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Rank of green building material criteria based on the three pillars of sustainability using the hybrid multi criteria decision making method

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ABSTRACT

A green building material (GBM) is an ecological, health-promoting, recycled, or high-performance building material that impacts the material selection to cover all three pillars (3Ps) of sustainability. The absence of clear instructions for GBMs and the difficulty of precision adjustments of GBM criteria with 3Ps sustainability make GBM selection a challenge. In addition, the consideration of all sustainability factors in GBM selection is a multi-criteria decision problem that requires mathematical techniques such as the multi criteria decision making (MCDM) method.

This study applies a hybrid MCDM methodology to resolve multiple incompatible and conflicting GBM criteria to align with 3Ps sustainability. The Decision-Making Trial and Evaluation Laboratory (DEMATEL) was used to analyze the efficacy of and interrelationship between GBM criteria. This tool is a hybrid model using fuzzy analytic network process (FANP) for aligning and ranking GBM criteria based on 3Ps sustainability. Additionally, the study inspects four groups of professionals in Malaysia who involved in GBM selection and modified one of the oldest GBM criteria models considering the criteria identified from a comprehensive literature review. The results show that the relationship between GBMs and sustainability criteria are different based on the separate 3Ps of sustainability. The evaluation and results provide a valuable reference for building professionals to enhance sustainable construction through green materials.

1. Introduction

The impact of building materials differs based on contamination and the material's function in each stage of its life cycle production from cradle to grave (Balaras et al., 2005; Moncaster and Symons, 2013). Green materials with low or no impact on humans and the environment can decrease embodied energy (Thormark, 2006; Venkatarama Reddy and Jagadish, 2003), energy consumption (Papadopoulos and Giama, 2007), CO_2 emission (Gonzalez and Navarro, 2006), indoor air pollution (Ries et al., 2006), and recyclability (Kubba, 2010). This strategy is required to achieve sustainability in building materials (Halliday, 2008; Barrett et al., 1999; Abidin, 2010). The mainstream theory for sustainability has become the idea of three pillars (3Ps): environmental, social and economic sustainability (Adams, 2006). These 3Ps have been drawn in a variety of ways: pillars (Forestry Commission of Great Britain, 2009), concentric circles (Scott Cato, 2009), or interlocking circles (Adams, 2006). Therefore, applying sustainability to materials selection requires achieving all 3Ps of sustainability.

Based on sustainability criteria, selecting materials with low embodied energy, waste, energy consumption, and pollution directly reduces the environmental burdens of construction materials and indirectly affects the other two dimensions of sustainability: economic and social (Weißenbergera et al., 2014). Economically, building materials with low energy consumption contribute to sustainability criteria (Abeysundara et al., 2009). Socially, the type of material contributes to the residents' health status. People spend over 80% of their time indoors (Frontczak and Wargocki, 2011), and hazardous materials can directly affect indoor

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air quality and therefore the occupants' health (Birt and Newsham, 2009). Green building materials (GBMs), as an important term in the 20th century, has been potential to minimize these total impacts in terms of material selection (Ip and Miller, 2012; Changa et al., 2015).

Usually, the material selection process considers some typical concerns such as quality, performance, aesthetics, and cost, and this process would reveal the material performance criterion overall. Nowadays, the evolution process of material selection has moved more towards the attention to green and sustainable performance criterion. One of those is “State-of-the-art” in GBMs performance criteria; that undoubtedly consider multi-attribute. GBM as high performance building material is an environmentally, healthy, and recyclable material which is performed of efficiently reducing impacts to environment and human health during its whole life cycle (LC). Although the material selection process is fundamentally the same for both green and non-green material, but the variance of GBMs criteria encounter a greater burden for GBMs selection procedure. This process is becoming quite complex and multi-criteria decision problems when is aimed to align with 3Ps of sustainability.

Many assessment tools such as Building for Environmental and Economic Sustainability (BEES) (BEES) and Leadership in Energy and Environmental Design (LEED) (LEED) focus on sustainability in terms of material selection. However, the majority of these tools focus on environmental issues and do not consider economic or social sustainability (Sinou and Kyvelou, 2006). Therefore, to consider all three sustainability pillars in material selection, mathematical decision techniques need to be developed (Rao, 2008; Rao and Patel, 2010). Selecting building materials is a multi-criteria decision problem, largely based on experience rather than using a numerical approach (Jato-Espino et al., 2014; Pacheco-Torgal et al., 2014; Nassar et al., 2003). In this regard, multiple-criteria decision making (MCDM) has developed as part of procedure research, designing computational and mathematical tools to help decision makers evaluate performance criteria (Behzadian et al., 2012; Zavadskas et al., 2015). Building material selection typically encompasses multiple conflicting criteria that need to be evaluated to make more informed and better decisions. Numerous studies in the construction industry use multi-criteria decision making methods (Behzadian et al., 2012; Shapira and Goldenberg, 2005; Ugwu et al., 2006; Wong and Li, 2008; Bahareh et al., 2011; Wang et al., 2012), but no work has been done yet to address selecting green building materials with MCDM (Pacheco-Torgal et al., 2014; Florez and Castro-Lacouture, 2013; Franzoni, 2011). The aim of this study is to develop a methodological and systematic approach for building material selection that aligns, prioritizes, and weights the GBM criteria considering the three pillars (3Ps) of sustainability and their network relations (Akadiri and Olomolaiye, 2012). In addition, the objectives of this research are the following:

1 Recognize and categorize the GBM criteria and expand the correlation with sustainability criteria.
2 Analyze the efficacy of and the interrelationship between the GBM criteria with the applicable method.
3 Pairwise compare and express the valuation and magnitude of the GBM criteria based on the 3Ps of sustainability.
4 Analyze and weight the GBM criteria based on 3Ps sustainability with the appropriate methods.

To achieve these objectives, this study uses the hybrid multi-criteria decision making (MCDM) methodology to resolve multiple incompatible and conflicting GBM criteria to align with 3Ps sustainability (Šaparauskas and Turskis, 2006). Specifically, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) was used to analyze the efficacy of and the interrelationship between the GBM criteria, and fuzzy analytic network process (FANP) was used for the best weighting of the GBM criteria based on 3Ps sustainability. The DEMATEL is a useful tool for analyzing correlations among factors using the crisp values (Vafadarnikjoo, 2014), and the FANP method is a multi-criteria decision making method based on the analytic hierarchy process that enables the existence of interdependences among criteria (Saaty and Cillo, 2009).

2. Literature review

2.1. The role of sustainability in selecting building materials

Sustainability is a complex concept that has become one of the major issues in material science (Kates, 2010). Selecting building materials is one of several factors that can influence sustainability in the construction industry (Behzadian et al., 2012). Disagreement on the environmental impacts from building materials is inevitable, but it has the capability to steer the sustainability criteria to reduce the total impact (Torgal and Jalali, 2011). Sustainability is a guiding influence for all human work, including the construction industry, that improves the quality of human life within the carrying capacity of the supporting eco-systems (IUCN/UNEP/WWF, 1991). The 2005 World Summit on Social Development defined 3Ps of sustainability: environment, economic, and social; which can be mutually reinforcing (Forestry Commission of Great Britain, 2009; United Nations General Assembly, 2005). Based on this definition, the consideration of all three sustainability pillars is required for a suitable strategy to align sustainability with the selection of building materials to minimize their total impacts. Some research has studied sustainability in terms of selecting building materials (Akadiri and Olomolaiye, 2012; Akadiri et al., 2013; Govindan et al., 2016); and, classified sustainable building materials criteria into the three pillars of sustainability. However, the aim of this research is to weight and align the GBM criteria with the three sustainability pillars.

The words “sustainable” and “green” are often used interchangeably, but they do not mean the same thing. The definition of “green” focuses on products and people, while “sustainable” (Kates, 2010) is a much wider term based on the 3Ps that examines the implications of those products and services used over a much longer period of time. Green engineering is raising to the design, commercialization and use of procedures and products that are economically feasible while reducing the generation of the source of pollution and minimizing the risk to human health and the environment (Braz. J. Chem. Eng., 2272). But, the term of ‘green’ deals directly with an elimination of hazardous materials and constituents that possess hazardous characteristics (IECR, 2015; Separation and Purification Technology, 2015).

Historically, green buildings can be traced back to ancient times with the use of eco-friendly materials. However, the official green building movement started during the energy crisis, and the concept of sustainability was researched and developed in the 1960s and 1970s (Mao et al., 2009). The initial effort was published in the book Silent Spring (Carson, 1962), which described sustainable development as related to green building (Mao et al., 2009). A green building material considered as an ecological, health-promoting, recycled, or high-performance building material that is capable of efficiently minimizing the environmental impacts and human health damage during its entire life cycle (Li, 2013). GBMs comprise a growing list of products and materials currently in the market used to build, furnish, and power buildings (Bezdek, 2008). To be on these lists, materials have to meet certain eco-friendly criteria such as being manufactured from recycled materials or containing low volatile organic compound (VOC) levels (United States Environmental Protection Agency). The ideal building material would have no negative environmental impacts, or perhaps even positive environmental impacts, including impacts on air, land, and water purification (Franzoni, 2011). The potential of GBMs is based on the three sustainability criteria (United States Environmental Protection Agency):

- Environmental benefits: Enhance and protect ecosystems; improve air and water quality; decrease waste streams to air and land; and preserve and restore natural and renewable resources.
- Economic benefits: Decrease operating costs; create, expand, and shape markets for green products and services; improve occupant productivity; and optimize life-cycle economic performance.
- Social benefits: Enhance occupant comfort and health; heighten aesthetic qualities; minimize strain on local infrastructure; and improve overall quality of life.

However, no perfect green material exists. In practice, a growing number of green materials can reduce or eliminate negative impacts on people and the environment (Halliday, 2008; Mickaityte et al., 2008). The absence of a standard for GBMs has led this study to aligning GBMs with 3Ps sustainability.

In this research, the precision adjustment of GBM criteria with the three sustainability pillars intensified the difficulty of selecting building materials. For instance, a manufactured material made with natural or renewable resources can be considered a GBM (Spiegel and Meadows, 2010b). This material directly affects the environmental dimension of sustainability, but it could also indirectly affect the other two dimensions (social and economic) of sustainability. The best advantage of this material is reducing the final production cost, which falls under the economic dimension of sustainability (Chikhia et al., 2013) and the affordable characteristic of GBMs (Akadiri and Olomolaiye, 2012). Conversely, affordable GBMs can be manufactured using natural and renewable resources, which aligns with the environmental, social, and economic sustainability dimensions. With this material description, all GBMs and sustainability criteria have mutual effects that lead to unexpected consequences in terms of GBM selection (Fig. 3). Therefore, based on the aim of this study, the methodical and systematic approach for weighting the aligned GBMs with sustainability criteria should consider the relationships and effects of each criterion.

2.2. Hybrid multi-criteria decision making (MCDM)

The MCDM has been considered as an active method for research since 1970s and is concerned with structuring and resolving decision and planning problems related to multiple criteria (Köksalan et al., 2011). It has ability to concept an inclusive judgement and theoretical implications from many indicators that considered in different fields such as ‘environmental performance’ (Rowley et al., 2012). Besides, MCDM has been used extensively to evaluate sustainability, and a good overview can be found in to provide a path towards the achievement of a sustainable future (Cinelli et al., 2014).

The analytic hierarchy process (AHP) has been commonly used in MCDM to measure quantitative and qualitative criteria (Saaty, 1980). AHP decomposes an MCDM problem into a hierarchical structure by assuming that the criteria relationships in different levels are independent (Saaty and Vargas, 1987). According to this research (section 2.1), the network relation and effect of all of the criteria on GBMs and sustainability must be considered. AHP has difficulty with interval judgments to implement in real-life problems (Velasquez and Hester, 2013). Additionally, the assumption in AHP of independent relationships at different levels of the hierarchical structure is not always true in MCDM problems (Ayag and Ozdemir, 2012). Thus, analytic network process (ANP) as a generalization of AHP created by Saaty in 1996 to address problems involving interdependent relationships between criteria (Saaty, 1996). This method applies a network structure instead of a hierarchical structure and. In current research, ANP could be an applicable method for considering the network relation between GBMs and sustainability criteria. This method can assess the consistency of the decisions and processes by breaking down the problem into smaller parts, appropriate for a more detailed analysis. Analyzes of construction industry experts' correspond to the information could be sometimes ambiguous evidence or judgments. Thus, to address these uncertain human judgments, the fuzzy ANP method was developed (Mikhailov and Singh, 2003); this method has been appropriately applied to increase the capabilities of the ANP method for commerce with inconsistent and uncertain judgments. Due to the fuzzy logic in the pair wise comparison of elements, the ANP method becomes more flexible and provides more accurate and truthful results (Ayag and Ozdemir, 2012).

Recently, the fuzzy ANP method has been successfully applied in various fields, alone or as a hybrid with other methods (Buyukozkan and Cifci, 2012; Dagdeviren and Yuksel, 2010; Nguyen et al., 2014; Sevkli et al., 2012; Tavana et al., 2013; Vinodh et al., 2011). ANP certainly has shortcomings, which cannot be evaluated for one element in isolation. Identifying the drawbacks and strengths of ANP requires the pair wise comparison of elements (Konidari and Mavrakis, 2007). This problem can be exponentially complex with the number of criteria and their interdependencies (Wolfslehner et al., 2005). Thus, a hybrid method is a decision-making tool that covers the futility and uselessness from one method with the usefulness and utility of another method (Wang and Yang, 2007). Therefore, based on recent literature which suggest combining methods (e.g., the DEMATEL and ANP methods (Vujanović et al., 2012), the DEMATEL, fuzzy ANP and TOPSIS methods (Chen and Chen, 2010), and the DEMATEL and FANP methods (Uygun et al., 2015)), and based on the objectives of this study, two separate MCDM techniques (including FANP and DEMATEL) are considered in current study to cover the research methodology.

The complexity of the multi criteria problem of this study can be reduced through the collaboration of the Decision Making Trial and Evaluation Laboratory Model (DEMATEL) with the Fuzzy Analytical Network Process (FANP) method. The Fuzzy ANP alleviate ambiguity and uncertainty evidence of human judgment and increase the capability of ANP to provide more accurate and truthful results. And, DEMATEL converts the relationship among factors and fundamental dimensions from the complex system to a logical organizational model (Gabus and Fontela, 1972; Lin and Wu, 2004). With this method, the factor comparisons are significantly reduced, which does not require the comparison of all of the element pairs with respect to each element when establishing the inner dependencies of the elements (Liou et al., 2011). This method increases the sensitivity of interrelationships between the factors for choosing the outsource providers. Therefore, the hybrid DEMATEL and FANP method was applied as the logical, organizational, and applicable method for aligning and considering the network relationship among GBM criteria and 3Ps sustainability with a pairwise comparison of factors. The research methodology used for this study is summarized in Section 3 with four sub-sections.

3. Research methodology

This study considered four groups of professionals involved in building material selection including: the supervisor, consultant, contractor, and supplier. The four sub-sections in the methodology section describe the procedure for obtaining the cause and effect for network relationships among GBMs and sustainability criteria:

1 Identify and classify the GBM criteria to determine the basic model of the network relationship among GBM criteria and 3Ps sustainability.
2 Collect data with interviews and surveys.
3 Analyze the correlation among GBMs criteria using the DEMATEL method as the logical and organizational method.
4 Use FANP to align and precisely weight the GBM criteria and 3Ps sustainability considering the network relationship among all of the factors.

In research methodology, combinations of methods are adopted to enable in depth study of the GBMs criterion and 3Ps of sustainability, which helped to achieve the research aim and objectives. Information collected from comprehensive literature review, and followed by a pilot survey for adjustment the questionnaires to the concept of GBMs and sustainability in term of building material selection. Besides, the survey and consequent interviews with professionals was used to conclude based on the research objectives; and established a model for significant GBMs criteria. This model was confirmed via experts' review through survey. Fig. 1 illustrates the research methodology.

3.1. Identifying the criteria of green building materials (GBMs)

To identify the GBM criteria, data were preliminary obtained from a comprehensive literature reviews including articles and books related to green materials. The reviews suggest three basic steps of building product selection which can begin after establishing the project-specific goals (Froeschle, 1999):

- **Research**This step involves gathering all of the technical information to be evaluated, including manufacturers' information such as indoor air quality (IAQ) test data, source material characteristics, and recycled content data. In addition, this step may involve researching building codes, government regulations, building industry articles, model green building product specifications, and other sources of product data. Research step leads in identifying the full range of the project's building material options.

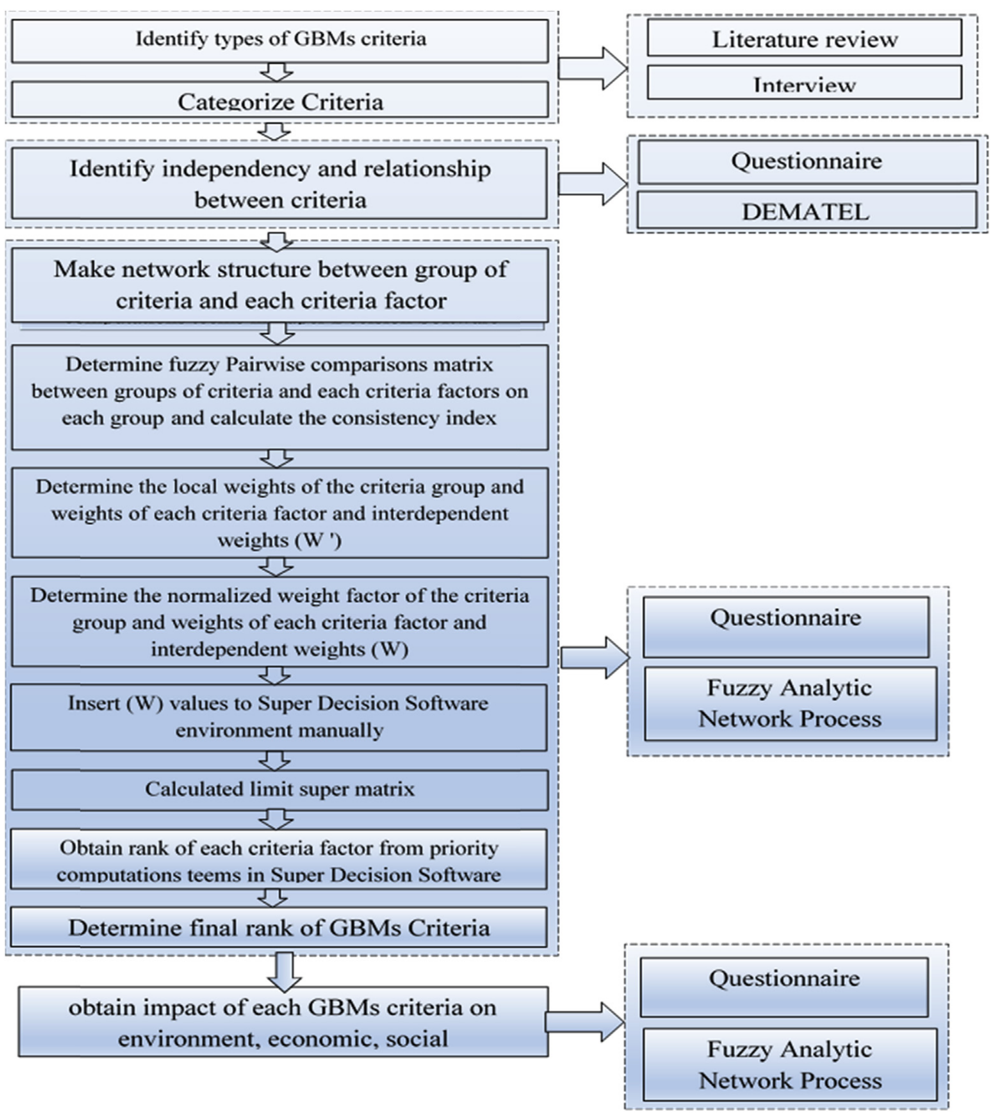

Fig. 1. The Flow of the research methodology in this study.

- **Evaluation**This step involves confirmation of the technical information and filling in information gaps. Evaluation and assessment are relatively simple when comparing similar types of building materials. However, this step is more complex when comparing different products with the same function. In this case, evaluation may require processing both descriptive and quantitative forms of data.
- **Selection**This step often involves the use of an evaluation to score the GBM criteria. The total score of each product evaluation will indicate the product with the highest attributes in 3Ps sustainability. Individual criteria included in the rating system can be weighted to accommodate project-specific goals and objectives. During the process of evaluating materials, two valuable tools are resource management and toxicity that impact our natural resources and the relative environmental and social health. In addition, performance issues are also a valuable tool for evaluating a material that encompasses durability, energy efficiency, the amount of waste generated, and the potential for reuse or recycling (U.S. Department of Energy).

In this research, the specifications and characteristics of GBMs are classified into three separate and continuous periods of the material life cycle from cradle to grave: cradle to gate (material production process), material lifespan, and the disposal phase (Table 1).

The oldest identification and recommendation of GBM criteria was conducted by Spiegel and Meadows (Spiegel and Meadows, 2010b) and Lynn Froeschle (Zhou et al., 2009). This study modified Lynn Froeschle's suggested model (Froeschle, 1999) considering the criteria identified in Table 1. Accordingly, resource efficiency (RE), indoor air quality (IAQ), energy efficiency (EE), water conservation (WC), and affordability (AF) were considered in this study as the main GBM criteria (see Fig. 2). The first two criteria (RE and IAQ) were classified in individual sub-criteria, but the remaining criteria were categorized based on the material's life cycle. The whole material life cycle is demotic and common from cradle to grave. Definitions of the main criteria are presented in Table 2.

3.2. Data collection from the questionnaire

The interviews and questionnaire survey were conducted as the secondary resources to the GBM factors in Malaysia. Three types of questionnaires were used in this study:

1. The first type was used to identify the independency and relationship between GBM and sustainability criteria by the DEMATEL method. Five-point Likert scale questions were used in this section (Appendix A in supplementary information).
2. The second type of questionnaire was used to rank the GBM criteria using the fuzzy analytic network process (FANP) method. This ranking was done on a scale of 1–9. FANP options were analyzed in a pair-wise comparison; for this purpose, the subjects were issued numbers from 1 to 9 according to their intensity of the role. Table 3 shows the linguistic scale (Appendix B – Part 1, in supplementary information).
3. The third type of questionnaire was used to determine the impact of each criterion on the environmental, economic, and social GBM selection. Five-point Likert scale questions were used in this section. The questionnaires were distributed through email or personally requested from the respondents (Appendix B – Part 2, in supplementary information).

For this study, 80 experts from Malaysia including: supervisors, consultants, contractors, and suppliers were selected. The respondents had to meet two criteria before being invited to participate in the survey: have extensive work experience within the construction industry in Malaysia and have gained in-depth knowledge of green building materials. Table 4 shows the background information of the respondents: 58.2% of the respondents came from the public sector (A), 32.6% came from the private sector (B), and the rest were mainly selected researchers and academics (C). Furthermore, the experts had over five years of experience in green building materials, and nearly 63% of the respondents had between 5 and 10 years of industrial experience. The flow of the research methodology for this study is schematically illustrated in Fig. 1. The following sections describe the methods that were applied in each stage.

3.3. Hybrid multi-criteria decision-making methods (MCDMs)

Totally, a hybrid method is a decision-making tool that covers the futility and uselessness from one method with the usefulness and utility of another method (Wang and Yang, 2007). Based on the

Table 1
GBM Specifications over their Life Cycle.

Cradle to gate	Material lifespan	Disposal to grave
Low energy consumption during production (Bank et al., 2011; Crosbie et al., 2011)	Energy efficiency during lifespan (Goggins et al., 2010)	Energy efficiency in disposal phase (Thormark, 2006; U.S. Environmental Protection Agency, 2009; epa.gov)
Low cost product (Ries et al., 2006; Emmitt and Yeomans, 2008; Lipiatt, 2007)	Low cost maintenance (Ries et al., 2006; Wong et al., 2008)	Low cost in disposal phase (Lipiatt, 2007; Chen et al., 2010; Asokan et al., 2009)
Low water consumption during production (EPA-841-R-08-00, 2004)	Low water consumption (EPA-841-R-08-00, 2004; U.S. Geological Survey, 2005)	Water conservation (EPA-841-R-08-00, 2004; U.S. Geological Survey, 2005)
Use recycled content (U.S. Environmental Protection Agency, 2009; epa.gov; Asokan et al., 2009)	Durable (Joseph and Tretsiakova-McNally, 2010; Zhou et al., 2009; Wong and Li, 2008)	Reusable or recyclable (U.S. Environmental Protection Agency, 2009; epa.gov; Abdul Khalil et al., 2013; Asokan et al., 2009)
Use natural or renewable resources (Bank et al., 2011; Crosbie et al., 2011; Khoshnava et al., 2014; Abdul Khalil et al., 2013)	Low-VOC for indoor air (Spiegel and Meadows, 2010a; Bahareh et al., 2011)	Low or non-toxic (Spiegel and Meadows, 2010a; TSCA, 1976)
Resource efficient manufacturing process (Calkins, 2009; Kibert, 2008)	Moisture resistant (United States Environmental Protection Agency)	Minimal chemical emissions (Bahareh et al., 2011)
Locally available (Bunz et al., 2006; Calkins, 2009; Abdul Khalil et al., 2013; Ugwu et al., 2006)	Healthfully maintained (Spiegel and Meadows, 2010a; TSCA, 1976; Lee et al., 2011)	Healthfully maintained (TSCA, 1976; Lee et al., 2011)
Salvaged, refurbished, or remanufactured (Bondanza, 2011)		
Low or non-toxic production process (Spiegel and Meadows, 2010a)		
Minimal chemical emissions (Bahareh et al., 2011)		
Low-VOC assembly (Yu and Kim, 2010)		
Healthfully maintained (TSCA, 1976)		
Systems or equipment (Kim and Rigdon, 1998)		

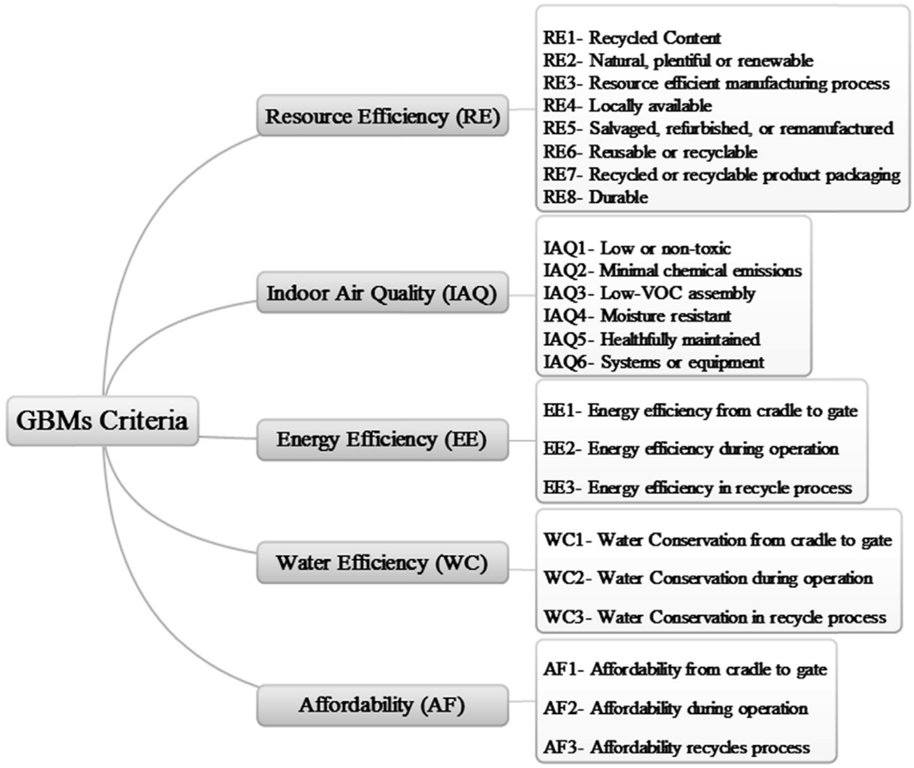

Fig. 2. Green building materials criteria for this study.

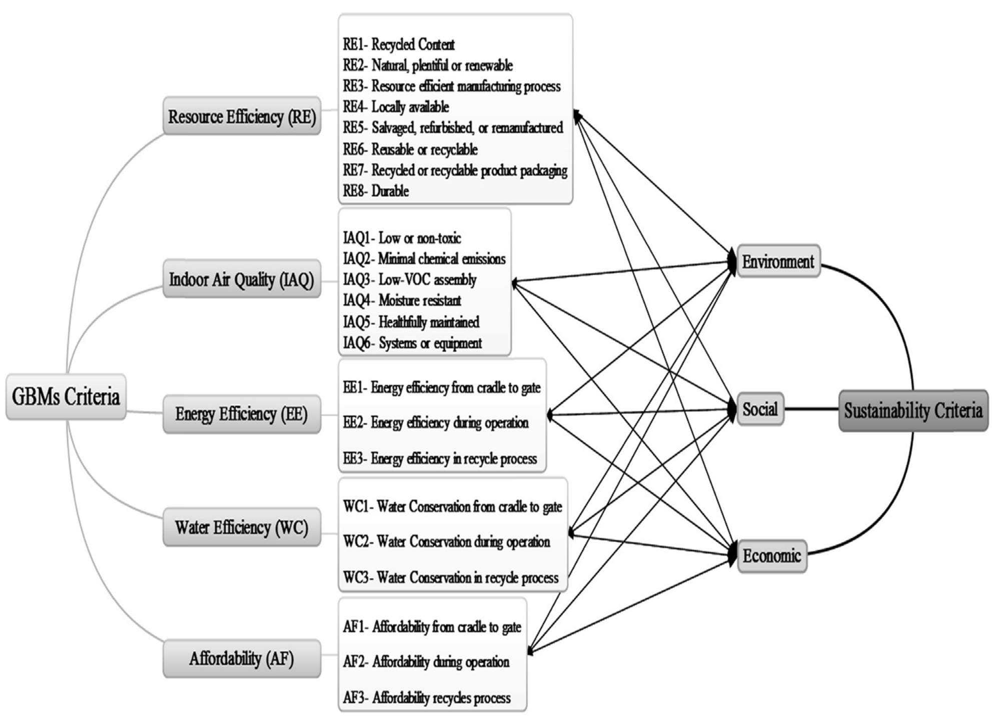

Fig. 3. The prototype and basic model of mutual and network relations among GBMs and sustainability criteria.

objectives of this study, two separate MCDM techniques are considered to cover the research methodology. AHP is common MCDM method which has been used to measure quantitative and qualitative criteria (Saaty, 1980). The decision makers with AHP method may feel that some of the criteria are more important in compare with the others, and have more effect on chain's turnover. However, if there are a number of feedbacks and mutual relationship among criteria, an insignificant criterion can turn to an

Table 2
Definition of the main GBM criteria in this study.

Main GBMs Criteria	Definition
Resource efficiency (RE)	Product manufactured with resource efficient processes including energy consumption, minimizing waste, and reducing greenhouse gases
Indoor air quality (IAQ)	Promotes healthy IAQ by identifying indoor air pollutants or enhancing the air quality
Energy efficiency (EE)	Materials or components that help reduce energy consumption in buildings and facilities
Water Conservation (WC)	Products and systems that help reduce water consumption in buildings and conserve water in landscaped areas
Affordability (AF)	The building product's life cycle cost is comparable to conventional material or are within a project-defined percentage of the overall budget

Table 3
Linguistic scale for importance.

Linguistic scale for importance	Fundamental scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally important(EI)	1	(1, 1,1)	(1, 1,1)
Intermediate1(IM1)	2	(1, 2, 3)	(1/3, 1/2, 1)
Moderately important(W)	3	(2, 3, 4)	(1/4, 1/3, 1/2)
Intermediate2(IM2)	4	(3, 4 ,5)	(1/5, 1/4, 1/3)
Important(M)	5	(4, 5, 6)	(1/6, 1/5, 1/4)
Intermediate3(IM3)	6	(5, 6, 7)	(1/7, 1/5, 1/6)
Very important(S)	7	(6, 7, 8)	(1/8, 1/7, 1/6)
Intermediate4(ID)	8	(7, 8, 9)	(1/9, 1/8, 1/7)
Absolutely important(E)	9	(9, 9, 9)	(1/9, 1/9, 1/9)

Table 4
Background information of the selected experts.

Role of the respondents				
Sector	Public	Private	Academic	
Percentage	32.6	58.2	9.2	
Position				
Category	Supervisor	Consultant	Supplier	Contractor
Number	20	20	20	20
Industrial experience of the respondents				
Years	Five or below	5–10	11-15	Above 16
Percentage	0	62.5	20.4	17.1

important one in the case of using AHP method. So, AHP is not receptive of communicating feedbacks (Bayazit, 2006). So it's needed to apply the methodology for getting more virtual results when there is network relationship among criteria.

The ANP method has solved this problem entirely. But, it has some limitation which are not appropriate to be used in this research. One of the most significant problems e is the existence of too many norms in decision making model which leads to a long-some questionnaire or complicated super matrixes in ANP.

Since experts usually don't have enough time, patience and tolerance to answer such questionnaires and super matrixes may need to be compared more than AHP method; not coming to a logical judgment is possible. Therefore, applying ANP is too complicated and it takes a lot of time (Lee, 2009). Among existing methods, DEMATEL method would be presented as a perfect one to evaluate and weight the norms (Saadati., 2010).

1. Through taking advantages from the principals of Graph theory, this technique, extracts affecting and being affected mutual relationships between the ingredients of Graph, and define the gravity of effects by a numeral score.
2. Using the feedback of each relationship is one of the advantages of this method; which means that in structure of this technique each ingredient can effect on all other ones in same, upper or lower levels while being impressible by any of them at the same time.
3. In addition, the significance and gravity of each parameter would be specified not only by upper and lower ones but all the existing parameters or in other words by the whole model.

Applying this method also requires decision maker's enough knowledge about the target of decision making and the environment of this possess, and all the cession ingredients. Since always this perfect knowledge about system doesn't exist, decision maker can't be completely sure while judging binary comparisons. Thus, DEMATEL method would be also used to solve this problem.

3.3.1. Decision-making trial and evaluation laboratory (DEMATEL)

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique was implemented to show the dependencies of each GBM criterion. An expert team was organized to support the model formulation. DEMATEL is a comprehensive method for building and analyzing a structural model involving causal relationships between complex criteria (Chiou et al., 2011). The methodology, according to the concrete characteristics of objective affairs, can confirm the interdependence among the variables or attributes and restrict the relationship that reflects the characteristics with an essential system and development trend (Wu and Lee, 2007; Chiu et al., 2006; Hori and Shimizu, 1999). The solution steps to obtain the dependencies of each criterion are as follows:

Step 1: Generating a direct relation matrix.

Based on the questionnaire, the experts and decision making team were asked to note the degree of direct effect between each pair of elements based on their experience, assessed on a five-level scale: 1 (no influence), 2 (low influence), 3 (medium influence), 4 (high influence), and 5 (very high influence). The initial direct-relation matrix was obtained by converting their assessments into values. The assessments by each expert give us an initial expert direct matrix, $X^{(k)}$, where k is the number of experts (k = 1, 2, …, p). The diagonal elements of each matrix, $X^{(k)}$, were all set to zero. The initial expert direct matrix $X^{(k)}$ can be represented as:

$$T=\left[t_{ij}\right]_{n\times n}, i,j=1,2,\ldots,n \quad X^{(k)}=\left[a_{ij}^{(k)}\right]_{n\times n}=\begin{matrix} E1 \\ E2 \\ \cdot \\ \cdot \\ E_n \end{matrix}\begin{pmatrix} E_1 & E_2 & \cdots & E_n \\ 0 & a_{12}^{(k)} & \cdots & a_{1n}^{(k)} \\ a_{21}^{(k)} & 0 & \cdots & a_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}^{(k)} & a_{n2}^{(k)} & \cdots & 0 \end{pmatrix} \tag{1}$$

where n is the number of the element, and i, j = 1, 2, …. n.

Then, the initial expert direct matrix was used to acquire the direct-relation matrix:

$$H = \frac{1}{p}\sum_{k=1}^{p}\left[a_{ij}^{(k)}\right]_{n\times n} = \left[h_{ij}\right]_{n\times n} \tag{2}$$

Step 2: Calculating a normalized initial direct relation matrix.

Based on the initial direct relation matrix for dependencies of each criteria factor, H, the normalized direct-relation matrix, N, was derived from the following equation:

$$N = \lambda * H$$

$$N = \lambda * H$$
$$\lambda = \frac{1}{\max_{1\le i\le n}\sum_{j=1}^{n} h_{ij}}, i,j = 1,2,\ldots,n \tag{3}$$

Step 3: Calculate the total-relation matrix.

Based on the normalized direct relation matrix, the total relation matrix, T, was obtained from the following equation:

$$T = N(I-N)^{-1} \tag{4}$$

Step 4: Setting a threshold value.

This step is needed to isolate minor effects presented in the total relation matrix, *T* and to then obtain an appropriate cause-effect diagram. Therefore, decision makers must set a threshold value (z) for the influence level. Some elements, whose influence level in the total relation matrix, *T*, are higher than the threshold value, can be chosen and converted into the cause-effect diagram.

Step 5: Drawing a cause-effect diagram.

The sum of the rows and the sum of the columns are denoted as vector *R* and vector *C* in the following equations:

$$\begin{aligned} T^{Z} &= \left[t_{ij}\right]_{n\times n}, i,j = 1,2,\ldots,n, t_{ij} \ge z \\ R &= [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1}, \\ C &= [c_i]_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n}, \end{aligned} \tag{5}$$

The cause-effect diagram, or impact relation map (IRM), can be obtained by mapping the dataset of ($R + C$, $R - C$). Indeed, the horizontal axis ($R+$) is named “relation,” which deciphers how much importance the element has, while the vertical axis ($R-$) is named “Influence,” which separates elements into a cause group and an effect group. Generally, when the ($ri+$) is positive, then the element i is affecting other elements and i belongs to the cause group. Otherwise, if ($ri-$) is negative, then the element i is being influenced by others and i belongs to the effect group.

Step 6: Obtaining the dependency matrix.

$$\text{In this step, the sum of each column in } T = \left[t_{ij}\right]_{n\times n}, i,j = 1,2,\ldots,n \tag{6}$$

is equal to one by the normalization method and the dependency matrix can thus be obtained.

3.3.2. Fuzzy analytic network process

The ANP developed by Saaty in 1996 (Saaty and Cillo, 2009) is a generalization of AHP. The ANP is a general theory of relative measurement used to derive relative composite ratio scales from individual ratio scales that represent relative measurements of the influence elements that interact with respect to control criteria. The ANP captures the dependence outcome and dependence within and between the clusters of elements, i.e., rather than the strict hierarchy structure of AHP, ANP dissolves the boundaries towards a network structure to cover interdependencies and influences between elements of different clusters (Oztaysi and Ucal, 2009). ANP comprises two parts (Azizi and Modarres, 2007): the first contains a control hierarchy or network relative to the goal, criteria and sub-criteria that govern process interactions and the second contains an influence network among the elements and clusters. A decision network includes clusters, elements, and links. Relevant elements exist within a network or a subnetwork in a cluster. The clusters and their elements are determined for each control criterion. ANP has inner and outer dependencies. The interactions and feedback within the clusters are called inner dependencies, while interactions and feedback between the clusters are called outer dependencies (Hori and Shimizu, 1999).

Similar to FAHP, fuzzy analytic network process (FANP) extends ANP to capture vagueness and uncertainty in decision making. Similar to the ANP method, fuzzy ANP (FANP) has a number of advantages. The FANP method uses a linguistic scale that helps the expert or the decision maker prepare a more flexible method in reaching a conclusion (Mardani et al., 2015). Because FANP is a comprehensive, multipurpose decision method, previous researches have used FANP to solve many complex decision-making problems, such as risk prioritization in freeway public private partnership projects, as shown by Valipour *et al.* (Valipour et al., 2015), Dağdeviren and Yüksel (Spiegel and Meadows, 2010b), Eshtehardian *et al* (Eshtehardian et al., 2013). and Shafiee (Shafiee, 2015). Shafieezadeh *et al* (Shafieezadeh and Hajfataliha, 2009). declared that ANP is the most accurate method to model complex decision-making problems. According to Rabbani et al. (2014) (Rabbani et al., 2014), ANP-based decision analysis approach can measure all tangible and intangible criteria in the model; ANP is a relatively simple, intuitive approach that can be accepted by managers and other decision-makers; and ANP allows for more complex relationships between the decision levels and attributes because it does not require a strict hierarchical structure. Additionally, ANP is more adapted to real-world problems. Hence, AHP and ANP methods might fail to adequately handle the associated ambiguities and inherent uncertainty with mapping the decision-maker's concept to exact numbers (Vahidnia et al., 2008).

3.3.2.1. FANP model based on Chang's method

3.3.2.1. FANP model based on Chang's method. Chang's method is relatively simpler than other FAHP methods. The steps of Chang's extent analysis method are provided below:

$$\text{Let } X = \{x_1, \ldots x_n\} \tag{7}$$

be an object set and

$$U = \{u_1, u_2 \ldots, u_n\} \tag{8}$$

be a goal set. According to Chang's extent analysis, each object is taken as an extensive analysis for each goal (gi) performed. Thus, m, the extent analysis values for each object, can be obtained with the following signs:

$$\mathrm{M}_{\mathrm{gi}}^{1}, \mathrm{M}_{\mathrm{gi}\ldots}^{2} \mathrm{M}_{\mathrm{gi}}^{\mathrm{m}}\ \mathrm{i} = 1,2\ldots\mathrm{n} \tag{9}$$

where M_{gi}^{j}($j = 1,2, \ldots,m$), whereby all are triangular fuzzy numbers.

Step 1: The value of fuzzy synthetic extent with respect to the i^{th} object is defined as:

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} \tag{10}$$

To obtain $\sum_{j=1}^{m} M_{g_i}^{j}$, the fuzzy addition operation of *m extent* analysis values for a particular matrix is performed as:

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right) \tag{11}$$

To obtain $[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}]^{-1}$, the fuzzy additional operation of $M_{g_i}^{j} (j = 1,2, \ldots, m)$ values are performed as:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right) \tag{12}$$

Then, compute the inverse of the vector in Eq. (4) such that:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \tag{13}$$

Step 2: The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as:

$$V(M_2 \geq M_1) = \sup_{y \geq x} [\min(\mu_{M_1}(x), \mu_{M_2}(y))] \tag{14}$$

and can be equivalently expressed as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 & \text{if} \quad m_2 \geq m_1 \\ 0 & \text{if} \quad l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{15}$$

where d is the ordinate of the highest intersection point D between μ_{m_1} and μ_{m_2}. To compare M_1 and M_2, both of the values of V ($M_1 \geq M_2$) and V ($M_2 \geq M_1$) are needed.

Step 3: The degree possibility for a convex fuzzy number to be greater than k convex fuzzy numbers, $M_i (i = 1,2, \ldots, k)$ can be defined by: (16).

V ($M \geq M_1, M_2, \ldots, M_K$) = V[($M \geq M_1$) and($M \geq M_2$) and, …, ($M \geq M_K$) = min V($M \geq M_i$), i = 1,2, …,k.

Assume that $d' (Ai) = \min V (S_i \geq S_K)$. For $k = 1, 2, \ldots, n; k \neq I$. Then, the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T \tag{17}$$

where Ai are n elements.

Step 4: The normalized weight vectors are:

$$d(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)} \tag{18}$$

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{19}$$

where W is a non-fuzzy number.

4. Result

In this study, the criteria and sub-criteria are classified based on Fig. 2. The hypothesis of network relationship and mutual effects among GBM criteria and 3Ps sustainability was obtained after the first step of research methodology which was focused on identify and classify the basic model GBM criteria.

According to comparison of different MCDM methods (Guitouni and Martel, 1998; Moffett and Sarkar, 2006; Polatidis et al., 2006), the ANP has been acknowledged as a powerful method to determine complex interrelationships and to incorporate feedback among decision levels and attributes. In order to alleviate human judgments, fuzzy set theory has been compounded through ANP methods. The main contribution of fuzzy set theory is its ability to display vague data. A FANP advances the ANP technique by the inclusion of the fuzzy set concept in ANP procedures. In this study, the FANP was used to align and precisely weight the GBM criteria and 3Ps sustainability considering the network relationship among all of the factors.

By applying FNP model, first questionnaire that was Likert base scale was analyzed in order to understand respondents' score regarding the relationship between GBMs criteria). Then, the DEMATEL method as the logical and organizational method was used to analyze the correlation among GBMs criteria based on first questionnaire responses.

The final ranking of GBMs criteria based on 3Ps of sustainability obtained through second questionnaire, and ANP model with three layers (Fig. 4). Lastly, the final ranking of every GBMs criterion based on separate 3Ps of sustainability was concluded through Interpolation of respondents replying to third questionnaire. According to the research methodology of this study (Fig. 1), the third questionnaire was used to determine the impact of each criterion on the environmental, economic, and social GBM selection. So, the final weighting of GBMs criteria recalculated for every 3Ps of sustainability through ANP model and Interpolation of respondents replying to third questionnaire.

4.1. Identification of the relationship and independency between criteria

After the identification and categorization of the GBM criteria, a network structure was constructed by experts to create mutual influence between criteria. An inner dependency and relationship between different groups of criteria and inner dependency within each criterion was established in this structure. The DEMATEL technique was implemented to show the criteria dependencies. An expert team was organized to support the model formulation. The solution steps to obtain the dependencies of each GBM criterion are as follows:

4.2. Generate a direct relation matrix

Based on the questionnaire (Type A), the experts and decision making team were asked to note the degree of direct effect between each pair of elements based on their experience. The initial expert direct matrix was obtained from Equation (1) and (2). The initial expert direct relation matrix for dependencies of each criteria is shown in Table 5.

Table 5 shows the initial direct-relation matrix was obtained by converting their assessments into values. Based on the first questionnaire (Appendix A), the experts and decision making team weighed on a five-level scale based on their experience which were asked to grade the degree of direct effect between each pair of elements.

4.3. Calculate the total-relation matrix

Based on the normalized direct relation matrix, the total relation matrix, T, was obtained from Equation (5). The threshold value for the dependency of each safety performance factor was 0.450 for this study.

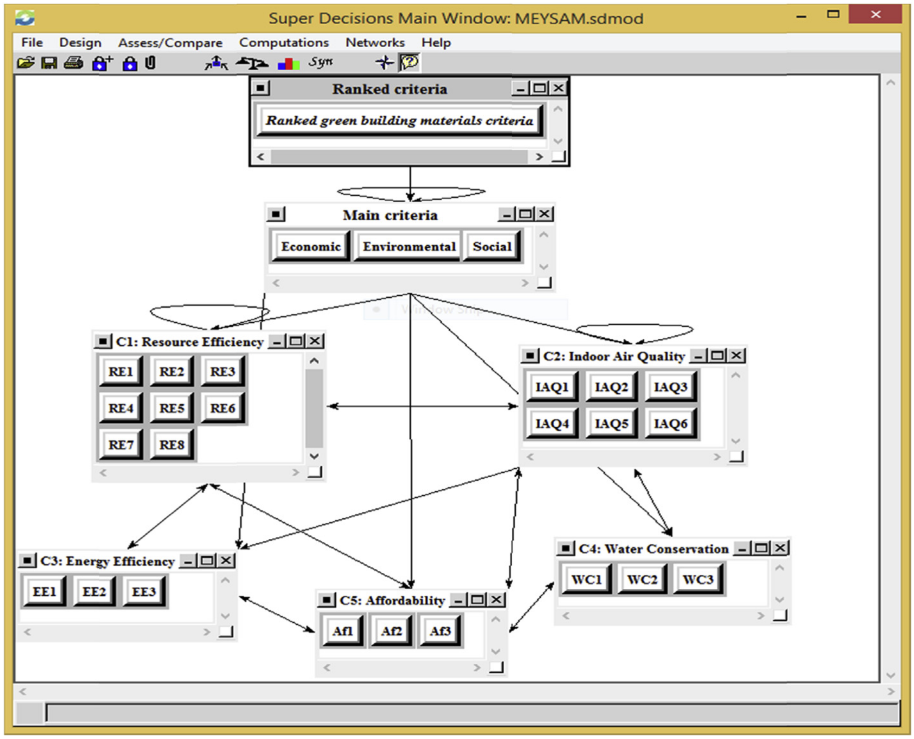

Fig. 4. A snapshot of the ANP Model in the SUPER DECISIONS software.

Table 5
The initial expert direct relation matrix for the dependencies of each criterion.

	RE1	RE2	RE3	RE4	RE5	RE6	RE7	RE8	IAQ1	IAQ2	IAQ3	IAQ4	IAQ5	IAQ6	EE1	EE2	EE3	WC1	WC2	WC3	AF1	AF2	AF3
RE1	1	5	5	3	4	5	3	2	2	3	3	2	2	2	3	4	5	2	3	3	5	4	5
RE2	5	1	4	5	5	5	4	4	5	5	5	4	5	4	5	5	5	4	5	5	5	5	5
RE3	5	4	1	3	4	3	2	2	2	4	2	2	2	4	5	2	2	2	2	2	4	3	3
RE4	3	5	3	1	2	2	2	2	1	1	1	1	1	1	4	1	1	1	1	1	4	1	1
RE5	4	5	4	2	1	4	2	2	1	1	1	1	1	1	3	1	3	3	1	2	3	1	2
RE6	5	5	3	2	4	1	2	1	1	1	1	1	1	1	5	3	5	3	3	2	5	4	5
RE7	3	4	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
RE8	2	4	2	2	2	1	1	1	1	1	1	3	1	1	2	2	2	1	1	1	1	4	1
IAQ1	2	5	2	1	1	1	1	1	1	5	5	3	5	2	1	4	3	2	1	2	3	5	4
IAQ2	3	5	4	1	1	1	1	1	5	1	4	5	5	2	1	3	3	1	1	1	2	4	2
IAQ3	3	5	2	1	1	1	1	1	5	4	1	1	4	2	3	2	2	1	1	1	3	3	4
IAQ4	2	4	2	1	1	1	1	3	3	5	1	1	3	2	1	2	2	1	1	1	2	3	1
IAQ5	2	5	2	1	1	1	1	1	5	5	4	3	1	1	1	2	2	1	1	1	2	3	3
IAQ6	2	5	4	1	1	2	1	1	2	2	2	2	1	1	1	1	1	1	1	1	2	1	1
EE1	3	5	5	4	3	5	1	2	1	1	3	1	1	1	1	1	1	1	1	1	5	1	1
EE2	4	5	2	1	1	3	1	2	4	3	2	2	2	1	1	1	1	1	1	1	1	5	1
EE3	5	5	5	1	3	5	1	2	3	3	2	2	2	1	1	1	1	1	1	1	1	1	5
WC1	2	4	2	1	3	3	1	1	2	1	1	1	1	1	1	1	1	1	1	1	5	1	1
WC2	3	5	2	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	1
WC3	3	5	2	1	2	2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	5
AF1	5	5	4	4	3	5	1	1	3	2	3	2	2	2	5	1	1	5	1	1	1	1	1
AF2	4	5	3	1	1	4	1	4	5	4	3	3	3	1	1	5	1	1	5	1	1	1	1
AF3	5	5	3	1	2	5	1	1	4	2	4	1	3	1	1	1	5	1	1	5	1	1	1

4.4. Obtain the dependency matrix

In this step, the sum of each column in $T = [t_{ij}]_{n \times n}, i,j = 1,2,\ldots,n$ is equal to one by the normalization method, and thus the dependency matrix can be obtained. The dependency matrix for each safety performance factor is shown in Table 6.

4.5. The ANP network structure for green building material evaluation

Following the identification of the dependency between green building material factors is the process of inserting data in Super Decision Software. The Super Decisions software implements the Analytic Network Process for decision making with dependence and feedback developed by Dr. Thomas Saaty. The program was written by the ANP Team, working for the Creative Decisions Foundation. The first step in building the ANP model is to decide on the logical groupings of the nodes and clusters for the problem structure. The clusters that build the model are the following green building material groups: resource efficiency (RE), indoor air quality (IAQ), energy efficiency (EE), water conservation (WC), and affordability (AF). An indirect dominance factor comparison in

Table 6
The dependency matrix for each safety performance factor.

	RE1	RE2	RE3	RE4	RE5	RE6	RE7	RE8	IAQ1	IAQ2	IAQ3	IAQ4	IAQ5	IAQ6	EE1	EE2	EE3	WC1	WC2	WC3	AF1	AF2	AF3
RE1	0	1	1	0	0	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1
RE2	1	0	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	0	0	0	1	1	1
RE3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1
RE4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
RE5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1
RE6	1	1	0	0	1	0	1	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	1
RE7	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1
RE8	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
IAQ1	0	1	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	1	1	1
IAQ2	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0
IAQ3	0	1	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1
IAQ4	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0	1	0
IAQ5	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0	1	0	1	0	1	0
IAQ6	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	0
EE1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
EE2	1	1	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
EE3	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
WC1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
WC2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
WC3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AF1	1	1	1	1	1	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0
AF2	1	1	1	0	0	0	0	1	1	1	0	1	1	1	0	1	0	0	1	0	0	0	0
AF3	1	1	1	0	1	1	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0

factor set Ci was conducted according to their influence on REij, IAQij, EEij, WCij and AFij by considering factor set Ci (i = 1, 2,…, 5) as the primary standard and factor set REij (j = 1, 2, …, 8), IAQij (j = 1, 2, …, 6), EEij (j = 1, 2, 3), WCij (j = 1, 2, 3), and AFij (j = 1, 2, 3) as a secondary standard to construct the judgment matrix. Fig. 4 shows a snapshot of the ANP model that was developed with the super decisions software. The purpose of this section is to estimate the priorities of green building materials associated with selecting the most green materials. The model consists of a single network with all of the clusters and their nodes in one window.

4.6. Pair wise comparison matrices between criteria groups and criteria factors

Upon the formation of the ANP green building material rank structure and consensus on its elements, the next step is performing a pair wise comparison on the evaluation criteria. The first task of this step was to develop a questionnaire that can assess the relationships between the elements of the network model. The next step was to conduct pair wise comparison matrices in Microsoft Excel to solve the FANP matrix. First, a pair wise comparison questionnaire was prepared. The questionnaire contained a series of well-structured questions that compare two elements' relative importance and any dependence between the two elements. The questionnaire was then distributed to the participants, who were asked to sequentially compare two components or elements at a time with respect to the control criterion. The construction of the network hierarchy structure for the pair wise comparison matrices can evaluate the respective importance of the various risk groups and the various risk factors within the same groups. The interdependence matrix of each criterion must be determined relative to the other risk factors based on fuzzy scales. The scale used was based on Chang's fuzzy AHP method (Chang, 1996). A triangular fuzzy number was inserted in the related Microsoft Excel sheet according to the result received from this linguistic scale. All of the average comparisons obtained from the expert answers were solved using Microsoft Excel. The average answer obtained from Excel was keyed into the Super Decision Software to calculate the consistency of the pair wise comparison matrices. Before proceeding further with the analysis phase, each pair wise comparison matrix was checked for consistency. Consistency implies that the judgments in specifying the pair wise comparison of the elements exhibit coherence. To minimize the amount of time going back and forth, requesting contributors to rectify their inconsistent judgments, the questionnaire was developed with the ability to analyze each contributor's consistency. Table 7 shows a sample of the pair wise comparison matrix and Coefficient rate of "Energy Efficiency (EE)."

Solving FANP matrices supplies us with the normalized weight vectors (W) using Chang's extent analysis method. Here, "W" is a non-fuzzy number. The normalized weight vectors of elements and sub-elements were calculated using Microsoft Excel. This particular Excel sheet was creates normalized weight vectors, which were inserted into the Super Decisions software. The normalized weight vectors for "Energy Efficiency (EE)" are provided below as a numerical example:

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1}$$

$$\begin{aligned} s_{c_{11}} &= (2.33, 3.5, 5) \otimes (0.0645, 0.0882, 0.1263) \\ &= (0.1505, 0.3088, 0.6315) \end{aligned}$$

$$\begin{aligned} s_{c_{12}} &= (4, 6, 8) \otimes (0.0789, 0.1034, 0.132) \\ &= (0.2580, 0.5294, 1.010) \end{aligned}$$

Table 7
A sample of the pairwise comparison matrix and CR of "Energy Efficiency (EE)".

EE	EE1	EE2	EE3	W
EE1	(1, 1, 1)	(1, 2, 3)	(1/3, 1/2, 1)	0.468
EE2	(1/3, 1/2, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	0.0635
EE3	(1, 2, 3)	(2, 3, 4)	(1, 1, 1)	0.468
				CR = 0.0515

$$s_{c_{14}} = (1.58, 1.83, 2.5) \otimes (0.0789, 0.1034, 0.132) = (0.1021, 0.16176, 0.3157)$$

The degrees of possibility were calculated as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 & \text{if} \quad m_2 \geq m_1 \\ 0 & \text{if} \quad l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases}$$

$$V(s_{c_{11}} \geq s_{c_{12}}) = 0.6287,\ V(s_{c_{11}} \geq s_{c_{14}}) = 1,\ V(s_{c_{12}} \geq s_{c_{11}}) = 1,\ V(s_{c_{12}} \geq s_{c_{14}}) = 1,\ V(s_{c_{14}} \geq s_{c_{11}}) = 0.529, V(s_{c_{14}} \geq s_{c_{12}}) = 0.119$$

For each pairwise comparison, the minimum of the degrees of possibility was determined as follows:

$$V(M \geq M_1, M_2, \ldots, M_K) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and}, \ldots, (M \geq M_K)] = \min V(M \geq M_i),\ i = 1, 2, \ldots, k$$

$$V(s_{c_{11}} \geq s_{c_{12}}, s_{c_{14}}) = \min\{0.6287,\ 1\} = 0.6287,\ V(s_{c_{12}} \geq s_{c_{11}}, s_{c_{14}}) = \min\{1, 1\} = 1$$

$$V(s_{c_{14}} \geq s_{c_{11}}, s_{c_{12}}) = \min\{0.529, 0.119\} = 0.119$$

These values yielded the following weight vector:

$$W' = (d'(A_1),\ d'(A_2), \ldots, d'(A_n))^T$$

$$W' = (0.6287, 1, 0.119)$$

Via normalization, the local weights of the criteria were determined as follows:

$$d(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)}$$

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T$$

$$W = (0.359, 0.572, 0.068).$$

The limit super-matrix was derived by raising the weighted super-matrix to powers by multiplying it by itself. When the columns of numbers became identical, the limit matrix has been reached. Consequently, the matrix multiplication process was then stopped. Table 7 shows a section of the limited super-matrix for green building material criteria assessment. The key importance of the limit super-matrix is that it provides the priorities for the different factors that structure the problem. Because the columns of the limit super-matrix are all identical, the priorities for all of the elements in any cluster can be read directly from any column. The summary part of the limit matrix is shown in Table 8.

4.7. Final ranking of green building material criteria

The limit matrix outcome weights were used to obtain the final ranking. The final ranking of each green building material criterion was obtained from the results of the limit matrix from the priorities of the Super Decision software. The final result evaluation of the criteria is shown in Table 9.

The final ranking of GBMs criteria based on 3Ps of sustainability obtained through second questionnaire (Fig. 1), and ANP model with three layers (Fig. 4). Besides, the final ranking of every GBMs criterion based on separate 3Ps of sustainability was concluded through Interpolation of respondents replying to third questionnaire. According to the research methodology of this study (Fig. 1), the third questionnaire was used to determine the impact of each criterion on the environmental, economic, and social GBM selection. So, the final weighting of GBMs criteria recalculated for every 3Ps of sustainability through ANP model and Interpolation of respondents replying to third questionnaire.

4.8. Validity of result

4.8.1. Reliability of questionnaires

In this study, the reliability test was performed for each type of questionnaire. The values of Cronbach's alpha for the impact of all respondents was mostly greater than 0.75 which is well above the threshold of 0.50 recommended by Yip and Poon (2009) (Yip and Poon, 2009) and Lu and Yan (2007) (Lu and Yan, 2007) for general attitude or perception of assessments similar to this study and were considered to be good and acceptable. However, some researchers suggested Cronbach alpha is a relevant measure for interval and ratio scales, and it is not the most appropriate for ordinal scales (Zumbo et al., 2007; Gadermann et al., 2012; Cinelli et al., 2016). The results of Cronbach's alpha for all types of questionnaires are shown in Table 10.

4.8.2. Consistency ratio (CR)

During the process of decision making when comparing different attributes, is possible inconsistency issue occur because decision problems are complicated in nature. Therefore, the inconsistency test is necessary for reliability and validity of respondent's questionnaires to comparison matrix before the vector priority of the comparison matrix can be calculated. If the inconsistency test for the comparison matrix is failed, the inconsistent elements in the comparison matrix has to be revised, otherwise, the result of decision analysis process is meaningless. The most widely used consistency index is the consistency ratio (CR) (Saaty, 1991), that is,

$$CR = \frac{CI}{RI} < 0.1 \tag{20}$$

where $CI = \frac{\lambda max - n}{n-1}$ is the consistency index, and RI is the appropriate Consistency index which is called Random Consistency Index (RI). RI is the average random index based on Matrix Size shown in Table 11, λ_{max} is the maximum eigenvalue of matrix A, and n is the order of matrix A. Compare the value of CR with the consistency threshold 0.1 to judge whether the comparison is consistent.

Table 8 shows the consistency ratio (CR) determined for the pairwise comparison matrix and CR of "Energy Efficiency (EE)" as a sample.

4.9. Kendall's Concordance Test

According to Chan et al. (2003), the ranking exercise in a questionnaire survey with Likert scale is based on the individual perceptions of the respondents, but not an objective judgment (Chan et al., 2003). A subjective assessment of the ranking result is made for the analysis of the perception of the GBMs criteria in the survey of this study. Emphasis is only given to the ranking GBMs criteria which are placed as the most significant and the least significant in the ranking exercise.

Table 8
The summary part of limit matrix.

Cluster node label	RE1	RE2	RE3	RE4	RE5	RE6	RE7	RE8
RE1	0.066753	0.066753	0.066753	0.066753	0.066753	0.066753	0.066753	0.066753
RE2	0.108896	0.108896	0.108896	0.108896	0.108896	0.108896	0.108896	0.108896
RE3	0.025262	0.025262	0.025262	0.025262	0.025262	0.025262	0.025262	0.025262
RE4	0.00719	0.00719	0.00719	0.00719	0.00719	0.00719	0.00719	0.00719
RE5	0.010749	0.010749	0.010749	0.010749	0.010749	0.010749	0.010749	0.010749
RE6	0.02988	0.02988	0.02988	0.02988	0.02988	0.02988	0.02988	0.02988
RE7	0.006619	0.006619	0.006619	0.006619	0.006619	0.006619	0.006619	0.006619
RE8	0.002521	0.002521	0.002521	0.002521	0.002521	0.002521	0.002521	0.002521

Table 9
The final ranking of the GBM criteria based on sustainability criteria.

No	Criteria	Weight	No	Criteria	Weight	No	Criteria	Weight
1	Af1	0.150697	9	WC1	0.058507	17	IAQ6	0.013408
2	RE2	0.108896	10	EE3	0.039322	18	IAQ2	0.01263
3	EE1	0.08364	11	IAQ5	0.031172	19	RE5	0.010749
4	IAQ3	0.074164	12	RE6	0.02988	20	RE4	0.00719
5	Af2	0.071114	13	EE2	0.029372	21	RE7	0.006619
6	IAQ1	0.070378	14	RE3	0.025262	22	IAQ4	0.005193
7	RE1	0.066753	15	WC3	0.02343	23	RE8	0.002521
8	Af3	0.061323	16	WC2	0.017779			

Table 10
Cronbach's alpha Value for each Type of Questionnaire.

Type of questionnaire	Cronbach's alpha Value
Questionnaire A	0.946
Questionnaire B- part 1	0.924
Questionnaire B- part 2	0.936

Table 11
The average random index.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The Kendall's concordance analysis, which is a non-parametric test, was used to measure the level of agreement of different respondents on their rankings of factors based on mean scores within a particular group. This statistical test aims to ascertain whether the respondents within a particular group respond in a consistent manner or not (Kvam and Vidakovic, 2007). The value of the Kendall's coefficient of concordance (W) ranges from 0 to 1, where 0 reveals perfect disagreement and 1 indicates perfect agreement. A significant value of W (actual p-value < allowable value of 0.05) can reject the null hypothesis that there is a complete lack of consensus amongst respondents within one group.

Table 12 shows the final result from Kendall's Concordance Test. Based on Kendall's Concordance Test, the final result from this test for all groups and purposed model was near one, which imply there is a difference in the perception of respondent groups and results of purpose model. However, the value of W was less than allowable value (0.05) that means the null hypothesis (there is a complete lack of consensus among respondents within one group than results of purpose model) can be rejected. As a result, there was no significant difference in the perception of respondent groups (Supervisors, Consultants, Suppliers, and Contractors) and final ranking of GBMs criteria from purposed model.

5. Discussion

Selection of green building materials represents an important strategy in the design and construction of a building. A principal challenge therefore is the identification of assessment criteria based on the concepts and principles of green align with sustainability, and the process of prioritizing and aggregating relevant criteria into an assessment framework. Literature reviews indicate that there is no specific definition or standard currently exists for green materials, and the selection of green building material become very difficult, ambiguous, and problematic. The absence of clear instructions for GBMs and the difficulty of precision adjustments of GBM criteria with 3Ps sustainability make GBM selection a challenge that may encounter an unexpected result according to the network relation among GBMs and sustainability criteria.

Furthermore, the consideration of all sustainability factors in GBM selection made it a multi-criteria decision problem that requires mathematical techniques such as the multi criteria decision making (MCDM) method. To resolve multiple incompatible and conflicting GBM criteria align with 3Ps sustainability, the study applied a hybrid MCDM methodology, including: fuzzy analytic network process (FANP) for aligning and ranking GBM criteria based on 3Ps sustainability and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) to analyze the efficacy of and interrelationship between GBM criteria. To achieve the goals of the study, a preliminary survey and interview were conducted to determine the main GBM criteria based on the specifications from Spiegel and Meadows (2010b) and Froeschle (1999) (Dagdeviren and Yuksel, 2010; Zhou et al., 2009). And, to rank and weight the importance of the GBMs criteria with aligned 3Ps of sustainability, this study applied three types of questionnaires.

Table 13 shows final GBM criteria ranking with aligned 3Ps of sustainability, and also polarized GBMs criteria according to concern of different sustainability pillars. In this final results, ranked and weighted the GBMs criteria with aligned 3Ps of sustainability was polarized and determined based on three different sustainability pillars: social, economic, and environmental. Also, Fig. 5 shows the four different bar charts together based on Table 13.

Based on the final weight of the ranked GBM criteria (Fig. 5-A):

Affordability (with three sub-criteria) is one of the main GBM criteria that stands in the first 10 top ranks. Froeschle (1999) defined the affordable term as one of the GBM criteria that provides the specification for materials with life cycle costs comparable to conventional materials (Zhou et al., 2009). Totally, thoughtfulness of life-cycle costs against first-costs of building materials is very important. The GBMs are not significantly costlier than their complement conventional building materials. Rehm and Ade (2013) provided the first in-depth investigation into actual green building construction costs in New Zealand that compared 17 green buildings' actual cost data. The results implied that the green buildings are not inherently more expensive due to their provision of materials and systems (Rehmand and Ade, 2013). Whereas, the GBMs maybe more expensive at first, it should be affordable during lifetime with reduced energy costs, replacement and maintenance cost, and worker productivity. In this research, affordability (AF) is

Table 12
Kendall's concordance test result.

No	Criteria	All respondents		Supervisor		Consultant		Supplier		Contractor	
		Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
1	Af1	0.150697	1	0.123182	1	0.111063	2	0.125471	1	0.127144	1
2	RE2	0.108896	2	0.078812	4	0.124560	1	0.090125	5	0.105302	3
3	EE1	0.08364	3	0.101271	2	0.085281	4	0.090171	4	0.113241	2
4	IAQ3	0.074164	4	0.092712	3	0.090281	3	0.089351	6	0.079157	4
5	Af2	0.071114	5	0.042182	10	0.081217	5	0.096178	2	0.059493	7
6	IAQ1	0.070378	6	0.072032	6	0.062371	7	0.059129	7	0.061645	6
7	RE1	0.066753	7	0.065036	7	0.060281	8	0.053037	8	0.067321	5
8	Af3	0.061323	8	0.047923	9	0.043418	10	0.095548	3	0.042832	10
9	WC1	0.058507	9	0.028947	14	0.072103	6	0.038477	9	0.055193	8
10	EE3	0.039322	10	0.076731	5	0.053281	9	0.034078	10	0.048028	9
11	IAQ5	0.031172	11	0.030934	13	0.034032	11	0.030521	12	0.032049	12
12	RE6	0.02988	12	0.031943	12	0.026034	13	0.031824	11	0.032927	11
13	EE2	0.029372	13	0.058730	8	0.023472	15	0.027837	13	0.028194	13
14	RE3	0.025262	14	0.040281	11	0.028437	12	0.026091	14	0.026038	14
15	WC3	0.02343	15	0.004738	22	0.025847	14	0.025391	15	0.019832	17
16	WC2	0.017779	16	0.003281	23	0.008128	20	0.020183	16	0.018502	18
17	IAQ6	0.013408	17	0.018302	17	0.018273	16	0.018062	17	0.007194	22
18	IAQ2	0.01263	18	0.013028	18	0.009382	19	0.015921	18	0.009641	20
19	RE5	0.010749	19	0.02343	15	0.015932	17	0.013271	19	0.022954	15
20	RE4	0.00719	20	0.020173	16	0.012637	18	0.008129	20	0.010493	19
21	RE7	0.006619	21	0.011028	19	0.007012	21	0.003193	23	0.020392	16
22	IAQ4	0.005193	22	0.006931	21	0.004938	22	0.004912	21	0.004018	23
23	RE8	0.002521	23	0.008372	20	0.002018	23	0.003098	22	0.008408	21
Kendall's coefficient of concordance (W)		0.085		0.094		0.088		0.075		0.079	

Table 13
Final GBM criteria ranking in various categories of sustainability.

No	Final	Social	Economical	Environmental
1	Af1	RE2	Af1	Af1
2	RE2	Af1	RE2	RE2
3	EE1	IAQ3	EE1	EE1
4	IAQ3	Af2	Af2	IAQ3
5	Af2	IAQ1	RE1	IAQ1
6	IAQ1	RE1	Af3	RE1
7	RE1	Af3	IAQ3	Af3
8	Af3	IAQ5	WC1	Af2
9	WC1	EE3	IAQ1	EE3
10	EE3	EE2	EE3	RE6
11	IAQ5	RE6	EE2	EE2
12	RE6	EE1	RE3	RE3
13	EE2	IAQ2	RE6	IAQ5
14	RE3	WC1	IAQ5	IAQ2
15	WC3	RE5	WC3	WC1
16	WC2	RE4	IAQ2	RE5
17	IAQ6	IAQ4	WC2	IAQ6
18	IAQ2	RE3	RE5	RE7
19	RE5	WC3	IAQ6	WC3
20	RE4	RE7	RE4	RE4
21	RE7	WC2	RE7	WC2
22	IAQ4	IAQ6	IAQ4	IAQ4
23	RE8	RE8	RE8	RE8

divided into three sub-criteria (AF_1, AF_2, and AF_3) based on the material's life cycle. AF_1 covers from cradle to gate, the portion of a product's life cycle from inception to the point where it leaves the manufacturer. The weight of AF_1 (0.150697) is more than some of the teen terminative GBM criteria (0.124781). The AF_2 is the affordability criteria that belong to the operation and consumption phase of GBM, which is prioritized as a top 10 criteria in GBM selection.

Resource efficiency (RE) is one of the main GBM criteria (with eight subcriteria) and is focused on resource-efficient processes including energy consumption, minimizing waste, and reducing greenhouse gases during the material life cycle. The European Commission defines resource efficiency as part of the Europe 2020 Strategy which means using the Earth's limited resources in a sustainable manner while minimizing impacts on the environment (The European Commission). This term focuses on decreasing the embodied energy and other impacts allied with the extraction, processing, transport, maintenance, and disposal of building materials. According to the GBMs criteria (Fig. 2), there is eight subcriteria for this study. The research recognized RE_2 (natural, plentiful or renewable) and RE_1 (recycled content) as the first top teen criteria in the GBM selection process. The six remaining subcriteria of RE (0.082221) are below the weight of RE_2 (0.108896), which indicates the value of natural, plentiful or renewable terms of the resource efficiency criteria in the selection procedure.

The scope of **Energy efficiency** (EE) as one of the main GBMs criteria is ranked from energy efficient during extracting and manufacturing process to different categories such as thermal efficiency, load reduction and energy waste reduction to minimize the energy footprint during GBMs life cycle (Sasnauskaite et al., 2007). There are energy efficiency rating systems in different countries which have been measured and described as the effective tools to foster carbon reduction during building life cycle (Todd et al., 2013). In this study, the EE criteria (with three subcriteria) imply materials that reduce energy consumption during the building material's life cycle. EE_1 is the embodied energy of a material that is ranked as the third criteria in GBM selection. Additionally, the other two subcriteria of EE are well established in this ranking.

Indoor air quality (IAQ) and pollution are becoming concerns not just of scientists, but also of the legal community. They focus is on efforts to control the quality of indoor air through the development of regulations. Wei et al. (2015) were reviewed around fifty-five green building schemes in 31 certifications worldwide. Their findings showed that the IAQ is included in all of the certifications for evaluating the health risk of indoor occupants (Wei

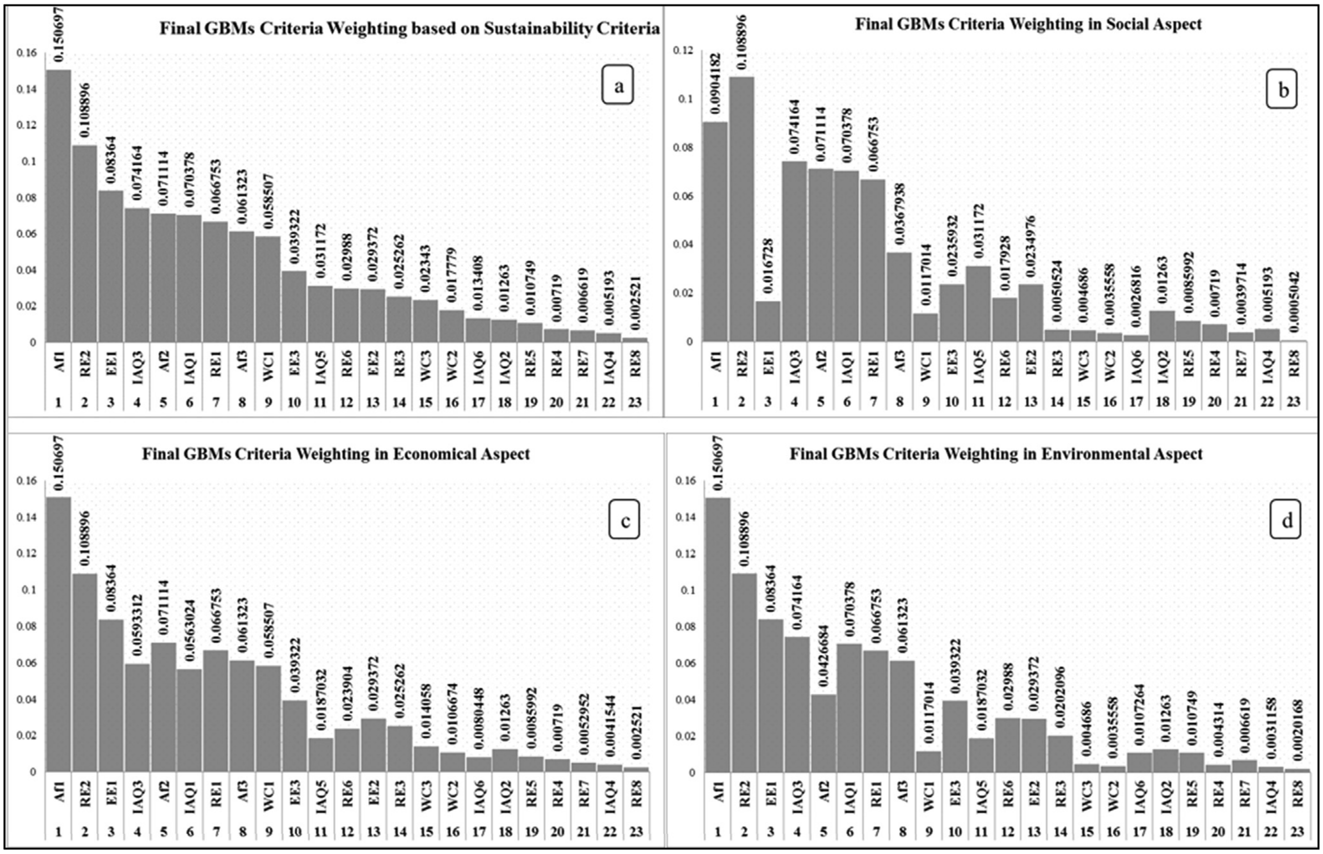

Fig. 5. Final GBM criteria weighting: a) based on Sustainability criteria, b) based on Social Aspect, c) based on Environmental Aspect, d) based on economical Aspect.

et al., 2015). It is important to maintain high IAQ to guarantee the health of occupants in buildings. This study considered the IAQ as a main GBM criteria (with six subcriteria) that functionally improves IAQ and promotes healthy IAQ by identifying indoor air pollutants or enhancing the air quality. Among all 6 IAQ subcriteria, IAQ_3 (low-VOC assembly) and IAQ_1 (low or non-toxic material) are ranked among the top teens GBM criteria.

Base on Fig. 5A, the last main GBM criterion is **Water efficiency** (WC) with three subcriteria; the scope of this criterion is defined in the life cycle of materials from cradle to grave. The overall weight of WC is ranked in the middle of the final ranking.

The social aspects of the final GBM criteria ranking (Fig. 5-B) indicate:

Mostly, the definition, comprehension, and operation of social sustainability is difficult (Boström, 2012), because the social sustainability appears to present different and more severe challenge (Bebbington and Dillard, 2009). For instance, Development and consumption of natural fibers is a socially responsible scheme, supporting incomes of lots moderated farmers and workers (Tambyrajah, 2012). Indoor air quality is an important criterion in the social aspect of selecting materials based on this chart (Boström, 2012). The IAQ sub-criteria show a notable jump in the ranking level. Additionally, RE_2 moved to the first criteria for the selection, suggesting the significance of the natural and renewable term for the social aspect of sustainability. EE_2 is another important term in the social aspect that increased its weight from level 13 to 10. This increase shows the social importance of energy efficiency in the operation of the material life cycle.

The environmental aspects of the final GMB criteria ranking (Fig. 5-C) shows:

There are different environmental costs such as environment demolition, resource depletion, energy use, air and water pollution which is implied through materials selection from extraction, to use and disposal stage. Environmental sustainability discusses to the ability of something to continue without hurtful to the earth's ecological balance (Adams and Frost, 2008). Material selection is often the first step for reducing the environmental impact. For instance, environmentally preferred of natural fibers as GBMs can significantly reduce the environmental impact. In this study, the Resource Efficiency subcriteria are prominent for the environmental aspect. Totally, the material with efficient resource has minimum environmental impact based on this research.

The economical aspects of the final GMB criteria ranking (Fig. 5-D) shows:

The general definition of economic sustainability is the ability of an economy to support a defined level of economic production indefinitely. Consideration the economical aspect in materials selection should be conserves a healthy balance with ecosystems. According to the study result, Fig. 5-D shows the final ranking for the economic aspect; the affordability sub-criteria was well fixed in the higher level of the GBM criteria ranking.

6. Conclusion

The development of a green material index was the prime objective of the study, and a model has been successfully applied in ranking building materials to provide the best solution for a green and sustainable project. A total of 23 criteria were identified thorough literature review and discussion with selected experts in the use of green materials for building projects. By considering a hybrid MCDM methodology, the study tried to resolve multiple incompatible and conflicting GBM criteria to align with 3Ps sustainability.

Obtained results indicate that the relationship between GBMs and sustainability criteria are different based on the separate 3Ps of sustainability.

The GBM criteria prioritizing and aligning with the sustainability criteria revealed that affordability is one of the important GBM criteria in the selection procedure that assembles materials with life-cycle cost specifications comparable to conventional materials. Resource efficiency was highlighted as the second most important criteria. The results suggest that natural, renewable, and recycled content are resource-efficient criteria for GBM selection. The embodied energy was weighted as the third specification for the energy efficiency term in GBM selection. Additionally, non-toxic materials with low-VOC assemblies highlight the indoor air quality characteristic in the GBM selection procedure. The final criteria ranking considering the social aspect highlights the IAQ categories for GBM selection as a health issue, particularly using natural and renewable resources and energy efficient materials during the life product of materials. Consideration of these criteria will ensure a green material selection and consequently a sustainable development in building design and construction.

The present study is only a tentative beginning in this direction. This research has opened up opportunities for further research in selecting the best green building materials. The findings in this research can be further extended and modified to accomplish the ultimate goal of promoting and improving green practices in construction. The evaluation and results can provide a valuable reference for building professionals who seek to enhance sustainable construction through green materials.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.10.066.

References

Abdul Khalil, H.P.S., Sri Aprilia, N.A., Bhat, A.H., Jawaid, M., Paridah, M.T., Rudi, D., 2013. A Jatropha biomass as renewable materials for biocomposites and its applications. Renew. Sustain. Energy Rev. 22, 667–685 (2013) Contents.

Abeysundara, Y., Babel, S., Gheewala, S., 2009. A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka. Build. Environ. 44, 997–1004.

Abidin, N.Z., 2010. Investigating the awareness and application of sustainable construction concept by Malaysian developers. Habitat Int. 34 (4), 421–426 (2010).

Adams, W.M., 2006. The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century. Report of the IUCN Renowned Thinkers Meeting, 29–31 January 2006. Retrieved on: 2009-02-16.

Adams, C.A., Frost, G.R., 2008. Integrating sustainability reporting into management practices. Account. Forum 32 (Issue 4), 288–302.

P.O. Akadiri, P.O. Olomolaiye, Development of sustainable assessment criteria for building materials selection, J. Eng. Constr. Archit. Manag. 19(6) (2012) 18–37

Akadiri, Peter O., Olomolaiye, Paul O., Chinyio, Ezekiel A., 2013. Multi-criteria evaluation model for the selection of sustainable materials for building projects. Automation Constr. 30, 113–125 (2013).

Asokan, P., Osmani, M., Price, A.D.F., 2009. Assessing the recycling potential of glass fibre reinforced plastic waste in concrete and cement composites. Clean. Prod. 17 (9), 821–829 (2009).

Ayag, Z., Ozdemir, G.R., 2012. Evaluating machine tool alternatives through modified TOPSIS and alpha-cut based fuzzy ANP. Int. J. Prod. Econ. 140 (2), 630–636.

Azizi, M., Modarres, M., 2007. A strategic model for location selection of wood industry: an application of ANP. J. Appl. Sci. 7 (3), 326–333. http://dx.doi.org/10.3923/jas.2007.326.333.

Bahareh, R., Rehan, R., Kasun, H., 2011. Sustainability assessment of flooring systems in the city of Tehran: an AHP-based life cycle analysis. Constr. Build. Mater. 25 (4), 2053–2066 (2011).

Balaras, C.A., Droutsa, K., Dascalaki, E., Kontoyiannidis, S., 2005. Heating energy consumption and resulting environmental impact of European apartment buildings. Energy Build. 37 (5), 429–442.

Bank, L.C., Thompson, B.P., McCarthy, M., 2011. Decision-making tools for evaluating the impact of materials selection on the carbon footprint of buildings. Carbon Manag. 2 (4), 431–441 (2011).

Barrett, P.S., Sexton, M.G., Green, L., 1999. Integrated delivery systems for sustainable construction. Build. Res. Inf. 27 (6), 397–404 (1999).

Bayazit, O., 2006. Use of analytic network process in vendor selection decisions. Benchmarking: An Int. J. 13 (No. 5), 566–579.

Bebbington, J., Dillard, J., 2009. Social sustainability: an organizational-level analysis. In: Dillard, J., Dujon, V., King, M. (Eds.), Understanding the Social Dimension of Sustainability. Routledge, New York, pp. 157–173.

Building for Environmental and Economic Sustainability (BEES) http://www.nist.gov/el/economics/BEESSoftware.cfm/.

Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., Ignatius, J., 2012. A state of the art survey of TOPSIS applications. Expert Syst. Appl. 39, 13051–13069.

Bezdek, R.H., 2008. Green building: balancing fact and fiction," S. E. Cannon and U. K. Vyas, moderators. Real Estate Issues 33 (2), 2–5.

Birt, Benjamin, Newsham, Guy R., 2009. Post-occupancy Evaluation of Energy and Indoor Environment Quality in Green Buildings: a Review'. National Research Council Canada, 2009, Ontario.

Bondanza, Jackie, 2011. Book: How to Design and Build a Green Office Building: a Complete Guide to Making Your New or Existing Building Environmentally Healthy. Atlantic Publishing Group. March 31, 2011.

Boström, M., 2012. A missing pillar? Challenges in theorizing and practicing social sustainability: introduction to the special issue. Sustain. Sci. Pract. Policy, Winter 8 (1), 3e14.

Non green perspective on biodegradable polymer nanocomposites"A comment on'A Review on Carbon Nanotubes in an Environmental Protection and Green Engineering Perspective' published in Braz. J. Chem. Eng. 27(2), 227242.

Bunz, K.R., Henze, G.P., Tiller, D.K., 2006. Survey of sustainable building design practices in North America. Eur. Asia, Archit. Eng. 12 (1), 33–62 (2006).

Buyukozkan, G., Cifci, G., 2012. A novel hybrid MCDM approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS to evaluate green suppliers. Expert Syst. Appl. 39, 3000–3011.

Calkins, M., 2009. Materials for Sustainable Sites: a Complete Guide to the Evaluation, Se- Lection, and Use of Sustainable Construction Materials. Wiley, Hoboken, N.J, 2009.

Carson, Rachel, 1962. Silent Spring. N.p.: Houghton Mifflin. Print.

Chan, A.P.C., Chan, D.W.M., Ho, K.S.K., 2003. Partnering in construction: critical study of problems for implementation. J. Manag. Eng. ASCE 19 (No. 3), 126–135.

Chang, D.-Y., 1996. Applications of the extent analysis method on fuzzy AHP. Eur. J. Operational Res. 95 (3), 649–655. http://dx.doi.org/10.1016/0377 2217(95) 00300–2.

Changa, Yuan-Hsiou, Huangb, Po-Hsien, Wua, Bing-Yu, Chang, Shang-Wen, 2015. A study on the color change benefits of sustainable green building materials. Constr. Build. Mater. 83, 1–6, 15 May 2015.

Chen, J.K., Chen, I.S., 2010. Using a novel conjunctive MCDM approach based on DEMATEL, fuzzy ANP, and TOPSIS as an innovation support system for Taiwanese higher education. Expert Syst. Appl. 37, 1981–1990.

Chen, Y., Okudan, G.E., Riley, D.R., 2010. Sustainable performance criteria for construction method selection in concrete buildings. Automation Constr. 19 (2), 235–244 (2010).

Chikhia, Mourad, Agoudjil, Boudjemaa, Boudenne, Abderrahim, Gherabli, Abdelkader, 2013. Experimental investigation of new biocomposite with low cost for thermal insulation. Energy Build. 66, 267–273 (2013).

Chiou, C.Y., Hsu, C.W., Chen, H.C., 2011. Using DEMATEL to explore a casual and affect model of sustainable supplier selection. In Business Innovation and Technology Management (APBITM). In: IEEE International Summer Conference of Asia Pacific (pp. 240–244).

Chiu, Y.J., Chen, H.C., Tzeng, G.H., Shyu, J.Z., 2006. Marketing strategy based on customer behavior for the LCD-TV. Int. J. Manag. Decis. Mak. 7 (no.2/3), 143–165, 2006.

Cinelli, M., Coles, S.R., Kirwan, K., 2014. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol. Indic. 46, 138148.

Cinelli, M., Coles, S.R., Sadik, O., Karn, B., Kirwan, K., 2016. A framework of criteria for the sustainability assessment of nano-products. J. Clean. Prod. 126, 277287.

Crosbie, T., Dawood, N., Dawood, S., 2011. Improving the energy performance of the built environment: the potential of virtual collaborative life cycle tools. Automation Constr. 20 (2), 205–216 (2011).

Dagdeviren, M., Yuksel, I., 2010. A fuzzy analytic network process (ANP) model for measurement of the sectoral competition level (SCL). Expert Syst. Appl. 37, 1005–1014.

Emmitt, S., Yeomans, D.T., 2008. Specifying Buildings: a Design Management Perspective (261 pp), 2nd ed. Elsevier, Amsterdam. 2008.

EPA Document EPA-841-R-08-00, National Water Quality Inventory, 2004 Report, www.epa.gov/305b.

www.epa.gov/epawaste/conserve/rrr/imr/cdm/recycle.htm.

Eshtehardian, E., Ghodousi, P., Bejanpour, A., 2013. Using ANP and AHP for the supplier selection in the construction and civil engineering companies: case study of Iranian company. KSCE J. Civ. Eng. 17 (2), 262–270. http://dx.doi.org/10.1007/s12205-013-1141-z.
Florez, Laura, Castro-Lacouture, Daniel, 2013. Optimization model for sustainable materials selection using objective and subjective factors. Mater. Des. 46, 310–321 (2013) Contents.
Forestry Commission of Great Britain. Sustainability. Retrieved on: 2009-03-09.
Franzoni, Elisa, 2011. Materials selection for green buildings: which tools for engineers and architects. Procedia Eng. 21, 883–890 (2011).
Froeschle, Lynn M., 1999. Environmental assessment and specification of green building materials. Constr. Specif. 53. October 1999.
Frontczak, M.J., Wargocki, P., 2011. Literature survey on how different factors influence human comfort in indoor environments. Build. Environ. 46 (no. 4), 922–937. http://dx.doi.org/10.1016/j.buildenv.2010.10.021.
Gabus, A., Fontela, E., 1972. World Problems, an Invitation to Further Thought within the Framework of DEMATE. Battelle Geneva Research Centre, Switzerland, Geneva.
Gadermann, A.M., Guhn, M., Zumbo, B.D., 2012. Estimating ordinal reliability for Likert type and ordinal item response data. A conceptual, empirical and practical guide. Practical Assessment. Res. Eval. 17, 113.
Goggins, J., Keane, T., Kelly, A., 2010. The assessment of embodied energy in typical reinforced concrete building structures in Ireland. Energy Build. 42 (5), 735–744 (2010).
Gonzalez, M.J., Navarro, J.G., 2006. Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. Build. Environ. 2006 41 (7), 902–909.
Govindan, K., Shankar, K.M., Kannan, D., 2016. Sustainable material selection for construction industry–a hybrid multi criteria decision making approach. Renew. Sustain. Energy Rev. 55, 1274–1288.
Guitouni, A., Martel, J.M., 1998. Tentative guidelines to help choosing an appropriate MCDA method. Eur. J. Operational Res. 109, 501–521.
Halliday, S., 2008. Sustainable Construction. Butterworth Heinemann, (London).
Hori, S.S., Shimizu, Y., 1999. Designing methods of human interface for supervisory control systems. Control Eng. Pract. 7 (no.11), 1413–1419, 1999.
Questionable green ionic liquid: Comment on “Extractive desulfurization of liquid fuels by energy efficient green thiazolium based ionic liquids”. Industrial & Engineering Chemistry Research, 2015, 54(7), pp.22592259.
Ip, K., Miller, A., 2012. Life cycle greenhouse gas emissions of hemp-lime wall constructions in the UK. Resources, Conservation Recycl. 69, 1–9.
IUCN/UNEP/WWF, 1991. Caring for the Earth: a Strategy for Sustainable Living. Gland, Switzerland. Retrieved on: 2009-03-29.
Jato-Espino, Daniel, Castillo-Lopez, Elena, Rodriguez-Hernandez, Jorge, Canteras-Jordana, Juan Carlos, 2014. A review of application of multi-criteria decision making methods in construction. Automation Constr. 45, 151–216 (2014).
Joseph, P., Tretsiakova-McNally, S., 2010. Sustainable non-metallic building materials. Sustainability 2 (2), 400–427 (2010).
Kates, Robert W. (Ed.), 2010. Readings in Sustainability Science and Technology - an Introduction to the Key Literature of Sustainability Science CID Working Paper No. 213. Center for International Development, Harvard University, Cambridge, MA. Harvard University, December 2010.
Khoshnava, S.M., Rostami, R., Ismai1, M., Valipour, A., 2014. The using fungi treatment as green and environmentally process for surface modification of natural fibers. Appl. Mech. Mater. 554, 116–122 (2014).
Kibert, C.J., 2008. Sustainable Construction: Green Building Design and Delivery, second ed. John Wiley and Sons, Inc., Hoboken, New jersey, USA,. 2008.
Kim, J., Rigdon, B., 1998. Sustainable Architecture Module: Qualities, Use, and Examples of Sustainable Building Materials. Sustainable Architecture Compendium, National Pollution Prevention Center, University of Michigan, 1998.
Köksalan, M., Wallenius, J., Zionts, S., 2011. Multiple Criteria Decision Making: from Early History to the 21st Century. World Scientific, Singapore.
Konidari, P., Mavrakis, D., 2007. A multi-criteria evaluation method for climate change mitigation policy instruments. Energy Policy 35 (12), 6235–6257.
Kubba, Sam, 2010. Book: Green Construction Project Management and Cost Oversight. 2010 Elsevier Inc.
Kvam, P.H., Vidakovic, B., 2007. Nonparametric Statistics with Applications to Science and Engineering. John Wiley & Sons.
Lee, A.H.I., 2009. A fuzzy supplier selection model with the consideration of benefits, opportunities, costs and risks. Expert Syst. Appl. 36, 2879–2893.
Lee, Donghoon, Lee, Sungho, Tai, Jeong, Sunkuk, Kim, Department, Kim, 2011. A lifecycle health performance tree for sustainable healthy buildings. Indoor Built Environ. 2012 21 (1), 16–27.
Leadership in Energy and Environmental Design (LEED) http://www.usgbc.org/leed.
Li, Yunlu, 2013. The Green Building Materials Enterprises in the Management of Innovation and Production Technology Improvement. Springer Berlin Heidelberg, Seite, ISBN 978-3-642-34651-4, pp. 879–886. http://dx.doi.org/10.1007/978-3-642-34651-4_118.
Lin, C.L., Wu, W.W., 2004. A fuzzy extension of the DEMATEL method for group decision making. Eur. J. Operational Res. 156, 445–455.
Liou, J.J.H., Wang, H.S., Hsu, C.C., Yin, S.L., 2011. A hybrid model for selection of an outsourcing provider. Appl. Math. Model. 35, 5121–5133.
Lipiatt, B.C., 2007. BEES 4.0 – Building for Economic and Environmental Sustainability (Technical Manual and User Guide). National Institute for Standards and Technology. Retrieved February 7, 2008, from. www.fire.nist.gov.
Lu, S.K., Yan, H., 2007. An empirical study on incentives of strategic partnering in China: views from construction companies. Int. J. Proj. Manag. 25 (3), 241–249.
Mao, X., Lu, H., Li, Q., 2009. In: International Conference on Management and Service Science, 2009. MASS '09, pp. 1–5. http://dx.doi.org/10.1109/ICMSS.2009.5303546.
Mardani, A., Jusoh, A., Zavadskas, E.K., 2015. Fuzzy multiple criteria decision-making techniques and applications–two decades review from 1994 to 2014. Expert Syst. Appl. 42 (8), 4126–4148.
Mickaityte, A., Zavadskas, E.K., Kaklauskas, A., Tupenaite, L., 2008. The concept model of sustainable buildings refurbishment. Int. J. Strategic Prop. Manag. 12 (1), 53–68.
Mikhailov, L., Singh, M.G., 2003. Fuzzy analytic network process and its application to the development of decision support systems. IEEE Trans. Syst. 33, 33–41.
Moffett, Alexander, Sarkar, Sahotra, 2006. Incorporating multiple criteria into the design of conservation area networks: a mini-review with recommendations. Divers. Distributions 12, 125–137 (2006).
Moncaster, A.M., Symons, K.E., 2013. A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. Energy Build. 66, 514–523. November 2013.
Nassar, K., Thabet, W., Beliveau, Y., 2003. A procedure for multi-criteria selection of building assemblies. Automation Constr. 12 (5), 543–560 (2003).
Nguyen, H.T., Dawal, S.Z.M., Nukman, Y., Aoyama, H., 2014. A hybrid approach for fuzzy multi-attribute decision making in machine tool selection with consideration of the interactions of attributes. Expert Syst. Appl. 41, 3078–3090.
Oztaysi, B., Ucal, I., 2009. Comparing MADM techniques for use in performance. In: presented at the the 10th International Symposium on the Analytic Hierarchy Process, Pittsburgh, Pennsylvania, 2009.
Pacheco-Torgal, Fernando, Cabeza, Luisa F., Labrincha, João, de Magalhaes, Aldo Giuntini, 2014. Eco-efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-labelling and Case Studies. Wood head Publishing Series in Civil and Structural Engineering.
Papadopoulos, A.M., Giama, E., 2007. Environmental performance evaluation of thermal insulation materials and its impact on the building. Build. Environ. 2007 42 (5), 2178–2187.
Polatidis, H., et al., 2006. Selecting an appropriate multi-criteria decision analysis technique for renewable energy planning. Energy Sources Part B 1, 181–193.
Rabbani, A., Zamani, M., Yazdani-Chamzini, A., Zavadskas, E.K., 2014. Proposing a new integrated model based on sustainability balanced scorecard (SBSC) and MCDM approaches by using linguistic variables for the performance evaluation of oil producing companies. Expert Syst. Appl. 41 (16), 7316–7327.
Rao, R.V., 2008. A decision making methodology for material selection using an improved compromise ranking method. Mater Des. 2008 29 (10), 1949–1954.
Rao, R.V., Patel, B.K., 2010. A subjective and objective integrated multiple attribute decision making method for material selection. Mater Des. 2010 31 (10), 4738–4747.
Rehm, M., Ade, R., 2013. Construction costs comparison between ‘green’ and conventional office buildings. Build. Res. Inf. 41 (2), 198–208.
Ries, R., Bilec, M., Gokhan, N.M., Needy, K.L., 2006. The economic benefits of green buildings: a comprehensive case study. Eng. Econ. 2006 51 (3), 259–295.
Rowley, H.V., Peters, G.M., Lundie, S., Moore, S.J., 2012. Aggregating sustainability indicators: beyond the weighted sum. J. Environ. Manag. 111, 2433.
Saadati, S., 2010. A Model for Identify the Most Important Effective Parameters for Successfully 2-layer Supply Chain with Using of DEMATEL Method (Case Study). Master thesis. Iran University of Science and Technology (2010).
Saaty, T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York.
Saaty, T.L., 1991. Some mathematical concepts of the analytic hierarchy process. Behaviormetrika 29, 1–9.
Saaty, T.L., 1996. Decision Making with Dependence and Feedback: the Analytic Network Process. RWS Publications, Pittsburgh.
Saaty, Thomas L., Cillo, Brady, 2009. The Encyclicon, Volume 2: a Dictionary of Complex Decisions Using the Analytic Network Process. RWS Publications, Pittsburgh, Pennsylvania, ISBN 1-888603-09-7.
Saaty, T.L., Vargas, L.G., 1987. Uncertainty and rank order in the analytic hierarchy Process. Eur. J. Operational Res. 32 (1), 107–117.
Šaparauskas, J., Turskis, Z., 2006. Evaluation of construction sustainability by multiple criteria methods. Technol. Econ. Dev. Econ. 12 (4), 321–326.
Sasnauskaite, V., Uzsilaityte, L., Rogoza, A., 2007. A sustainable analysis of a detached house heating system throughout its life cycle. A case study. Int. J. Strategic Prop. Manag. 11 (3), 143–155.
Scott Cato, M., 2009. Green Economics. Earthscan, London, ISBN 978-1-84407-571-3, pp. 36–37.
What is so green about multi-walled carbon nanotubes based composite membranes? Separation and Purification Technology, 2015, (151), pp.9596.
Sevkli, M., Oztekin, A., Uysal, O., Torlak, G., Turkyilmaz, A., Delen, D., 2012. Development of a fuzzy ANP based SWOT analysis for the airline industry in Turkey. Expert Syst. Appl. 39, 14–24.
Shafiee, M., 2015. A fuzzy analytic network process model to mitigate the risks associated with offshore wind farms. Expert Syst. Appl. 42 (4), 2143–2152. http://dx.doi.org/10.1016/j.eswa.2014.10.019.
Shafieezadeh, M., Hajfataliha, A., 2009. A conceptual framework for supply chain coordination in fuzzy environment. J. Theor. Appl. Inf. Technol. 8 (2), 123–135.
Shapira, A., Goldenberg, M., 2005. AHP-based equipment selection model for construction projects. J. Constr. Eng. Manag. 131 (12), 1263–1273 (2005).
Sinou, M., Kyvelou, S., 2006. Present and future of building performance assessment tools. Manag. Environ. Qual. Int. J. 17 (5), 570–586 (2006).

Spiegel, R., Meadows, D., 2010a. A Guide to Product Selection and Specifications Green Building Materials, third ed. Canada: John Wiley and Sons, Inc., Hoboken, New Jersey. 2010.
Spiegel, R., Meadows, D., 2010b. Green Building Materials: a Guide to Product Selection and Specification. John Wiley & Sons.
Tambyrajah, D., 2012. International Natural Fiber Organization (INFO). Personal information, The Netherlands.
Tavana, M., Momeni, E., Rezaeiniya, N., Mirhedayatian, S.M., Rezaeiniya, H., 2013. A novel hybrid social media platform selection model using fuzzy ANP and COPRAS-G. Expert Syst. Appl. 40, 5694–5702.
The European Commission; http://ec.europa.eu/environment/index_en.htm.
Thormark, C., 2006. The effect of material choice on the total energy need and recycling potential of a building. Build. Environ. 2006 41 (8), 1019–1026.
Todd, J., Pyke, C., Tufts, R., 2013. Implications of trends in LEED usage: rating system design and market transformation. Build. Res. Inf. 41 (6), 662e76.
Torgal, F.P., Jalali, S., 2011. Eco-efficient Construction and Building Materials. Springer-Verlag London Limited. http://dx.doi.org/10.1007/978-0-85729-892-8_1.
OSHA § 2602. “Definitions,” The Toxic Substances Control Act (TSCA), 15 U.S.C. s/s 2601 et seq., 1976.
Ugwu, O.O., Kumaraswamy, M.M., Wong, A., Ng, S.T., 2006. Sustainability appraisal in infrastructure projects (SUSAIP): Part 1. Development of indicators and computational methods. Automation Constr. 15 (2), 239–251 (2006).
United Nations General Assembly, 2005. 2005 World Summit Outcome, Resolution A/60/1. adopted by the General Assembly on 15 September 2005. Retrieved on: 2009-02-17.
United States Environmental Protection Agency, http://www3.epa.gov/.
U.S. Department of Energy; http://www.energy.gov/.
U.S. Environmental Protection Agency, Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008. EPA-530-F-009–021. Washington, D.C., November 2009. www.epa.gov/epawaste/nonhaz/municipal/pubs/msw2008rpt.pdf.
U.S. Geological Survey, “Estimated Use of Water in the United States in 2000,” 2005, http://pubs.usgs.gov/circ/2004/circ1268/index.html.
Uygun, Özer, Kaçamak, Hasan, Kahraman, Ünal Atakan, 2015. An integrated DEMATEL and Fuzzy ANP techniques for evaluation and selection of outsourcing provider for a telecommunication company. Comput. Industrial Eng. 86, 137–146 (2015).
Amin Vafadarnikjoo, Corrigendum to “Using fuzzy DEMATEL to evaluate the green supply chain management practices”, J. Clean. Prod., Volume 82, 1 November 2014, Pages 232
Vahidnia, M., Alesheikh, A., Alimohammadi, A., Bassiri, A., 2008. Fuzzy analytical hierarchy process in GIS application, the International Archives of the photogrammetry. Remote Sens. Spatial Inf. Sci. 37 (B2), 593–596.
Valipour, A., Yahaya, N., Md Noor, N., Kildienė, S., Sarvari, H., Mardani, A., 2015. A fuzzy analytic network process method for risk prioritization in freeway PPP projects: an Iranian case study. J. Civ. Eng. Manag. 21 (7), 933–947.
Velasquez, M., Hester, P.T., 2013. An analysis of multi-criteria decision making methods. Int. J. Operations Res. 10 (2), 56–66.
Venkatarama Reddy, B.V., Jagadish, K.S., 2003. Embodied energy of common and alternative building materials and technologies. Energy Build. 2003 35 (2), 129–137.
Vinodh, S., Ramiya, A.R., Gautham, S.G., 2011. Application of fuzzy analytic network process for supplier selection in a manufacturing organization. Expert Syst. Appl. 38, 272–280.
Vujanović, D., Momčilović, V., Bojović, N., Papić, V., 2012. Evaluation of vehicle fleet maintenance management indicators by application of DEMATEL and ANP. Expert Syst. Appl. 39, 10552–10563.
Wang, Jian-Jun, Yang, De-Li, 2007. Using a hybrid multi-criteria decision aid method for information systems outsourcing. Comput. Operations Res. 34 (12), 3691–3700. December 2007.
Wang, H., Bai, H., Liu, J., Xu, H., 2012. Measurement indicators and an evaluation approach for assessing strategic environmental assessment effectiveness. Ecol. Indic. 23, 413–420 (2012).
Wei, Wenjuan, Ramalho, Olivier, Mandin, Corinne, 2015. Indoor air quality requirements in green building certifications. Build. Environ. 92, 10–19.
Weißenbergera, Markus, Jenschb, Werner, Langc, Werner, 2014. The convergence of life cycle assessment and nearly zero-energy buildings: the case of Germany. Energy Build. 76, 551–557. June 2014.
Wolfslehner, B., Vacik, H., Lexer, M.J., 2005. Application of the analytic network process in multi-criteria analysis of sustainable forest management. For. Ecol. Manag. 207, 157–170.
Wong, J.K.W., Li, H., 2008. Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems. Build. Environ. 43 (1), 108–125 (2008).
Wong, J., Li, H., Lai, J., 2008. Evaluating the system intelligence of the intelligent building systems: Part 1: development of key intelligent indicators and conceptual analytical framework. Automation Constr. 17 (3), 284–302 (2008).
Wu, W.W., Lee, Y.T., 2007. Developing global managers’ competencies using the fuzzy DEMATEL method. Expert Syst. Appl. 32 (no.4), 499–507, 2007.
Yip, R.C.P., Poon, C.S., 2009. Cultural shift towards sustainability in the construction industry of Hong Kong. J. Environ. Manag. ASCE 90 (11), 3616–3628.
Yu, C.W.F., Kim, J.T., 2010. Building pathology investigation of sick buildings: VOC emissions. Indoor Built Environ. 2010 19 (1), 30–39.
Zavadskas, E.K., Turskis, Z., Bagocius, V., 2015. Multi-criteria selection of a construction site for a deep-water port in the Eastern Baltic Sea. Appl. Soft Comput. 26, 180–192.
Zhou, C.C., Yin, G.F., Hu, X.B., 2009. Multi-objective optimization of material selection for sustainable products: artificial neural networks and genetic algorithm approach. Mater. Des. 30 (4), 1209–1215 (2009).
Zumbo, B.D., Gadermann, A.M., Zeisser, C., 2007. Ordinal versions of coefficients alpha and theta for Likert rating scales. J. Mod. Appl. Stat. Methods 6, 2129.