Abstract

A big challenge in sustainable projects is selection of appropriate construction method and is considered to be the decisive factor for its success. Many environment friendly prefabricated elements are entering into the market at an increasing pace. This has increased the workload and inquisitiveness of the stakeholders who will need information about their environmental, technical and esthetic aspects. The use of prefabrication in sustainable construction is advantageous but appropriate decision criteria and their weightage for applicability assessments for a project from every stakeholder's perspective is found to be deficient. Decisions to use prefabricated elements are still largely based on anecdotal evidence or cost-based evaluation rather than holistic sustainable performance. But authenticated information is seldom available and suitability within the project requirements is always debatable. Environmental decisions, being closely coupled with society’s built-in uncertainties and risks, are uncertain since ecological systems as well as social systems change in the future. Thus the selection of a suitable construction method has been perceived as a multi-criteria decision-making problem highly intensive in knowledge with partial information and uncertainty. This knowledge or perception base from the minds of experts has to be collected and processed for a decision. Fuzzy synthetic evaluation method using analytic hierarchy process by Saaty has been adopted to provide an analytical tool to evaluate the applicability of prefabricated or on-site construction method.

Keywords: Buildings; Cast-in-situ construction; Precast construction environment; Mathematical modeling; Sustainability

1. Introduction

With mounting threats of environmental pollution, natural resource depletion and accompanying social problems, sustainable development in construction has become a growing concern (Neama, 2012). Construction of Green Buildings has now become a flagship of Sustainable Development in construction sector and offers an opportunity to create environmentally responsible and occupant friendly buildings. However, definition, scope and various approaches of Green Buildings compared to conventional buildings is still not well understood. Also, little emphasis has been laid on the importance of selecting more environment-friendly designs during the project appraisal stage when environmental matters are best incorporated. Project
appraisal based on a multi-dimensional approach would need a sustainability model to allow the alternatives to be ranked (Ding, 2008).

Conventional on-site construction methods have long been criticized for non-sustainability, low productivity, poor quality and safety records, long construction time, and large quantities of waste in the industry (Abioye, 2015; Agamuthu, 2008). Prefabrication is a manufacturing process, taking place at a specialized facility, to form component parts of the final installation. Several benefits of applying prefabrication technology in construction are commonly listed as: shortened construction time, lower overall construction cost, improved quality, enhanced durability, better architectural appearance, enhanced occupational health and safety, material conservation, less construction site waste, less environmental emissions, and reduction of energy and water consumption (Yee and Hon, 2001; Blismas et al., 2006).

Pasquire demonstrated that decisions to use precast elements are still largely based on anecdotal evidence rather than rigorous data, as no formal measurement criteria are available (Blismas et al., 2006). Gluch and Baumann also indicated that holistic and methodical assessments of the precast applicability to a particular project have been found to be deficient, and common methods of evaluation simply take material, time, labor and transportation costs into account when comparing various construction methods, without explicit regard for the sustainability, long-term cost or soft issues, such as health and safety of workers, energy consumption, and environmental impacts of a project (Gluch and Baumann, 2004). Also, for individual building projects, precast technology is not always the only available option, nor is it always better than on-site construction method due to various project characteristics and available resources. If not employed appropriately, change orders, severe delays in production, erection schedules, substantial cost overruns, and constructability problems may be encountered in the use of precast concrete systems (Sacks et al., 2004). The selection of appropriate construction method of a project, considered to be a decisive factor for its success, is perceived as a knowledge problem. The construction companies do not have formal systems to collect, process and manage this knowledge held in the minds of the professionals (Murtaza et al., 1993; Ferrada and Serpell, 2014). Ying Chen identified 33 performance criteria based on the sustainable triple bottom line and requirements of different project stakeholders, consisting of 16 economic criteria, 8 social criteria, and 9 environmental criteria (Chen et al., 2010). Wei Pan and Andrew Dainty developed 50 criteria grouped under cost, time, quality, health and safety, sustainability, etc. but cost was again ranked most important and sustainability, process and procurement were weighted lower. All of these demonstrate that criteria for decisions regarding construction methods are unclear and unrecorded. But considering the relative importance or weightage of each criteria from the perspective of every stakeholder in the decision making process is a difficult task. Thus the selection of a CM among alternative CMs is a multicriteria decision-making problem including both quantitative and qualitative criteria. In decisions related to environment and social factors, the values of the qualitative criteria are often imprecisely defined for the decision-makers. The conventional approaches to CM selection problem tend to be less effective in dealing with the imprecise or vague nature of the linguistic assessment. Thus we have a mix of both tangibles like cost and time and intangibles relating to subjective ideas and beliefs of the individual and the world of experience. So we need to use a coherent theory that can deal with both these worlds of reality without compromising either (Saaty, 1987). The Analytical Hierarchy Process formulates and analyzes decisions by simplifying a complex multi-criteria decision problem and uses the numerical ratings from the pair-wise comparisons to establish an importance weight for each criterion. The aim of this paper is to solve CM selection problem using approach of fuzzy synthetic evaluation group decision-making (Kahraman et al., 2003). Criteria derived from prior studies have been

### Notation

- \( u_1, u_2, \ldots, u_n \) are a set of evaluation factors or criteria
- \( v_1, v_2, \ldots, v_m \) are a set of evaluation grades
- \( V_i \) is a probable evaluation which can be described as excellent, good, normal, poor or very poor
- \( R \) is the fuzzy relation matrix from \( U \) to \( V \)
- \( r_{ij} \) is the membership degree (\( i = 1, 2, \ldots, n; j = 1, 2, \ldots, m \))
- \( N \) is the number of appraisal stakeholders
- \( x_{ij} \) is the number of the appraisal commissioners
- \( W \) is the weight set
- \( w_1, w_2, \ldots, w_n \) weights for evaluation criteria
- \( D \) is called the decision making set
- \( CM \) is the construction method
- \( W_{ECO} \) is the Weight vector for economic criteria
- \( W_{ENV} \) is the Weight vector for environmental criteria
- \( W_{SOC} \) is the Weight vector for Social criteria
- \( D_{PC1}, D_{PC2} \) and \( D_{PC3} \) are the decision making sets for Precast
- \( D_{CSI1}, D_{CSI2}, D_{CSI3} \) are the decision making sets for Cast in Situ
- \( R_{PC-ECO}, R_{PC-ENV}, R_{PC-SOC} \) are the Fuzzy Relation Sets for Precast construction
- \( R_{CS-ECO}, R_{CS-ENV}, R_{CS-SOC} \) are the Fuzzy Relation Sets for Cast in Situ construction
employed in the model developed to support and automate the complex considerations of precast and Cast in Situ CM on Green building projects. This will assist the integrated design team members in the selection of appropriate construction methods in concrete buildings during early project stages. As a result, the likelihood of sustainable construction is enhanced, both to meet society’s environmental goals and account for the social and economic impacts of Buildings and thus earn higher credits according to Green Building Rating Systems (Bansal, 2015; Kuncheva, 2001).

2. Literature review

Zuo and Zhao presented a systematic review of existing studies and found that focus is mainly on environmental aspects and social sustainability is being largely overlooked (Zuo and Zhao, 2014). Among all sectors, buildings are one of the largest sources of carbon dioxide and greenhouse gas (GHG) emissions. Developing a low carbon society is a global trend to achieve sustainability and counter the climate change issue (Zuo et al., 2012). Green building Rating systems (Smith, 2015) provide an effective framework for assessing Green Quotient of buildings. The advantages and industrialization of construction sector provide opportunities for prefabrication to better serve sustainable building projects. Worldwide, the highest precast construction levels in 1996 were located in Denmark (43%), the Netherlands (40%), Sweden and Germany (31%) (Jaillon and Poon, 2009). In the United States, the share of precast reinforced concrete construction is only 6% while the average across the European Union is 18% (Sacks et al., 2004).

Although the U.S. precast concrete industry produces technologically and architecturally complex building elements, such as double tees, inverted tee and ledger beams, hollow-core slab elements, and façade panels, in building construction market, the percentage of precast concrete systems is pretty low (approximately 1.2%) (Sacks et al., 2004). The construction industry in India is around USD 500 million and precast has only 2% share vis-à-vis the traditional method of cast-in-situ construction. However, a gradual shift is occurring and precast construction technology is rapidly gaining a foothold in the Indian construction market and primary among them is the need for affordable housing (VanGeem, 2006). Studies have been made comparing carbon emissions of Precast and conventional cast-in-situ construction methods for high rise buildings (Dong et al., 2015). A lack of incorporation of innovative sustainable technology into corporate strategy was reflected (Pan et al., 2012). The indicators collected from existing literatures and construction sector-based respondents recommend development of practical and simple tools for decisions ensuring sustainability. Govindan et al. (2016) perceived the selection of sustainable materials as a hybrid multi criteria decision making problem with a specific examination of UAE. Si et al. evaluated the application of Multi Criteria Decision making methods to the selection of Green technologies for retrofitting existing buildings. They also suggested that social criteria are as important as environmental or economic criteria which are based on rather quantitative data (Si et al., 2016). Another research on delivering sustainable buildings in context of China identified that additional cost, incremental time and limited availability of green suppliers and information are critical barriers to foster sustainable construction practices (Shi et al., 2013). A recent research analyzing econometric data from Qatar identified characteristics and organizational behavior attributes for Sustainable Construction Adoption. The factors internal to the firms like their risk taking tendencies, claimed competitive advantages or history of changes in modus operandi etc were reflected (Hassan et al., 2016). The problem of CM selection for sustainability involves Economic, Environmental and Social criteria out of which, some can be measured quantitatively and some can be estimated qualitatively. AHP allows decision-makers to make qualitative decisions objectively, enables systematic decision-making by expressing the interaction and hierarchy of factors, thus reducing the risk of a rough estimation. The hierarchy can be complex enough to capture the situation and also sensitive to any small changes (Saaty, 2008). This paper lays the groundwork for automated tools to help make project level decisions regarding prefabrication strategies and facilitates the achievement of a healthy built environment.

3. Research methodology

3.1. Analytic hierarchy process (AHP)

Choosing the appropriate construction method satisfying the triple bottom line of sustainability viz. Environmental, Economic and Social criteria from every stakeholder’s perspective is a multi criteria Group Decision making problem. Saaty’s analytic hierarchy process (AHP) (Thiranun and Xu, 2015), (Saaty, 1987) is being used to solve this problem which is an intuitively simple method to formulate and analyze decisions. AHP uses the numerical ratings from the pair-wise comparisons of criteria to establish a priority or importance weight. AHP allows decision-makers to make qualitative decisions objectively enabling systematic decision-making by expressing the hierarchy of factors in order of their weightage, thus reducing the risk of a rough estimation (Alonso & Lamata, 2006). Hence, this study adopted AHP to analyze client/developer, contractor et al. preferences in adoption of either precast or on-site construction method.

The three steps of AHP are decomposition into important criteria, comparative judgment of each with respect to another and finally synthesis into an aggregate form.
In the first step, a hierarchical structure is established to present the problem of choosing most apt CM. The next step compares criteria at the same level in pairs and measures their comparative contribution to higher Green Building rating. A comparison matrix was set up by comparing pairs of criteria or alternatives. A scale of values ranging from 1 (equally important) to 9 (extreme more important) was used to express stakeholders’ preferences. This pair wise comparison enabled the decision-maker to measure the contribution of each criterion to the objective independently, thereby simplifying the decision-making process. The final step conducts synthesis of preferences to calculate a composite weight for each alternative (Saaty, 2008).

3.2. Fuzzy synthetic evaluation

Fuzzy theory (Goguen, 1973; Negoita, 1988) was developed to provide decision-making capabilities in the presence of imprecise and uncertain information, which is usually expressed in linguistic terms. An important application of the fuzzy transform used in developing the extension principle is synthetic evaluation. Fuzzy synthetic evaluation uses fuzzy mathematics to transform and fathom unclear data, and has various attributes concerning evaluation of objects. Thus, a comprehensive assessment and general appraisal must be performed on related factors to produce the overall assessment (Saaty, 2008).

For both Precast and On-site construction method, suppose that domain $U = \{u_1, u_2, \ldots, u_n\}$ denotes a set of evaluation factors or criteria (shortened construction time, lower overall construction cost, improved quality, enhanced durability, better architectural appearance, enhanced occupational health and safety, material conservation, less construction waste, less environmental emissions); $V = \{v_1, v_2, \ldots, v_m\}$ denotes a set of evaluation grades, where $V_j$ denotes a probable evaluation which can be described as excellent, good, normal, poor or very poor. Every appraisal object has a fuzzy relation matrix $R$ from $U$ to $V$.

$$R = (r_{ij})_{nm}$$

where $r_{ij}$ denotes the membership degree $(i = 1,2, \ldots, n; j = 1,2, \ldots, m)$ and the appraisal object is measured as $v_j$ considering attribute $u_i$.

If N appraisal stakeholders make appraisal $v_j$ aiming at various factors in $U$ separately, where $x_{ij}$ denotes the number of the appraisal commissioners who determine $u_i$ as $v_j$, then the sum of each list of numbers in the table equals $N$.

If $r_{ij} = x_{ij}/N$, then the appraisal matrix of the stakeholders to a particular CM is obtained as $(r_{ij})_{nm}$.

However, the obtained appraisal matrix $R$ is not enough to appraise the CM yet; a fuzzy subset $W$ in $U$ called weight set that is, $W = \{w_1, w_2, \ldots, w_p\}$ in which $w_i > 0$ and $\sum w_i = 1$ should be obtained from AHP (The analytic hierarchy process: Applications and studies, 1993). The weight $W$ denoted the relative importance of the various criteria expressed by the decision makers or the stakeholders in this study. Moreover, a fuzzy subset $D$ in $V$ called the decision making set is also introduced and denotes the overall fuzzy appraisal of the stakeholder to the particular CM.

$$D = W \odot R = [d_1, d_2 \ldots d_m]$$

3.3. Questionnaire and data collection

First, stakeholders in decision making were interviewed to create the research model and questionnaire. For evaluation, criteria based on triple bottom line were employed. Chen projected 33 performance criteria (Chen et al., 2010) based on the sustainable triple bottom line and requirements of different project stakeholders, consisting of 16 economic criteria, 8 social criteria, and 9 environmental criteria. Wei (Pan et al., 2012) also developed 50 criteria out of which some were taken for this study. A nine-point Likert scale ranging from 1 (least important) to 9 (most important) was adopted. Ten experts were interviewed to formulate the hierarchy with the evaluation category and the criteria for each category. From many criteria, Saaty (MacCormac, 1983; Wasil and Golden, 2003) pointed out that human beings can simultaneously compare up to seven items. All of the criteria were weighed and top 7 criteria from each category were taken so that each level’s set of criteria does not exceed seven items (Fig. 1).

The second questionnaire (AHP questionnaire) was designed according to the analytic hierarchy structure. The various criteria under each level in the questionnaire were compared pair wise, producing values from 1 to 9 scale ratings. Experienced contractors and engineers validated questionnaire. The questionnaire was sent to industry practitioners within the construction industry who are primary participants in the precast concrete supply chain, including construction clients/developers, engineers, contractors, environmentalists, social workers and precast concrete manufacturers. All of them have different opinions and focus on construction method selection. Trends showed that clients were changing the way of their thinking taking “long-term cost” and environmental and social factors into account when selecting a construction method. In the Integrated Design of Green Buildings, every stakeholder is a part of decision making and he will have his own concerns depending upon his expertise. E.g. “Con structability” is the criterion that contractors may care most about, and clients may value “construction costs and time”. “Influence on job market” and “Pollution generation” are other social and environmental criteria as shown in Table 1.

3.4. Fuzzy analysis of data

Here we want to compare two main CMs – Precast and Cast-in situ. The evaluation criteria are based on the triple bottom line of economic, social and Environmental criteria as listed in Fig. 1.

The CMs are measured against these economic Criteria and given ratings as “Excellent(E)”, “Superior(S)”, etc.
“Adequate(A)” and “Inferior(I)”. “Excellent” means that CM is the best available with respect to the particular criterion. “Superior” means that the CM is among the best with respect to this criterion. “Adequate” means that, although not superior, CM can meet the minimum acceptable requirements for this criterion. “Inferior” means that the CM cannot meet the requirements for the particular criterion.

3.4.1. Economic criteria

The relations based on the consensus of the group of decision-makers with respect to different economic criteria are given in Table 2.

Now the criterion weight vector $W_{ECO}$, will be obtained by using Saaty’s analytic hierarchy process. The matrix of relative weights of subjective estimates is given in Table 3. The elements of each column are divided by the sum of that column (i.e., normalize the column) and the elements in each resulting row are added and this sum is divided by the number of elements in the row as shown in Table 4.

Using the matrix of subjective attribute weights in Table 3 and Saaty’s method, the following weight vector is obtained:

$$W_{ECO} = (0.342015, 0.239171, 0.166521, 0.118594, 0.068718, 0.046063, 0.018918)$$
Consistency checking: Consistency ratio (CR) checking is required to be checked whether the weights assigned based on expert reasoning is correct or not, usually its value is less than 0.1 which shows that the weights are consistent. A relative importance matrix to assign weights for comparing criteria as in Table 3. In this matrix diagonal elements are always 1 because criterion compared with itself will always be 1.

With the help of above subjective attribute weights matrix as in Table 3, we can calculate geometric mean (GM) as follows:

\[
\begin{align*}
\text{GM}_1 &= (1 \times 3 \times 3 \times 3 \times 5 \times 7 \times 7)^{1/7} = 3.513905 \\
\text{GM}_2 &= (1/3 \times 1 \times 3 \times 5 \times 3 \times 5 \times 7)^{1/7} = 2.443265 \\
\text{GM}_3 &= (1/3 \times 1/3 \times 1 \times 3 \times 3 \times 5 \times 9)^{1/7} = 1.717616 \\
\text{GM}_4 &= (1/3 \times 1/5 \times 1/5 \times 1 \times 3 \times 5 \times 7)^{1/7} = 1.047736 \\
\text{GM}_5 &= (1/9 \times 1/3 \times 1/7 \times 1/5 \times 1 \times 3 \times 7)^{1/7} = 0.5772 \\
\text{GM}_6 &= (1/9 \times 1/5 \times 1/7 \times 1/7 \times 1/5 \times 1 \times 7)^{1/7} = 0.346829 \\
\text{GM}_7 &= (1/9 \times 1/7 \times 1/9 \times 1/9 \times 1/9 \times 1/7 \times 1)^{1/7} = 0.161533
\end{align*}
\]

Hence total Geometric mean (GM) = \text{GM}_1 + \text{GM}_2 + \text{GM}_3 + \text{GM}_4 + \text{GM}_5 + \text{GM}_6 + \text{GM}_7 = 9.808084

Calculating normalized weights ([A_2]_{7X1} as weight matrix)

\[
\begin{align*}
W_1 &= \text{GM}_1/\text{GM} = 3.513905/9.808084 = 0.358266 \\
W_2 &= \text{GM}_2/\text{GM} = 2.443265/9.808084 = 0.249107 \\
W_3 &= \text{GM}_3/\text{GM} = 1.717616/9.808084 = 0.175123 \\
W_4 &= \text{GM}_4/\text{GM} = 1.047736/9.808084 = 0.106824 \\
W_5 &= \text{GM}_5/\text{GM} = 0.5772/9.808084 = 0.058849 \\
W_6 &= \text{GM}_6/\text{GM} = 0.346829/9.808084 = 0.035362 \\
W_7 &= \text{GM}_7/\text{GM} = 0.161533/9.808084 = 0.016469
\end{align*}
\]

Consistency can now be checked using following formulae:

\[
[A_3] = [A_1] \times [A_2],
\]

where \(A_1\) is relative importance matrix and \(A_2\) is weight matrix

Also \([A_4] = [A_3]/[A_2]\).

The calculations are tabulated in Table 5. Calculating average of \([A_4]\) i.e. \(\lambda_{\text{max}}\)

\[
\lambda_{\text{max}} = (7.280872 + 7.609021 + 6.838682 + 7.288072 + 7.607827 + 8.23268 + 8.087247)/7 = 7.563486
\]

Then Consistency Index = \((\lambda_{\text{max}} - n)/n - 1\), where \(n\) is size of matrix

Consistency Index = 0.093914

And Consistency Ratio (CR) = Consistency Index/Random Index

CR = 0.093914/1.32 = 0.071417 < 0.1 where Random index is already given for specified number of criteria and for seven criteria, its value is 1.32. Since value of CR is less than 0.1, hence the weights are consistent.

3.4.2. Environmental criteria

Similarly weight vector has to be generated for Environmental criteria and weights allocated have to be checked

Table 4

<table>
<thead>
<tr>
<th>Normalized column values</th>
<th>Sum of rows</th>
<th>Sum/7</th>
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<tbody>
<tr>
<td>0.431034</td>
<td>0.356923</td>
<td>0.395257</td>
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<td>0.142241</td>
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<td>0.422241</td>
<td>0.063462</td>
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<tr>
<td>0.142241</td>
<td>0.038462</td>
<td>0.026353</td>
</tr>
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<td>0.047441</td>
<td>0.063462</td>
<td>0.018445</td>
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<td>0.047441</td>
<td>0.038462</td>
<td>0.014493</td>
</tr>
<tr>
<td>0.047441</td>
<td>0.026923</td>
<td>0.014493</td>
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</tbody>
</table>

Table 5

<table>
<thead>
<tr>
<th>Calculating normalized weights ([A_2]_{7X1} as weight matrix)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W_1 = \text{GM}_1/\text{GM} = 3.513905/9.808084 = 0.358266)</td>
</tr>
<tr>
<td>(W_2 = \text{GM}_2/\text{GM} = 2.443265/9.808084 = 0.249107)</td>
</tr>
<tr>
<td>(W_3 = \text{GM}_3/\text{GM} = 1.717616/9.808084 = 0.175123)</td>
</tr>
<tr>
<td>(W_4 = \text{GM}_4/\text{GM} = 1.047736/9.808084 = 0.106849)</td>
</tr>
<tr>
<td>(W_5 = \text{GM}_5/\text{GM} = 0.5772/9.808084 = 0.058849)</td>
</tr>
<tr>
<td>(W_6 = \text{GM}_6/\text{GM} = 0.346829/9.808084 = 0.035362)</td>
</tr>
<tr>
<td>(W_7 = \text{GM}_7/\text{GM} = 0.161533/9.808084 = 0.016469)</td>
</tr>
</tbody>
</table>

Consistency Index = 0.093914
for consistency. The Fuzzy relations based on consensus of
decision makers with respect to different Environmental
criteria are given in Table 6. The matrix of relative weights
of subjective estimates is given in Table 7 which are nor-
malized in Table 8.

Using the matrix of subjective attribute weights and Saaty’s method, the following vector is obtained: $W_{ENV} = (0.416286, 0.276292, 0.161437, 0.101502, 0.044483).

### Consistency checking

Consistency ratio (CR) checking is again required for Environmental criteria to check whether the weights assigned based on expert reasoning is correct or not. If its value is less than 0.1, it shows that the weights are consistent. With the help of above subjective attribute weights matrix as in Table 7. We can calculate geometric mean (GM) as follows:

$$GM_1 = (1 * 3 * 3 * 5 * 3) ^{1/5} = 2.667269$$
$$GM_2 = (1/3 * 1 * 3 * 5 * 3) ^{1/5} = 1.715321$$

**Table 5**

<table>
<thead>
<tr>
<th>Criteria/alternatives</th>
<th>Economic Criteria</th>
<th>Environmental Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Disruption (SD)</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Waste (W)</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Recyclable Content (RC)</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Energy efficiency in building use (EE)</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Energy consumption in design and construction (EC)</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 6**

<table>
<thead>
<tr>
<th>Criteria/alternatives</th>
<th>Fuzzy relations between alternatives and evaluation criteria (Environmental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Disruption (SD)</td>
<td>0.8 0.4 0.3 0.1 0.2 0.5 0.4 0.3</td>
</tr>
<tr>
<td>Waste (W)</td>
<td>0.9 0.5 0.4 0.1 0.4 0.3 0.2 0.2</td>
</tr>
<tr>
<td>Recyclable Content (RC)</td>
<td>0.2 0.3 0.4 0.6 0.9 0.8 0.5 0.2</td>
</tr>
<tr>
<td>Energy efficiency in building use (EE)</td>
<td>0.5 0.4 0.3 0.2 0.9 0.8 0.7 0.2</td>
</tr>
<tr>
<td>Energy consumption in design and construction (EC)</td>
<td>0.7 0.6 0.4 0.1 0.5 0.4 0.3 0.2</td>
</tr>
</tbody>
</table>

**Table 7**

<table>
<thead>
<tr>
<th>SD</th>
<th>W</th>
<th>RC</th>
<th>EE</th>
<th>EC</th>
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<tr>
<td>1</td>
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<td>1</td>
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<td>3</td>
</tr>
<tr>
<td>1/3</td>
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<td>5</td>
<td>1/3</td>
<td>1</td>
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<tr>
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<td>1/8</td>
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**Table 8**

Normalized subjective attribute weights.

<table>
<thead>
<tr>
<th>Normalized column values</th>
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<tr>
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<tr>
<td>0.157143</td>
<td>0.205761</td>
<td>0.408719</td>
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<tr>
<td>0.157143</td>
<td>0.067901</td>
<td>0.13624</td>
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<tr>
<td>0.157143</td>
<td>0.041152</td>
<td>0.027248</td>
</tr>
<tr>
<td>0.052381</td>
<td>0.067901</td>
<td>0.015974</td>
</tr>
</tbody>
</table>

**GM_3 = (1/3 * 1/3 * 1 * 3 * 3) ^{1/5} = 0.995988**

**GM_4 = (1/3 * 1/5 * 1/5 * 1 * 3) ^{1/5} = 0.524251**

**GM_5 = (1/9 * 1/3 * 1/7 * 1/5 * 1) ^{1/5} = 0.252007**

Hence total Geometric mean (GM) = GM_1 + GM_2 + GM_3 + GM_4 + GM_5 = 6.154835

Calculating normalized weights ([A_2]_{5X1} as weight matrix)

$$W_1 = GM_1/GM = 2.667269/6.154835 = 0.433362$$
$$W_2 = GM_2/GM = 1.715321/6.154835 = 0.278695$$
$$W_3 = GM_3/GM = 0.995988/6.154835 = 0.161437$$
$$W_4 = GM_4/GM = 0.524251/6.154835 = 0.085177$$
$$W_5 = GM_5/GM = 0.252007/6.154835 = 0.040945$$

Consistency can now be checked using following formulae:

$$A_3 = A_1 * A_2$$

Where $A_1$ is relative importance matrix and $A_2$ is weight matrix.
Also $A_4 = A_3/A_2$

The calculations for consistency ratio for Environmental Criteria are tabulated in Table 9.

Calculating average of $A_4$ i.e. $\lambda_{\text{max}}$

\[
\lambda_{\text{max}} = 5.111589 + 5.223955 + 4.790235 + 5.15542 + 5.379811/5 = 5.132202
\]

Then Consistency Index = $(\lambda_{\text{max}}-n)/n-1$, where $n$ is size of matrix

Consistency Index = 0.033051
And Consistency Ratio (CR) = Consistency Index/Random Index

=0.033051/1.12 = 0.029509 < 0.1

Where Random index is already given for specified number of criteria and for five criteria, its value is 1.12. Since value of CR is less than 0.1, the weights are consistent.

3.4.3. Social criteria

Weight vector has to be generated for Social criteria also the Fuzzy relations between alternatives and evaluation social criteria are given in Table 10, with subjective attribute weights in Table 11 which are normalized in Table 12.

\[W_{\text{SOC}} = (0.429685, 0.283571, 0.149804, 0.094487, 0.042453)\]

Consistency checking: Consistency ratio (CR) is checked whether the weights assign based on expert reasoning is correct or not. If its value is less than 0.1, it shows that the weights are consistent. With the help of above subjective attribute weights matrix as in Table 11, we can calculate geometric mean (GM) and normalized weights as follows:

\[
\text{GM}_1 = (1 * 3 * 3 * 5 * 5)^{1/5} = 2.954177
\]
\[
\text{GM}_2 = (1/3 * 1 * 3 * 5 * 5)^{1/5} = 1.899831
\]
\[
\text{GM}_3 = (1/3 * 1/3 * 1 * 3 * 3)^{1/5} = 0.995988
\]
\[
\text{GM}_4 = (1/3 * 1/5 * 1/5 * 1 * 3)^{1/5} = 0.524251
\]
\[
\text{GM}_5 = (1/9 * 1/3 * 1/7 * 1/5 * 1)^{1/5} = 0.252007
\]

Hence total Geometric mean (GM) = $\text{GM}_1 + \text{GM}_2 + \text{GM}_3 + \text{GM}_4 + \text{GM}_5 = 6.626254$

\[
W_1 = \text{GM}_1/\text{GM} = 2.954177/6.626254 = 0.445829
\]
\[
W_2 = \text{GM}_2/\text{GM} = 1.899831/6.626254 = 0.286713
\]
\[
W_3 = \text{GM}_3/\text{GM} = 0.995988/6.626254 = 0.150309
\]
\[
W_4 = \text{GM}_4/\text{GM} = 0.524251/6.626254 = 0.079117
\]
\[
W_5 = \text{GM}_5/\text{GM} = 0.252007/6.626254 = 0.038032
\]

Consistency can now be checked using following formulae:

\[A_3 = A_1 * A_2, \text{ where } A_1 \text{ is relative importance matrix and } A_2 \text{ is weigh matrix}
\]

Also $A_4 = A_3/A_2$

Calculations for consistency ratio for social criteria are tabulated in Table 13.
Calculating average of $A_4$ i.e. $\lambda_{\text{max}}$

$$\lambda_{\text{max}} = \frac{(5.254568 + 5.128857 + 4.94643 + 5.40641 + 5.746659)}{5} = 5.296585$$

Then Consistency Index = $\frac{\lambda_{\text{max}} - n}{n-1}$, where $n$ is size of matrix

Consistency Index = 0.074146

And Consistency Ratio = Consistency Index/Random Index = $\frac{0.074146}{1.12} = 0.066202 < 0.1$

where Random index is already given for five number of criteria as 1.12. Since value of CR is less than 0.1, the weights are consistent.

3.5. Composition of weight set and Fuzzy relation

Every CM Decision set can be obtained by composition of the weight set and Fuzzy relation set as follows – Out of the two composition techniques – Fuzzy max–min composition and Fuzzy max-product composition, Fuzzy max–min composition has been employed for this problem.

The max–min composition of $R(x, y)$ and $S(y, z)$ denoted by

$$R(x, y) \circ S(y, z)$$

Is defined by $T(x, z)$ as

$$T(x, z) = \mu_{R \circ S}(x, z) = \max \{\mu_R(x, y) \cdot \mu_S(y, z)\}$$

The CM decision making set for Precast can be $D_{PC1}$, $D_{PC2}$ and $D_{PC3}$ and for Cast in Situ can be $D_{CS1}$, $D_{CS2}$, $D_{CS3}$ on Economic, Environmental and Social criteria respectively.

\[
\begin{align*}
D_{PC1} &= W_{ECO} \circ R_{PC-ECO} \\
D_{PC2} &= W_{ENV} \circ R_{PC-ENV} \\
D_{PC3} &= W_{SOC} \circ R_{PC-SOC} \\
D_{CS1} &= W_{ECO} \circ R_{CS-ECO} \\
D_{CS2} &= W_{ENV} \circ R_{CS-ENV} \\
D_{CS3} &= W_{SOC} \circ R_{CS-SOC}
\end{align*}
\]

The calculations for one of them is shown below and the rest five can be calculated similarly-

$$D_{PC1} = W_{ECO} \circ R_{PC-ECO}$$

$$W_{ECO} = (0.342015, 0.239171, 0.166521)$$

The Fuzzy relation set of Precast CM for economic criteria ($R_{PC-ECO}$) are given in Table 14 which are max-min composed with $W_{ECO}$.

\[
\begin{align*}
\mu_{R}(x_1, z_1) &= \max \{\min (0.342015, 0.8), \min (0.239171, 0.9), \min (0.166521, 0.2), \min (0.118594, 0.1), \\
\mu_{R}(x_1, z_2) &= \max \{\min (0.342015, 0.4), \min (0.239171, 0.3), \min (0.166521, 0.3), \min (0.118594, 0.2), \\
\mu_{R}(x_1, z_3) &= \max \{\min (0.342015, 0.3), \min (0.239171, 0.4), \min (0.166521, 0.4), \min (0.118594, 0.2), \\
\mu_{R}(x_1, z_4) &= \max \{\min (0.342015, 0.1), \min (0.239171, 0.1), \min (0.166521, 0.6), \min (0.118594, 0.1), \\
\mu_{R}(x_1, z_5) &= \max \{\min (0.342015, 0.3), \min (0.239171, 0.4), \min (0.166521, 0.4), \min (0.118594, 0.5), \\
\mu_{R}(x_1, z_6) &= \max \{\min (0.342015, 0.4), \min (0.239171, 0.3), \min (0.166521, 0.3), \min (0.118594, 0.2), \\
\mu_{R}(x_1, z_7) &= \max \{\min (0.342015, 0.1), \min (0.239171, 0.1), \min (0.166521, 0.6), \min (0.118594, 0.1), \\
\mu_{R}(x_1, z_8) &= \max \{\min (0.342015, 0.4), \min (0.239171, 0.3), \min (0.166521, 0.3), \min (0.118594, 0.2), \\
\mu_{R}(x_1, z_9) &= \max \{\min (0.342015, 0.4), \min (0.239171, 0.3), \min (0.166521, 0.3), \min (0.118594, 0.2)
\end{align*}
\]

Defuzzification means calculating the crisp value of fuzzy number. The crisp value will approximately represent the deterministic characteristics of the fuzzy reasoning process based on the assessment matrix, and thus help convert the uncertainty into an applicable action when solving real world problems. The defuzzification way is as follows.

$$K = D \ast S$$

where $K$ is a defuzzification score, $D$ is the decision making set, and $S$ is the appraisal grade set. Here in this paper taken as- Excellent (E), Superior(S), Adequate (A), inferior

<table>
<thead>
<tr>
<th>Normalized column values</th>
<th>Sum</th>
<th>Sum/5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.47619</td>
<td>0.157143</td>
<td>0.157143</td>
</tr>
<tr>
<td>0.617284</td>
<td>0.205761</td>
<td>0.067901</td>
</tr>
<tr>
<td>0.408719</td>
<td>0.13624</td>
<td>0.027248</td>
</tr>
<tr>
<td>0.352113</td>
<td>0.211268</td>
<td>0.070423</td>
</tr>
<tr>
<td>0.294118</td>
<td>0.176471</td>
<td>0.176471</td>
</tr>
<tr>
<td>2.148424</td>
<td>1.417854</td>
<td>0.749022</td>
</tr>
<tr>
<td>0.429685</td>
<td>0.283571</td>
<td>0.149804</td>
</tr>
</tbody>
</table>

Table 12

Normalized subjective attribute weights.

<table>
<thead>
<tr>
<th>Normalized column values</th>
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<th>Sum/5</th>
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<tbody>
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</tr>
<tr>
<td>0.429685</td>
<td>0.283571</td>
<td>0.149804</td>
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</tbody>
</table>

Table 13

Calculations for Consistency Ratio (Social Criteria).

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$D_{PC1}$</td>
<td>$D_{PC2}$</td>
<td>$D_{PC3}$</td>
<td>$D_{CS1}$</td>
</tr>
<tr>
<td>$D_{CS2}$</td>
<td>$D_{CS3}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(I) can be defined in appraisal grading as 100, 75, 50, and 25 respectively. Using this scale, the CM Precast and Cast in situ scores on Economic, Environmental and social criteria are shown in the Table 15 below.

The above table shows a crisp score in every criteria domain for both the construction methods. These values have been derived based on experts’ opinions on the weightage of one criteria upon another and to what extent a particular CM satisfies that criteria again opined by the field expert/Stakeholder. Depending upon the significance of economic vs. environmental vs. social criteria in the domain of a particular project, a particular CM can be adopted.

4. Discussion

The scores show the collective inclination of current knowledge perception of different stakeholders toward particular criteria in economic, environmental and social domains. Precast CM scores higher than Cast-in-situ for Environmental criteria but scores less for social criteria. Both CMs are at par as far as economic criteria are concerned and this small parity can be borne if other two legs of sustainability tripod are satisfied. Precast construction directly and adversely affects the job market and thus scores less whereas Cast-in-situ or conventional construction is a major employment avenue in a country. Also the scores show that social awareness and environmental concerns are considered to be increasingly important when selecting construction methods. Workers’ health and safety, health of occupants, water and energy efficiency in building use, and reusability/recyclability issues are rated with higher priorities. Since Governments are giving incentives to projects with higher Green Building ratings, the stake holders would put more emphasis on criteria related to rating scheme points. As the Green Building rating schemes become more popular, increased environmental consideration in CM selection is an inevitable trend in the future. Though most of the Green Building Rating schemes allocate higher credits toward environmental criteria and specify lesser credit points to social and economic criteria but CM selection cannot ignore these criteria. The industrialization of construction elements has social implications relating to wage fixation, availability of technical and general labor etc.

Successful implementation of the CM selection tool proposed requires genuine and systematic process of opinion collection and early decision-making based on project factors. Adoption of Precast construction may appear to be more viable with recent advances in design and information technologies but the decision has to be supported by experts’ knowledge domain. The proposed tool provides transparency in invoking decision-makers’ judgment on relative importance of decision factors and helps users sort out what factors drive or impede its use on the project under consideration.

5. Conclusion

This research work deals with multi-criteria decision making problem of an expert during selection of suitable construction method of a green building. The contemporary industry emphasis on the apparent advantages of precast construction over cast-in-situ method in the era of industrialization and sustainable development needs to be proven. Holistic criteria considering both ‘hard’ and ‘soft’ factors capturing the sustainable performance of construction methods instead of traditional measures of cost, time and quality need to be employed. Since no formal and authenticated data on the applicability of construction methods are available, this study employed Zadeh’s Fuzzy synthetic evaluation technique to develop an analytical tool based on the experts’ collective preferences in the Integrated Green Building Design. An
appropriate balance between economic, social, and environmental issues of sustainable construction has been attempted reflecting the concerns of different experts/project stakeholders. The weightage allocated to each criteria has been obtained from pair wise comparisons and then the weights checked by finding the consistency ratio. The optimum construction method selected will satisfy all the project stakeholders and also the criteria being evaluated requires minimal information usually available in the early stages of conceptualization. Since the results give crisp score for different set of criteria, decision can easily be made giving due consideration to social, economic or environmental aspects as per project constraints. This paper lays the foundation for automated tools to help make project level decisions and strategies toward a healthy built environment. Same analytical model may be applied if some other criteria are adopted and the experts’ opinions change according to their perspective and requirements. Further empirical studies should be carried out for different type of projects to widen knowledge of the near-future market potential for industrialization of construction sector.

References


