OPTIMIZED FLOORING SYSTEMS SELECTION BY ANALYTIC HIERARCHY PROCESS

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ABSTRACT

Selecting an appropriate flooring system is essential for structures. Flooring system design has traditionally focused on weight loss and minimizing costs. However, in recent years, the focus of this sector has changed to include improving the environmental performance of building materials and construction systems. This paper illustrates a knowledge-based expert system as a tool to assess of flooring systems such as block joisted (BJ), steel-concrete composite (SCC), composite steel deck (CSD) and concrete slab (CS) based on sustainability criteria that are further divided into twenty sub-criteria. Analytical hierarchy process (AHP) is utilized as a multi-criteria decision making technique that helps to compute weights and rankings of sustainability criteria. For this purpose, some questionnaires completed by construction industry experts in order to compare criterions and sub-criteria in addition to assessment of optimized flooring systems. Then, results of the questionnaires are ranked by AHP and the most significant alternative is selected. The AHP results indicate that CSD system 47.9%, CS; 29.8%, SCC; 12.7% and BJ system 9.6% are the most and the least efficient systems, respectively.

1. INTRODUCTION

The selection of flooring system is one of the most underlying stages for the design and development of any structural components. Buildings designers and contractors have traditionally attempted to minimizing the costs and reducing the overall weight of the

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flooring system. Therefore, one of the challenges in the flooring system is to obtain cost-effective solutions with low-environmental and associated socio-economic impacts of construction activities to get sustainable development goals. Sustainability is a concept that has a great importance for society and for construction sector, because 50% of material resources taken from nature are building related, over 50% of national waste production comes from the building sector and 40% of the energy consumption is building related [1, 2]. Due to the increase in benefit of sustainable construction, buildings designers are motivated to select materials that are more sustainable. It is completely impossible that any individual material is meets and satisfies all criteria. So, it becomes a real challenge for designers to optimally select the material from the wide range of materials with various conflicting criteria, which ultimately leads to a multi-criteria decision making (MCDM) problem. MCDM methodology which is aimed at improving decision quality can play a main role in that decision making process, because it can address the different characteristics of sustainability criteria and aids in evaluating competing alternatives defined by their multiple attributes [3, 4]. Analytic hierarchy process (AHP) is a common MCDM technique that can be used to assign relative weights to various sustainability (sub) criteria and aggregate those estimates to specify an optional measure of sustainability [5]. The AHP prepares an organized description of the hierarchical interaction or connection among the elements (impacts, criteria or alternatives). It always begins with an aim statement and then develops a decision tree through top to bottom [6, 7]. In this regard, several studies have been performed on MCDM methods and applications. Reza *et al.* (2011) presented one such study evaluating flooring systems in the city of Tehran based on the triple-bottom-line sustainability criteria. They utilized an analytical hierarchy process as a multi-criteria decision-making technique and showed the expanded polystyrene block to be the most sustainable solution for that region [8]. López-Mesa *et al.* (2009) presented another example of this kind of study with their comparative analysis of structures between precast concrete floors and in-situ cast floors. In their research, they found that the environmental impact of precast floors was 12.2% lower than the in-situ solution, although their cost was 17.91% higher. Nevertheless, a persistent need still exists for decision-making tools that prepare cost-effective and low-environmental impact solutions in flooring system design [9]. Ceniceros *et al.* (2013) have studied the data mining techniques utilized to gain a decision support model for the design of one-way floor slabs, applied in a case study of Spain. The decision-making procedure took into account the embodied CO_2 and the total cost of the slabs in order to find eco-friendly and cost-effective solutions. A decision criterion was determined for this aim and was based on five levels of embodied CO_2 restriction; and the lowest cost solution for each level was selected [10]. Balali *et al.* (2014) studied to choose the best building structural system for thermal insulation out of five alternatives based on criteria like cost, ease of construction, energy saving, dead load, number of stories and life cycle time using AHP method [11]. Ebrahimi *et al.* (2018) assessed and prioritized the various concrete structures such as a common reinforced concrete structure, prefabricated, insulating concrete formwork, 3D panel and tunnel concrete formwork for buildings with limited floors in Iran. This study was carried out to evaluate and compare different cases from the viewpoint of various criteria like cost, time, applicability and technical characteristics with industrialization approach. At the end, according to the results of questionnaires completed by building industry experts, analysis by AHP, the optimized

structural system is introduced [12]. Patnaik *et al.* (2020) studied a hybrid AHP-MOORA (multi-objective optimization on the basis of ratio analysis) methodology for selecting the best alternative polymer composite materials. For applying the method the attributes related to polymer composites are gathered from the literature. The approach started with AHP and obtained the weightage by keeping purpose as wear resistant and structural applications. The summarized result indicates that the ranking of the composite materials using three methods are quite similar to each other [13].

The main purpose of this research is to find out that which one of the abovementioned flooring systems such as block joisted (BJ), steel-concrete composite (SCC), composite steel deck (CSD) and concrete slab (CS) systems is the most optimized from the viewpoint of economic, environmental and social criteria. At the end, according to the results of questionnaires filled out by building industry experts, analysis by analytic hierarchy process (AHP) and the mentioned criteria, the optimized flooring system is introduced.

2. FLOORING SYSTEMS

The floor systems are one of the main structural components to resist not only the gravitational loadings but also the lateral loads. They are mostly horizontal or sloped structures that sustain the different loads, which are later transmitted to the other elements of the structure. Advanced technologies and new materials are increasingly utilized in their assembly; however, reinforced concrete is still the most widely utilized material, due to its advantages over other materials [14].

2.1 Block joisted (BJ) flooring system

The BJ flooring system is a widespread method in construction of buildings in Iran. This system is combination of precast and in-situ concrete. So, it has many benefits like speed in construction, reduction of molding and reinforcement costs, high quality of the factory produced elements and taking into consideration there is no necessity to use crane in site. The joist and block system has the advantage of simple molding in the site, so it speeds up the construction process. This system makes rigid-diaphragm decks in building that causes the appropriate behavior of structure against lateral loadings (i.e., earthquake load) [15]. Fig. 1 provides a schematic view of the block-joisted flooring system.
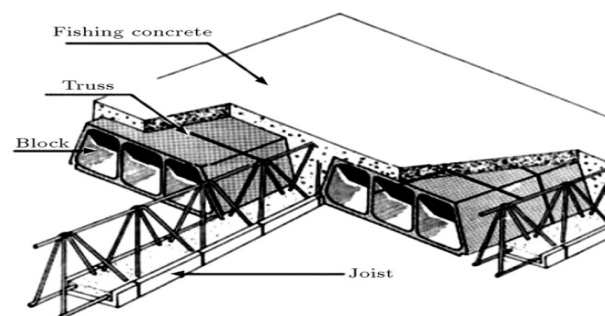

Figure 1. The details of block-joist flooring systems [15]

2.2 Steel-concrete composite (SCC) flooring system

Traditional SCC floors comprise of built-up or rolled structural steel beams and cast in-situ concrete floors connected together using shear connectors in such a procedure that they would act monolithically (Fig. 2). The main merit of steel-concrete composite construction lies in the utilization of the compressive strength of concrete slabs in conjunction with steel beams, in order to enhance the stiffness and strength of the steel girder.
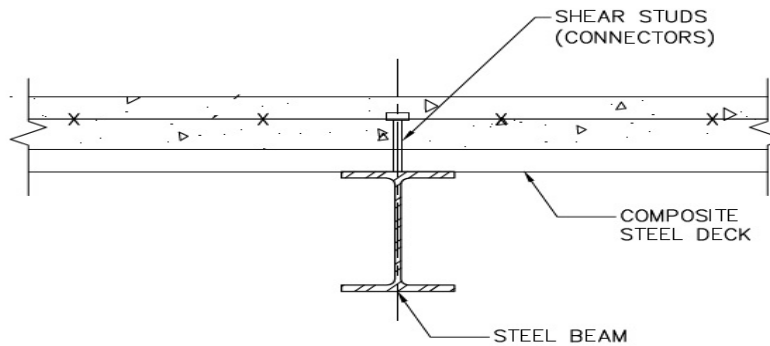

Figure 2. Steel-concrete composite floors details [16]

2.3 Composite steel deck (CSD) flooring system

More recently, composite floors using profiled sheet decking have become very popular in the tall buildings. CSD flooring systems are particularly competitive where the concrete floor has to be completed rapidly and where medium level of fire protection to steel work is enough. However, composite slabs with profiled decking are unsuitable when there is dynamic loading or heavy concentrated loading existed in structures. The alternative composite floor in such cases consists of pre-stressed or reinforced slab over steel beams connected together to act monolithically. A typical composite floor system using profiled sheets is shown in Fig. 3.
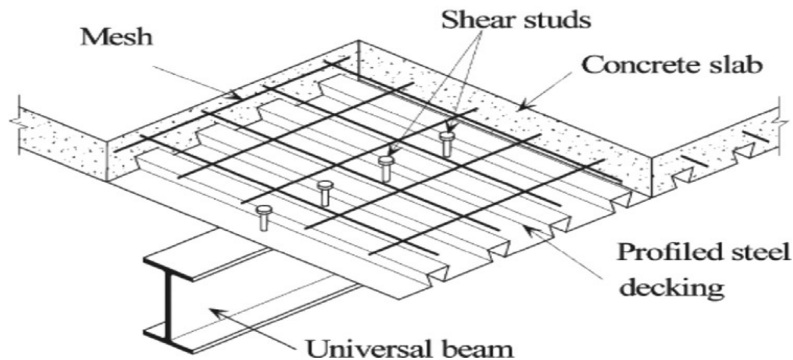

Figure 3. Composite steel deck floors details [17]

2.4 Concrete slab (CS) flooring system

CS is structural element whose thickness is small compared to its own width and length. Slabs are usually used in roof and floor construction (Fig.4). Concrete floor slabs may be in prefabricated or situ. The in-situ concrete slab floors are made using form-work, which is commonly built of wooden planks, steel or plastic. Reinforcing steel for slabs is primarily parallel to slab surface. Straight bar reinforcement is generally utilized, although sometimes alternative cranked bar are preferred.
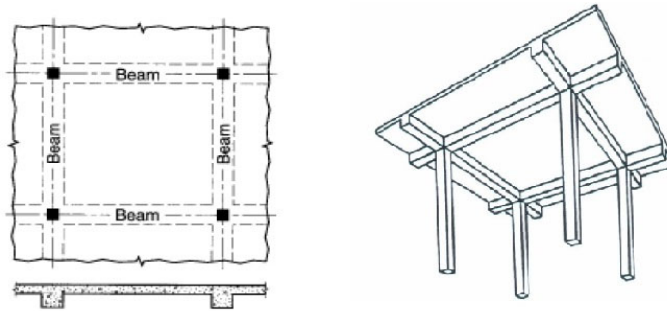

Figure 4. Concrete slab floors details [18]

3. OPTIMIZATION METHODOLOGY

The AHP is the optimization methodology used in this study. It is a MCDM tool and hence combines all the criteria of all the alternatives into a single value and ranks them in sequence. In fact, the AHP is a very powerful and flexible tool, because, the scores, and therefore the final ranking, are obtained on the base of the pair-wise relative assessment of both the criteria and the options provided by the user. The calculation made by the AHP are always guided by the decision maker's experience, and the AHP can thus be considered as a tool that is able to translate the assessments (both quantitative and qualitative) made by the decision maker into a multi-criteria ranking. In addition, the AHP is easy because there is no need to build a complex expert system with the decision maker's knowledge embedded in it. Application of AHP method needs the following four steps [19]:

3.1 Modeling

In this step, the problem and goal of decision-making changed into a hierarchy of decision elements related to each other. Decision elements consist of decision-making indices and decision alternatives. The AHP needs to break down a problem of multiple indices into a hierarchy of levels. Upper level shows the main goal of decision-making process. The second level shows main and basic indices which may break down into subordinate indices in next level. Accordingly, the last level presents decision-making alternatives.

3.2 Pairwise comparison matrix

Mental judgments of decision-makers used in comparison of criteria based on goal or

comparing alternatives based on criteria in a way if element i compared with element j, decision-maker will say one of the following modes for the importance of i in proportion to j (see table 1). It should be noted that if alternative B preferred to A, numerical value of this preference for B is $1/n$; where n is the very preferential value in the pairwise comparisons table.

3.3 Calculations of relative weights

Determination of decision elements weights is carried out through a set of numerical calculations. The next stage of AHP is to carry out required calculations for determining the priority of each decision element using information of pairwise comparisons matrices. Primary and general figure of pairwise comparisons matrices is presented in Eq. (1).

$$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

Table 1: Nine point scale of pair-wise comparison by Saaty (1980) [19]

Preferential value	Comparing i in proportion to j	Description
9	Perfectly important	Alternative A absolutely important than B and not comparable with j
7	Very important	Alternative A preferred very much than B
5	More important	Alternative A is important than B
3	Relatively important	Alternative A is a little important than B
1	Equally important	Alternative A and B are equally important or do not have any preference to each other
2,4,6,8		Middle values between preference values e.g. 8 shows an importance more than 7 an less than 9 for i

3.4 Calculation of consistency rate

Consistent matrix is defined as follows:

Consider n criteria including C_1, C_2, …, C_n, in which their pairwise matrix is as Eq. (2) and a_{ij} indicative of C_i preference on C_j. If Eq. (3) is true in the matrix, then matrix A is consistent.

$$A = [a_{ij}] \; i.j = 1,2, ..., n \tag{2}$$
$$[a_{ik}] \times [a_{kj}] = [a_{ij}] \quad i.j,k = 1,2, ..., n \tag{3}$$

In every consistent matrix, special value is equal to the matrix length. If there are n number of criteria, namely, $C_1, C_2, ..., C_n$ and denoting their weight as $W_1, W_2, ..., W_n$, respectively, then pairwise matrix for these elements is according to Eq. (4):

$$A = \begin{bmatrix} \dfrac{W_1}{W_1} & \cdots & \dfrac{W_1}{W_n} \\ \vdots & \ddots & \vdots \\ \dfrac{W_n}{W_1} & \cdots & \dfrac{W_n}{W_n} \end{bmatrix} \tag{4}$$

Theorem 1: If $\lambda_1, \lambda_2, ..., \lambda_n$ are special values of pairwise comparison matrix A, then total amount of their values is equal to n as shown in Eq. (5).

$$\sum_{i=1}^{n} \lambda_i = n \tag{5}$$

Theorem 2: The biggest special value (λ_{max}) is always greater than or equal to n (some of are negative).

$$\lambda_{max} \geq n \tag{6}$$

Theorem 3: If the matrix elements get away from consistency mode, then its special value will get a little away from its consistency mode.

On the other hand, Eq. (7) is true according to the definition for every square matrix A;

$$A \times W = \lambda . W \tag{7}$$

If matrix A is consistent, then a special value is equal to n (the biggest special value is equal to zero), therefore Eq. (8) is true;

$$AW = n \, W \tag{8}$$

If the pairwise comparison matrix A is inconsistent (theorem 3), the Eq. (9) is true

$$A \times W = \lambda_{max} . W \tag{9}$$

Since λ_{max} is always greater than or equal to n and if the matrix gets a little away from consistency mode, λmax will get a little away from n. Therefore, difference

between λ_{max} and n ($\lambda_{max} - n$) can be an appropriate criterion in measuring the matrix consistency. Undoubtedly, the $\lambda_{max} - n$ criterion depends on the matrix length (n) and such dependency can be removed by defining the criteria in form of Eq. (10) which is called consistency index (*CI*).

$$CI = \frac{\lambda_{\text{max}-n}}{n-1} \tag{10}$$

The *CI* value for the matrixes with random numbers calculated one may call it as Random Index (*RI*) matrix, that their values are equal to *n*-dimension matrixes according to Table 2.

Table 2: Random consistency indices adopted from Saaty (1988) [19]

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
RI	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57

Dividing *CI* of any matrix by *RI* of the same dimension is an appropriate criterion for judgment about consistency, which is called consistency rate (*CR*). If this value is less than or equal to 0.1, therefore, system consistency is accepted, otherwise judgments have to be reviewed. The *CR* obtained from Eq. (11) as follows:

$$CR = \frac{CI}{RI} \tag{11}$$

3.5 Evaluation criteria

The final criteria, which are obtained to select flooring system through studying criteria observed in previous researches and also gained by asking building industry experts, are shown in Fig. 5 that is consisting of four main criteria and their sub-criteria. Afterwards, criteria comparison and weight value of each one, estimated through pair-wise comparisons by the experts and geometrical average of the opinions with the assumption of equal decision-making power of respondents shown in Tables 3 to 6. To do so, the Expert Choice software is used to model and rank decision-making problems through AHP. The average of technical value of each criteria and sub-criteria are shown in above tables. In next part, final evaluation and ranking of flooring systems is done through the evaluation of each system for criteria and by technical value of criteria.

Table 3: Group pair-wise matrix of main criteria of optimized flooring system selection

Index A / Index B	Economic	Environmental	Social
Economic	1	0.5	2
Environmental	2	1	3
Social	0.5	0.333	1

Table 4: Group pairwise matrix of economic sub-criteria of selecting optimized flooring system

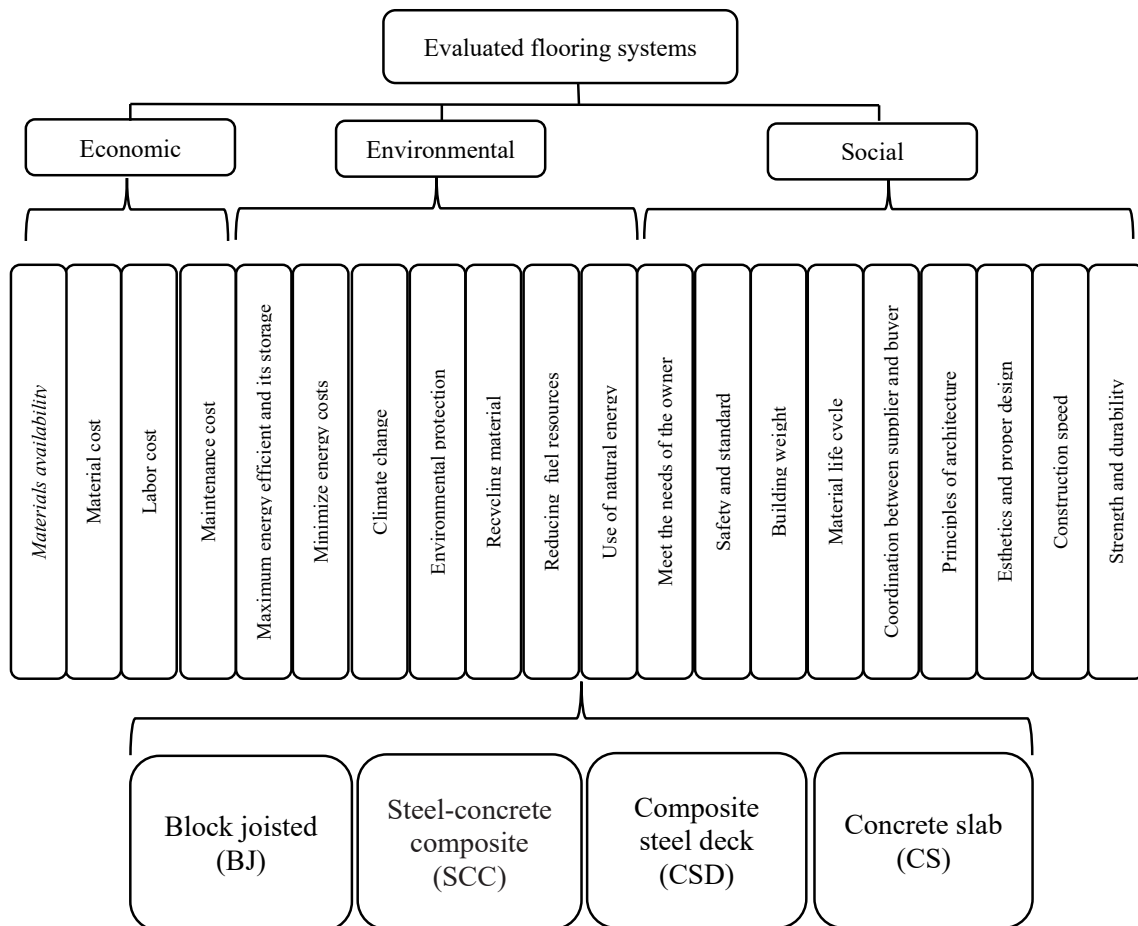| Index A / Index B	Materials availability	Material cost	Labor cost	Maintenance cost
Materials availability	1	0.5	2	0.5
Material cost	2	1	2	0.333
Labor cost	0.5	0.5	1	0.2
Maintenance cost	2	3	5	1

Figure 5. Hierarchy of decision-making of the evaluated flooring system

Table 5: Group pairwise matrix of environmental sub-criteria of selecting optimized flooring system

Index A / Index B	Maximum energy efficient and its storage	Minimize energy costs	Climate change	Environmental protection	Recycling material	Reducing fuel resources	Use of natural energy
Maximum energy efficient and its storage	1	5	4	3	2	3	2
Minimize energy costs	0.2	1	2	0.333	0.5	3	0.2
Climate change	0.25	0.5	1	0.2	0.25	0.333	0.5
Environmental protection	0.33	3	5	1	2	3	2
Recycling material	0.5	2	4	0.5	1	0.333	0.5
Reducing fuel resources	0.33	0.333	3	0.333	3	1	2
Use of natural energy	0.5	5	2	0.5	2	0.5	1

Table 6: Group pairwise matrix of Social sub-criteria of selecting optimized flooring system

Index A / Index B	Meet the needs of the owner	Safety and standard	Building weight	Material life cycle	Coordination between supplier and buyer	Principles of architecture	Esthetics and proper design	Construction speed	Strength and durability
Meet the needs of the owner	1	0.333	0.25	0.333	2	3	2	2	0.5
Safety and standard	3	1	0.5	2	3	2	3	0.5	0.333
Building weight	4	2	1	0.5	3	5	3	0.5	0.333
Material life cycle	3	0.5	2	1	2	3	2	2	0.5
Coordination between supplier and buyer	0.5	0.333	0.333	0.5	1	0.333	0.5	0.2	0.33
Principles of architecture	0.33	0.5	0.2	0.333	3	1	2	0.333	0.5
Esthetics and proper design	0.5	0.333	0.333	0.5	2	0.5	1	0.5	0.2
Construction speed	0.5	2	2	0.5	5	3	2	1	0.5
Strength and durability	2	2	3	2	3	2	5	2	1

4. RESULTS AND DISCUSSIONS

Based on the results obtained from the AHP analysis, the environmental criterion (0.495) has the highest priority and social criterion (0.147) has the lowest priority among all considered criteria. The relative weights of other criteria, all sub-criteria and their prioritization are listed in Table 7. Comparing the results shown in Fig. 6, the flooring systems constructed by CSD (47.9%) selected as the best system and the BJ system (9.3%) selected as the worst system. Relative weight of other systems and their prioritization is

shown in the same figure.

The consistency rate of results for pair-wise comparison matrix of the criteria for selecting flooring systems, which is calculated by Expert Choice software, was 3%. Accordingly, the calculated values for parameters *CI*, *CR*, *RI* and *λmax* for the selected alternatives are summarized in Table 8. It is concluded from this table that the value of parameter *CR* is less than or equal to acceptable value of consistency rate (10%) in AHP and thus will be marked as an accepted value.

Table 7: Relative weights of all criteria and sub-criteria

Main Criterion	Sub-Criterion	Weights	
		Sub-Criterion	Main Criterion
Economic	Materials availability	0.290	0.358
	Material cost	0.134	
	Labor cost	0.157	
	Maintenance cost	0.419	
Environmental	Maximum energy efficient and its storage	0.265	0.495
	Minimize energy costs	0.097	
	Climate change	0.052	
	Environmental protection	0.165	
	Recycling material	0.073	
	Reducing fuel resources	0.183	
	Use of natural energy	0.165	
Social	Meet the needs of the owner	0.071	0.147
	Safety and standard	0.126	
	Building weight	0.090	
	Material life cycle	0.163	
	Coordination between supplier and buyer	0.072	
	Principles of architecture	0.054	
	Esthetics and proper design	0.197	
	Construction speed	0.059	
	Strength and durability	0.168	

Table 8: Parameters in calculating CR in pairwise comparison matrix

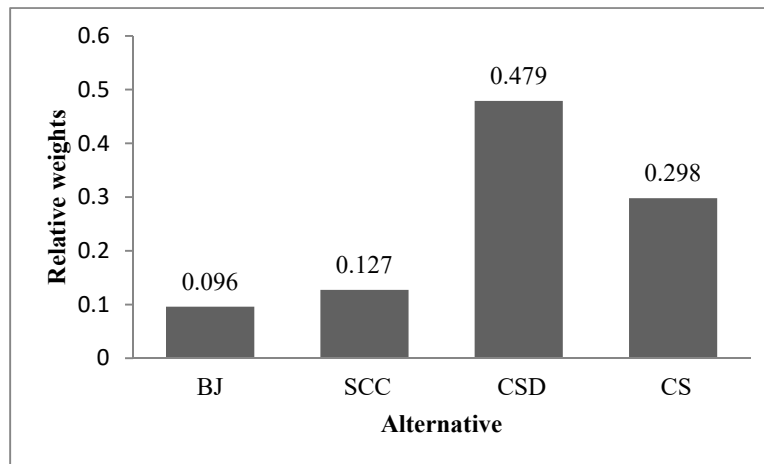| CR (%)	CI	RI	λ_{max}
7.672	0.0445	0.580	3.089

Figure 6. Relative weights of alternatives in proportion to the goal

5. CONCLUSION

A multi-criteria decision making method has been applied in this paper to assess diverse flooring systems based on sustainability criteria. The evaluation criteria have been selected from the literature based on the three main dimensions of assessment, economic, environmental and social criterions. For this purpose, some questionnaires completed by construction industry experts in order to compare criteria and sub-criteria and then, different flooring systems ranked by AHP and the most optimized choice selected. Finally, considering the significance of main criteria (e.g., economic 0.358, environmental 0.495 and social 0.147) and other sub-criteria that were compared for four flooring systems (namely, BJ, SCC, CSD and CS), the results of analysis demonstrate that the CSD system 47.9%, CS 29.8%, SCC 12.7% and BJ system 9.6% are the most and the least efficient systems, respectively.

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