary techniques include two methods which are weighted sum method (WSM) and weighted product method (WPM). Weighted sum method (WSM) uses each criteria score and multiplies the weight and sum to get the resulting cardinal scores. The score of the optimal alternative is the maximum. WPM is different from WSM, which is applied with the multiplication instead of sum it. The unique synthesizing criteria include Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Grey relation method, MCDA (Multi-Criteria Decision Analysis), and combined fuzzy methodology. AHP is a type of weight sum method and applied popularly in many domains. TOPSIS is a method where the ideal alternative has the best level for all criteria whereas the negative ideal is the one with all the worst criteria values (Hwang, 1981). Grey relational method belongs to grey systems theory whose principle of grey relation method is similar to TOPSIS, and uses the grey relation degree to show the closeness between the alternatives. MCDA combined fuzzy methodology has been applied to solve problems related with availability and uncertainty of information as well as the vagueness of human feeling and recognition. The outranking methods have the characteristic of allowing incomparability between alternatives which is important in situations where some alternatives cannot be compared for various reasons (Wang, 2009).

From the view of the construction model, multi-criteria decision techniques are mainly divided into three methods. Firstly, AHP (Analytical Hierarchy Process) and some decision rule-based methods can solve multiple criteria evaluation problems utilizing prior articulation of preferences. These kinds of methods transform the problem into essentially a single criterion problem which requires the decision maker's preference information at the start of the process. Secondly, other methods are to solve multiple criteria decision problems using prior articulation of preferences by constructing a value function such as goal programming. The detail process after the value function is established; the resulting single objective mathematical program is solved to obtain a preferred solution. Thirdly, some methods require preference information from the decision maker throughout the solution process which is referred to as interactive methods or methods that require progressive articulation of preferences. These methods have been well-developed for both the multiple criteria evaluation (Geoffrion, et al. 1972; Köksalan and Sagala, 1995) and design problems (Steuer, 1986). Multiple criteria design problems typically require the solution of a series of mathematical programming models in order to reveal implicitly defined solutions. The representation or approximation of "efficient solutions" is of interest. This category is referred to as "posterior articulation of preferences," meaning that the decision maker's involvement starts posterior to the explicit revelation of "interesting" solutions (Karasakal and Köksalan, 2009). If the mathematical programming models contain integer variables, the design problems become harder to solve.

4. Research methodology

The problem of evaluating the sustainability of frame construction has multiple conflicting criteria which include environmental protection, economic benefits and social benefits that need to be considered in making decisions. The problem consists of a number of alternatives which include brick, concrete and steel frame development. So the sustainable frame construction in residential buildings is a typical multi-criteria problem. It is very suitable for the AHP model. AHP is a useful multi-criteria decision technique developed by Saaty (Saaty, 1980). AHP technique can be used for quantifying relative priorities for a given set of alternatives on a ratio scale toward evaluating the sustainable construction model, and it can apply the judgment of experts (based on experience). It stresses the importance of the intuitive judgments of a decision-maker and the consistency of the comparison of alternatives in the multi-criteria decision-making process. AHP has already been applied in many fields related with sustainable development (Chatzimouratidis and Pilavachi, 2008, 2009; Ramanathan and Ganesh, 1993, 1995; Kablan, 2004). Based on the review of multi-criteria techniques above and considering that this preliminary research is aimed at developing a conceptual framework for the sustainable assessment of different structural systems in the context of the residential building process in China, AHP was chosen as the most appropriate evaluation method.

The research undertaken involved a review of government guidelines and other related literature, an investigation of case study project data, and interviews with experts. The case study projects were chosen in Wuhan city, which is located in the centre of China. Data from three different frame structure residential buildings were collected from the contractor. The investigation was made as a comparative analysis table which provided a reference for the interview with the experts. The interviews were conducted between 1 April and 1 May 2012. The interviewees consisted of 16 professionals who were familiar with sustainable construction in residential buildings and had more than 15 years of experience in the construction industry. To ensure representation of different project stakeholders, 9 of the experts were from the contractor company, 5 of them from the design company, and the remaining 2 were from the consulate company (i.e. Construction Supervision Unit). They were interviewed to obtain comparative scores between the factors based on the AHP method, which aids to establish the matrix of pairwise comparisons for determining the weights for each criterion. The relative importance can be scaled from 1-9 depending on the level of importance. Based on the matrix, criteria weights and the degree of consistency achieved in the pair-wise comparison are measured by a consistency ratio indicating whether the comparison made is sound. After obtaining the weights, each performance at the given level is then multiplied with its weight and then the weighted performances are summed to get the score at a higher level. The procedure is repeated upward for each hierarchy, until the top of the hierarchy is reached. The overall weights with respect to the goal for each decision alternative are then obtained. The alternative with the highest score is the best alternative (Wang 2009). The calculation process was done with MATLAB.

5. Conceptual evaluation framework

The AHP evaluation model of three frame building system consists of three levels including objective level, criteria level and alternatives level. The objective is to realize the overall optimal goal, which is to balance the needs of society, economy and the environment, in the selection of the most appropriate frame type. The criteria level includes environmental protection, economic benefits and social benefits. The environment protection criteria are composed of five indexes, which are: material-saving, energy-saving, land-saving, water-saving, and pollution control.

As to the material-saving, 55kg of steel and 221.5kg cement are required to construct 1 square meter of residential building. 1500kg of ore is required to produce 1 ton of steel. With respect to cement, 1100~1200kg of limestone, 150~250kg of clay, and 160~180kg of coal are required to produce 1 ton of cement clinker. All these materials are non-renewable (Tang, 2008). The material-saving criteria can be measured with respect to whether it is beneficial to apply lightweight high strength building materials, or to apply the industrial standard component during the design stage in order to reduce consumption during the construction stage of the frame structure building system. As to Energy-Saving, 6-litres of oil per square meter are required each year (equivalent to 8.57kg of coal) to heat a typical European residence, while 12.5kg of coal are required for a typical Chinese residence (Lu, 2005; Hu and Wang, 2009). The energy-saving technology criteria can be measured with respect to whether the frame structure building system is easier to connect with energy-saving windows and walls, which can reduce heat transfer through setting insulation layer on the wall and applying seal technology on the window; or whether it is easier to connect with energy-saving roofs and floors which can prevent heat transfer through the improvement of the thermal performance of the roofs and floors; or whether it is easier to connect with solar systems, for water heating system and power generation.

Land-saving can be measured with respect to whether the frame structure building system improves the intensive use of the land; enhancing the efficiency of the use of land; choosing the flexible load-bearing structure so as to achieve the rational division of the living space;

promoting new wall materials so as to save land resources, which is also meaningful to reflect the right choices and options for society (Yin 1993). Water-saving can be measured with respect to how the frame structure building system is beneficial in reducing the usage of water during construction, to connect with the recycle system so as to save the water consumption (Ren, 2009). As to Pollution control, the emission from the housing industry accounts for 25% of the total national greenhouse gases. It discharged 1.6~2.0 ton of CO_2 and 0.5~0.7 dust to produce 1 of ton steel. The amount of CO_2 discharged from the cement industry exceeded 13 billion ton while the amount of the dust exceeded 7000 thousand ton and the amount of the exhaust exceeded 600 thousand ton (Zhao, 2008). It can be measured with respect to whether the frame structure building system is beneficial in controlling noise, dust, surface water pollution and traffic congestion. For example, the use of clean “dry techniques” in steel construction can reduce pollution. The economic benefits criteria are made up of three indexes, which include construction cost, construction duration and main material consumption. The social benefits criteria are made up of three indexes, which include rapid housing supply to the society, benefit for the construction industry and benefit for living culture. Alternatives level includes three frame structure building system alternatives which are steel structure frame, concrete structure frame and brick structure frame. The established evaluation system is shown in Figure 1.

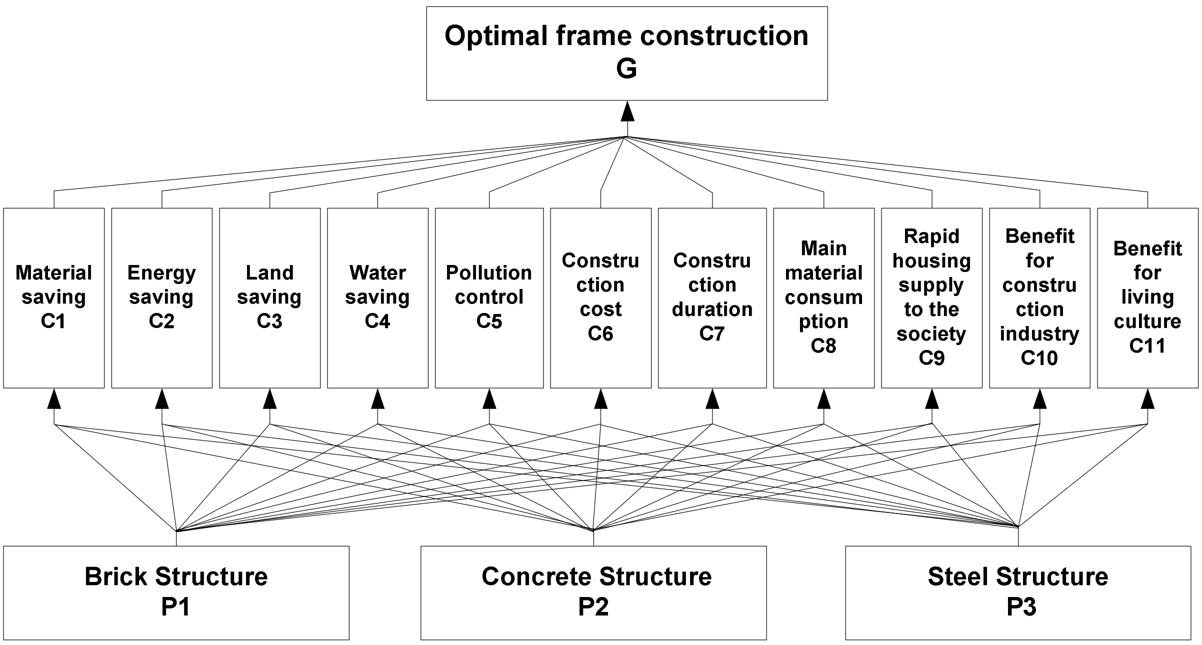

Figure 1: Evaluation framework for selecting frame structure building system

6. Preliminary testing and discussion of results

The preliminary testing of the conceptual framework involved a calculation of the AHP model. The scores were obtained from the judgment of experts and some indices were derived from the investigation of three kinds of frame building systems. Table 1 presents the results from a typical Chinese residential building construction project (in Wuhan, central

China). The comparative values were sent to the experts as a reference for them to provide their matrix of pairwise comparisons for determining the weights for each criterion. The matrix and the calculation process of each criterion were carried out in MATLAB.

Table1: Comparative analysis of three frames

Index			Unit	Steel Structure	Concrete Structure	Brick Structure
Index 1	Section steel consumption		Kg/m^2	35	0	0
Index 2	Steel bar consumption		Kg/m^2	12	30	15
Index 3	Cement consumption		Kg/m^2	30	140	75
Index 4	Gravel and sand consumption		Kg/m^2	150	800	650
Index 5	Timber consumption		m^3/m^2	0.0002	0.05	0.15
Index 6	Material logistics		T/m^2	0.3~0.6	1.0~1.2	1.3~1.5
Index 7	Land occupation		Given the brick structure as 1.0	0.3~0.4	0.8~1.0	1
Index 8	Water and power consumption		Given the brick structure as 1.0	0.5~0.6	1.2~1.5	1
Index 9	Construction noise		Given the brick structure as 1.0	0.5	1.5	1
Index10	Construction sediment volume		Given the brick structure as 1.0	0.2~0.3	0.7~0.8	1
Index 11	Demolish rubbish volume		T/m^2	0.355	1.25	1.95
Index 12	Labour consumption		day/m^2	3.5	5.5	7
Index 13	Cost/m^2 (construction area)	Multi-storey building	Given the steel structure as 1.0	1	1	0.87
Index 14		High rising building	Given the steel structure as 1.0	1	0.98	No exist
Index 15	Cost/m^2 (usable area)	Multi-storey building	Given the steel structure as 1.0	1	1.03	1.05
Index 16		High rising building	Given the steel structure as 1.0	1	0.99	No exist
Index 17	Construction duration		Given the steel structure as 1.0	1	1.45	1.95
Index18	Building life		years	70	70	50
Index19	aseismic performance			strong	Middle	weak
Index20	The working environment			good	middle	middle
Index21	Degree of industrialization		%	90%	50%	30%

The 11 criteria (C1 to C11 in Figure 1) comparison matrix and the calculation of the result of their weights are provided in Table 2 as an example. The pairwise values in Table 2 were derived from the experts. Following this overall comparison of the 11 criteria, each criterion (e.g. C1 = material saving) is compared against each frame alternative (i.e. steel, concrete and brickwork). An example of this (using criterion C1) is provided in Table 3.

Table 2: The criteria comparisons matrix and calculation result of weight*

G	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Weight
C1	1	1/6	3	5	1/5	1/3	5	3	5	9	7	**0.1071**
C2	6	1	7	8	3	4	5	6	7	9	8	0.3081
C3	1/3	1/7	1	2	1/5	1/5	2	1/3	2	5	4	0.0432
C4	1/5	1/8	1/2	1	1/7	1/6	1/2	1/5	1/2	3	2	0.0228
C5	5	1/3	5	7	1	2	5	3	6	9	8	0.1940
C6	3	1/4	5	6	1/2	1	5	2	6	9	8	0.1454
C7	1/5	1/5	1/2	2	1/5	1/5	1	1/4	2	4	3	0.0358
C8	1/3	1/6	3	5	1/3	1/2	4	1	4	8	7	0.0848
C9	1/5	1/7	1/2	2	1/6	1/6	1/2	1/4	1	5	3	0.0306
C10	1/9	1/9	1/5	1/3	1/9	1/9	1/4	1/8	1/5	1	2	0.0139
C11	1/7	1/8	1/4	1/2	1/8	1/8	1/3	1/7	1/3	1/2	1	0.0143

***(Consistency ration is：0.0749；C1 to C11 represent the 11 criteria specified in Figure 1)**

Table 3: Comparison of criterion C1 against alternatives (P1, P2, P3)*

C1 Material Saving	P1 Brick Structure	P2 Concrete Structure	P3 Steel Structure	Weight
P1 Brick Structure	1	1/5	1/3	**0.1095**
P2 Concrete Structure	5	1	2	0.5816
P3 Steel Structure	3	½	1	0.3090

***(Consistency ration is: 0.0036)**

This process is repeated for all the criteria (C2 to C11) against the alternatives (not presented here because of space limitations). The overall weight for each alternative (P1, P2, and P3) (provided in Table 4) is obtained using equation 1, where P and C represent the alternatives and criteria, respectively; ***j*** and ***i*** represent the resulting weight of each alternative (e.g. Table 3) and criteria (Table 2), respectively.

$$\sum_{j=1}^{3} \sum_{i=1}^{11} Pj\ Ci$$

Equation 1

So from equation 1, the overall weight for P1 (Brick) is: *(**0.1095**x**0.1071**) + (0.1047x0.3081) + (0.1095x0.0432) + (0.1047x0.0228) + (0.1047x0.1940) + (0.6144x0.1454) + (0.1047x0.0358) + (0.1047x0.0848) + (0.1095x0.0306) + (0.1095x0.0139) + (0.1220x0.0143) =* ***0.1800*****.** [The first set of values in bold are from Tables 3 and 2, respectively. The other values are similar calculations as in Table 3, and the resulting weights in Table 2]. The weights for P2 (concrete) and P3 (steel) were calculated in the same way with results presented in Table 4.

Table 4: The overall weights for the alternatives P1, P2 and P3

Alternatives	Overall Weight
P1 Brick structure	0.1800
P2 Concrete structure	0.3521
P3 Steel structure	0.4679

From the calculation results (Table 3), it can be seen that the weight of the steel structure is the highest. This implies that steel structure satisfies the overall goal of optimal frame construction. This result also suggests that the policies that encourage developing steel structure residential building are likely to be very important for sustainable construction in China. However it should be noted that this calculation result is based on the scores given by the experts. If another group of experts were interviewed, the result may not be the same, which embodies the characteristic of the AHP method. Another point to note is that this preliminary test was based on a project in the centre of China and may not reflect the situation across the country because of huge differences in different parts of China. For example there are wide variations in the market price of materials, energy, water (criteria C1, C2 and C4 in Table 2); the value of the land (criteria C3); the cost of construction (criteria C6), the level of demand for residential buildings (criteria C9); all these factors can change the result of the evaluation. However, this model is a useful framework for applying multi-criteria techniques to assess the sustainability of structural frames of residential buildings.

7. Conclusion

The increasing urbanization in China has created a high demand for residential buildings. Meeting this demand has huge resource implications with potentially harmful effects on the environment. A sustainable approach to construction is therefore a way forward to ensure that the competing needs for residential building, economic development and protection of the environment can be achieved. Through the comparative analysis of some evaluation tools, an evaluation index system and AHP model was established. And based on the scores given by the experts, calculated through MATLAB software, the result is that the most suitable frame structure building system of the residential building in this particular case is steel structure which can optimally balance between sustainable construction and the development of the society. Further research is however required to extend and test the model in other project contexts.

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