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## **Integrating and ranking sustainability criteria for housing**

### **ABSTRACT**

Numerous researchers have determined sustainability criteria relating to environmental performance but the other two sustainability components - economic and social performance - have not been taken into consideration in an integrated and hierarchy manner. Existing sustainability assessment methods (e.g., LEED, GBI, IGBC, and BREEAM) ignore the economic and social aspects, and sustainable criteria are not prioritized for decision making facilitation. To prioritize sustainable criteria for residential buildings in the triquetrous sustainability model including environmental, economic, and social in a global and integrated manner, a Fuzzy-AHP tool was employed and a structured expert-based development process comprised of seventeen building practitioners and eight academics from sixteen nations was conducted globally among carefully selected experts. A Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS) in residential buildings was developed at the end of this study. Assisted by programmers, the FWH-TS is expected to be developed into a PC software or Apps in the near future to improve construction management.

**Keywords:** Fuzzy-AHP, Fuzzy Weighted Hierarchy, Triquetrous Sustainability, Residential Building, Sustainable Environmental System

### **1.0 INTRODUCTION**

The notion of sustainability was realized by early human beings (Khalid et al., 2013) with our hunter-gatherer ancestors perceiving the essence of ensuring resources remain available through sustainable principles in a manner that was long forgotten until the last century (Hill & Bowen, 1997). The chance for reviving of sustainability concept appeared at the time when a new perception which labeled as ‘sustainable development’ was presented in 1987 in Brundtland’s Report (Abidin, 2009). Afterwards, many industries focused on sustainability practices and the building industry was not an exception (Lau, 2013). Sustainability has emerged as an increasingly important principle in construction due to the considerable industrial effects on both the environmental and society (Myers, 2005). The notion of sustainability in construction has primarily focused on the restricted resources, particularly energy and the reduction of the impact on the natural surroundings with the consideration of technical concerns such as materials and construction technologies (Amran et al., 2013). The recognition of non-technical concerns has become popular in terms of social and

economic sustainability in the 21st Century (Lawanson & Fadare, 2013). Globally, many regions are now witnessing a steady process of industrialization and urbanization, leading to an significant volume of construction work performed in the developmental phases (Dassen et al., 2013). In order to enhance the sustainable development of the economics and society alongside environmental sustainability, it is crucial to establish an effective sustainability hierarchy addressing all of the triquetrous criteria of environmental, economic, and social aspects (Manan et al., 2010).

Numerous researchers have determined the sustainability criteria for environmental performance but the other two components in sustainability including economic and social performances have not been taken into consideration in an integrated and hierarchy manner. Most of the existing sustainability assessment methods (e.g., LEED, GBI, IGBC, and BREEAM) consider only the environmental aspects and ignore the economic and social aspects and sustainable criteria which are therefore not prioritized to facilitate decision making (Zhang et al., 2006). Extending concepts pioneered by IGB and LEED to infrastructure (but which may apply equally well to residential, commercial, and institutional buildings), the Envision Rating System developed in 2010 by the Institute for Sustainable Infrastructure includes environmental and societal factors amongst the five categories that are evaluated: 1) quality of life, 2) leadership, 3) resource allocation, 4) natural world, and 5) climate and risk. While these assessment methods may incorporate some environmental considerations, they sometimes ignore societal aspects. Most importantly, these frameworks provide insufficient guidance on how to simultaneously evaluate and balance the tensions between the triple concerns.

Multi-Criteria Decision Making (MCDM) techniques are gaining recognition as supporting sustainable solutions and a number of methods derived from weighted averages, outranking, priority setting, and fuzzy principles are being used for sustainable decisions. Analytical Hierarchy Process (AHP) is a commonly employed MCDM technique based on the principle of decomposing complicated problems into a hierarchy with goal on the top, criteria and sub-criteria at levels and sub-levels, and decision options at the bottom of the hierarchy (Pohekar & Ramachandran, 2004). In order to make a decision, the most creative task is to choose the crucial criteria (Saaty, 2008). However, as there are numerous sustainable criteria in triquetrous sustainability, decision-making over these three groups is complicated and the prioritization of sustainability criteria could facilitate improved decision-making. The goal of this research is to determine and prioritize sustainable performance criteria for residential buildings in the triquetrous sustainability model including

environmental, economic, and social factors in a global and integrated manner. A Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS) in residential buildings was developed at the end of this study. In terms of theoretical contribution, this study fills the gap by providing a fuzzy weighted triquetrous sustainability model. In terms of practice, the developed FWH-TS is able to assist construction practitioners including developers, contractors, and consultants in making decisions to allot optimum budget and resources based on the priority weight of each sustainable criterion over the entire lifecycle for a residential building.

## **2.0 TRIQUETROUS SUSTAINABLE CRITERIA FOR RESIDENTIAL BUILDINGS**

The notable growth of sustainable development is undoubtedly a valuable transition in the evolving relationship between humans, nature, and groups of people (Hopwood et al., 2005). Sustainable development is defined by Ortiz et al. (2009) as improving the quality of life, and therefore enabling individuals to reside in healthy surroundings and enriching the social, economic, and environmental conditions for both the present and future generations (Ortiz et al., 2009). Efforts have been made to define sustainable development. However, most focus on only a few common elements; e.g., the environment, quality of life, and future generations. In Brundtland's (1987) report, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. This definition is favored since it contains the opportunity for adjusting people's needs with the bio-physical environmental management goals by means of economic development (Vallance et al., 2011). Sustainable development consists of fine-tuning the quality of life experienced while examining the needs of fellow citizens and future generations (Lützkendorf & Lorenz, 2005). The construction industry is among the primary exploiters of natural resources, both mineral and biological; therefore, actions by the construction industry bring about irreversible changes in the natural environment and increase atmospheric emissions (Spence & Mulligan, 1995). As a result of present worldwide population growth trends, this predicament is anticipated to rapidly become worse (Dixit et al., 2010). Therefore, the necessity of sustainable approach for the construction initiatives is clear in order to protect the environment, develop the economy, and support the society, providing the foundation for triquetrous sustainability.

Traditional residential building design has mainly concentrated on the technical feasibility along with the financial viability of the capital investment. However, the conversion to sustainable structures and urban communities ought to satisfy the complications posed by a variety of further

environmental, social, and economic concerns; e.g., growing energy charges, resource exhaustion, and new regulatory requirements (Georgiadou et al., 2012). Although the conventional design and the construction initiatives concentrate on cost, performance, and quality elements, sustainable design and construction offers the challenges of reducing both resource consumption and environmental degradation along with establishing a healthier built environment and making sure individual health and comfort (Sev, 2009). There is no existing comprehensive framework including all three aspects of sustainability within the building lifecycle. In order to establish such a comprehensive hierarchy for residential buildings, appropriate sustainable criteria have been selected from various publications together with industry guidelines; e.g., LEED (2002), GBI (2010), IGBC Green Homes (2009), DGNB (2009).

## **2.1 Environmental criteria for sustainability**

The environmental criteria includes six groups, viz.: a) sustainable site considerations; b) water efficiency considerations; c) energy and atmosphere considerations; d) materials and resources considerations; e) indoor environmental quality; and, f) innovation and design process considerations. Each criterion subsumes a range of detailed sub-criteria, discussed in the following paragraphs. The criteria are based on prior criteria from related frameworks (e.g., LEED and IGBC) and focus solely on the immediate surroundings of the construction site (i.e., they exclude wider implications such as load on public utilities such as drinking water or sewage systems resulting from the construction). The researchers compiled appropriate criteria based on their expertise and the other frameworks, eliminated overlapping criteria where they essentially measured the same concepts, and ensure criteria addressed reduced waste (in environmental efficiency) or appropriate societal measures.

### **a) Sustainable Site Considerations**

The criterion for sustainable site considerations criterion consists of four sub-criteria, viz. a1) land sensitivity considerations; a2) pollution reduction considerations; a3) considerations to develop damaged areas; and, a4) ecosystem preservation. Land sensitivity focuses on preventing - wherever possible - the unrecoverable impacts on the natural environment from executing a project. Managing erosion to decrease harmful effects on water and air quality is extremely important. In addition, developments should be patterned after other urban locations with respect to enhancing available infrastructure, preservation of green fields, and the maintenance of habitats and natural resources.

Land sensitivity considerations also include preservation of the natural topography of the site to prevent later disturbance to the site. According to this criterion, earthwork and excavation should be reduced during structural operations (GBI, 2010; IGBC Green Homes, 2009; LEED, 2002; Shen et al., 2007).

The second sub-criterion is pollution reduction considerations, which relates to efficient land use and actions taken to prevent land-based pollution. Possible air, water, light and noise pollution from the suggested project and the effects on the local climate should be investigated (Kim et al., 2005; LEED, 2002; Shen et al., 2007).

The third sub-criterion is the consideration for developing damaged areas, which deals with re-establishment of damaged and affected areas to produce habitats and to increase biodiversity. Rehabilitation of affected sites wherein development is challenging by actual or even recognized environmental pollution is crucial in order to lower the burden on untouched land (Lützkendorf & Lorenz, 2005).

The fourth sub-criterion is ecosystem preservation within which possible ecological risks and positive aspects connected with the suggested project should be investigated. A reduction of heat islands in order to diminish the effect on the microclimate and both human and wildlife habitats must be accounted for. In addition, preserving and developing green areas is a part of ecosystem preservation (IGBC Green Homes, 2009; LEED, 2002).

#### b) Water Efficiency Considerations

The water efficiency considerations are divided into three sub-criteria: b1) reduction of potable water consumption; b2) reduction of loss and waste; and, b3) implementation of alternative resources. The first sub-criterion is the reduction of potable water consumption, which deals with minimizing or eradicating the utilization of potable water for the landscaping and irrigation purposes, and the reduction of water consumption by maximizing water efficient fittings, water recycling, and water metering (GBI, 2010; LEED, 2002).

The second sub-criterion is the reduction of the loss and waste, to minimize the amount of water loss and waste by implementing treated grey water for flushing requirements, irrigation, landscaping, and

innovative wastewater technologies (IGBC Green Homes, 2009). The third sub-criterion is implementation of alternative resources, which focuses on making available rainwater harvesting systems in order to trap the roof water produced from the roof area. This is then exploited to support landscape irrigation or indoor water use (LEED, 2002).

#### c) Energy and Atmosphere Considerations

Energy and atmosphere considerations can be divided into four main sub-criteria: c1) commissioning of building systems; c2) energy performance considerations; c3) reduction of non-renewable energy use; and, c4) ozone protection considerations. The first sub-criterion is commissioning of building systems that concentrates on checking and ensuring essential building elements are calibrated and function as expected (LEED, 2002).

The second sub-criterion is energy performance considerations, relating to developing the best possible level of energy efficiency for the base building and systems. Afterwards, trying to attain increasing levels of energy performance above the required standard to reduce environmental effects related to significant energy use. In addition, encouraging improvement of thermally comfortable environments to minimize air-conditioning use in residential buildings, leading to reduced CO<sub>2</sub> emissions, is vital as an energy performance consideration. Application of high efficiency lighting systems should be supported with the intention to lessen energy intake (GBI, 2010; LEED, 2002).

Within the third sub-criterion, reduction of non-renewable energy, the emphasis is on the significant environmental effects linked to fossil fuel energy use by promoting on-site renewable energy self-supply development (Shen et al., 2007). The fourth sub-category is ozone protection considerations through preventing the use of particular refrigerants and ozone layer depleting gases (IGBC Green Homes, 2009).

#### d) Materials and Resources Considerations

This criterion is categorized into four sub-criteria: d1) waste management; d2) resource depletion considerations; d3) materials' properties; and, d4) implementation of regional materials. The first sub-criterion focuses on waste reduction program evaluation and discussion at site progress meetings. To escalate the amount recycling, materials ought to be accumulated separately as a way to

prevent mixing diverse waste materials. Reducing on-site waste by using off-site fabrication is crucial (Asif et al., 2007; IGBC Green Homes, 2009; LEED, 2002).

Resource depletion considerations focuses on the reuse of building materials and restricting the call for virgin materials. Implementing building products that entail recycled content materials should be escalated to minimize effects associated with extraction and processing of new virgin materials. In addition, the reduced use of and therefore depletion of both limited raw materials and long-cycle renewable materials by substituting them with instantly renewable materials is crucial (Ding, 2005; Shen et al., 2007).

Materials’ properties focuses on key attributes of materials; e.g., degree of processing required, maintainability, resistance to potential damage or decay, and technical performance (LEED, 2002; Pearce et al., 2012). The fourth sub-criteria is implementation of regional materials which focuses on increasing desires for building materials and products that are extracted and manufactured within the region, which both contributes to the regional economy and reduces environmental effects from transportation (Pearce et al., 2012).

#### e) Indoor Environmental Quality

Indoor environmental quality criterion is divided into four sub-criteria: e1) thermal comfort; e2) indoor air quality; e3) visual comfort; and, e4) aural comfort. The first sub-criterion is to assist construction designers to create an indoor climate in which building occupants feel thermally comfortable (Lai et al., 2009; Nicol & Humphreys, 2002).

Indoor air quality emphasizes ventilation effectiveness, construction IAQ management plan, environmental Tobacco smoke (ETS) control, monitoring and reduction of CO<sub>2</sub> emissions, indoor chemicals, and pollutant source control. Controllability of systems (thermal, ventilation and lighting systems) by occupants should be implemented to ensure high quality indoor air for occupants (Lützkendorf & Lorenz, 2005).

Visual comfort focuses on optimizing and balancing both visual comfort and low energy consumption (Ochoa et al., 2012). The fourth sub-criterion, aural comfort, focuses on ensuring that building walls and floor systems are designed with sufficient sound absorption capability to sustain

suitable acoustical quality for occupants and neighbors (Kim, et al., 2005; Lai et al., 2009; Wang et al., in press).

#### f) Innovation and Design process Considerations

The last environmental criterion is innovation and design process considerations: f1) innovation in design and f2) environmental design. Innovation in design offers design teams and project participants the opportunity to be awarded for performance above minimum requirements (Holden & Scerri, 2013). Georgiadou (2012) claims eco-innovation does not necessarily mean expensive solutions, but rather ones that are technically robust, socially responsible, and financially viable. Environmental design will be satisfied if knowledgeable designers are selected. Important criteria to reach high quality environmental design include life-cycle design, environmentally conscious design, and modular and standardized design (Shen et al., 2007). Environmental criteria and sub-criteria for sustainability are summarized in Table 1.

Table 1: Environmental Criteria for Sustainability

Level 1	Level2	Level 3	Authors
Environmental sustainability	1.1. Sustainable Sites Considerations	1.1.1. Land sensitivity considerations	(LEED, 2002), (IGBC Green Homes, 2009)
		1.1.2. Pollution Reduction Considerations	(Kim et al., 2005), (LEED, 2002), (Shen et al., 2007)
		1.1.3. Developing Damaged Areas	(GBI, 2010), (Shen et al., 2007), (Lützkendorf & Lorenz, 2005)
		1.1.4. Ecosystem Preservation	(Shen et al., 2007), (Kim et al., 2005), (LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
	1.2. Water Efficiency Considerations	1.2.1. Reduction of potable water consumption	(LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
		1.2.2. Reduction of loss and waste	(LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
		1.2.3. Implementation of alternative resources	(LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
	1.3. Energy and Atmosphere Considerations	1.3.1. Commissioning of building systems	(LEED, 2002)
		1.3.2. Energy performance considerations	(LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
		1.3.3. Reduction of non-renewable energy	(LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009), (Shen et al., 2007)
		1.3.4. Ozone protection considerations	(LEED, 2002), (IGBC Green Homes, 2009),



		(Shen et al., 2007)
<b>1.4. Materials and Resources Considerations</b>	<b>1.4.1.</b> Waste management	(LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
	<b>1.4.2.</b> Resource depletion considerations	(Ding, 2005), (LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009), (Shen et al., 2007)
	<b>1.4.3.</b> Properties of materials	(Lützkendorf & Lorenz, 2005), (Pearce et al., 2012), (LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
	<b>1.4.4.</b> Implementation of regional materials	(Pearce et al., 2012), (LEED, 2002), (GBI, 2010), (IGBC Green Homes, 2009)
<b>1.5. Indoor Environmental Quality</b>	<b>1.5.1.</b> Thermal comfort	(Lai et al., 2009), (LEED, 2002), (GBI, 2010), (Kim et al., 2005), (Nicol & Humphreys, 2002)
	<b>1.5.2.</b> Indoor air quality	(Lai et al., 2009), (Lützkendorf & Lorenz, 2005), (LEED, 2002),
	<b>1.5.3.</b> Visual comfort	(Lai et al., 2009), (Kim et al., 2005), (Ochoa et al., 2012)
	<b>1.5.4.</b> Aural comfort	(Lai et al., 2009), (Kim et al., 2005),
<b>1.6. Innovation and Design process Considerations</b>	<b>1.6.1.</b> Innovation in design	(Georgiadou et al., 2012)
	<b>1.6.2.</b> Environmental design	(Shen et al., 2007) (Holden & Scerri, 2013)

## 2.2 Social criteria for sustainability

Social sustainability criteria are classified into six major sub-criteria: a) Site and Equipment Considerations; b) Health and Comfort considerations; c) Job Opportunities; d) Safety Issues; e) Stakeholders’ Relationship; and, f) Architectural Issues.

### a) Site and Equipment Considerations

Site and equipment considerations include five sub-criteria: a1) quality of infrastructure; a2) security of the site; a3) quality of facilities; a4) barrier-free built environment considerations; and, a5) land use considerations. Quality of infrastructure addresses factors including access to public transportation, quality of leisure and recreation infrastructure, improvement of infrastructure, and infrastructure burden during construction; i.e., the additional demand for water, road, energy, services, and space (Ceron-Palma et al., 2013).

Security of the site emphasizes protection of entry points, monitoring devices, and natural access control which can be helpful to providing security for residents (Buys et al., 2005). The third

sub-criterion is quality of facilities which defined by Shen et al. (2007) as provision of community amenities for the harmonization of new settlements and local communities. The fourth sub-criterion is barrier-free built environment considerations that relate to access for physically disabled persons and protection against slipping and stumbling by all persons (Maria & Stella, 2006). The final sub-criterion is land use considerations, focusing on the land choice for project site in a way that preserves cropland and natural resources. Provision of property at the end of project demolition to allow the development of new projects in accordance with the requirements of local community is also important (Shen et al., 2010).

#### b) Health and Comfort Considerations

Health and comfort considerations criterion are categorized into six major sub-criteria: b1) thermal comfort; b2) visual comfort; b3) acoustical comfort; b4) indoor air quality; b5) daylight and exposure to sunlight; and, b6) indoor hygiene. Assessment must be made of thermal comfort, operative temperature, asymmetry of radiation temperature and flooring temperature, humidity, and vertical thermal gradient (Ceron-Palma et al., 2013).

Visual comfort can be attained by well-balanced illumination without interferences (e.g., direct and reflected glare), adequate lighting levels, and the possibility to alter illumination to meet specific requirements (DGNB, 2009).

The third sub-criterion of acoustical comfort is focused on attaining low levels of disturbance and background noise (Mötzl & Fellner, 2011). Indoor air quality criterion includes prevention of an increase in large particulate concentration within a home; e.g., indoor tobacco smoking, operation of gas stoves for cooking, and VOC pollutants (Lee et al., 2002; Sahely et al., 2005; Zavrl et al., 2009). The fifth is daylight and exposure to sunlight. Appropriate use of sunlight within buildings improves the staff productivity and reduces sick time. Sunlight has several advantages: it can enhance the quality of light in a space and decreases the amount of electrical lighting needed. More importantly, sunlight offers huge psychological advantages to building users; this may be a primary purpose for enhancing the use of sunlight rather than simply cutting back on electrical lighting demands (Maria & Stella, 2006). The sixth sub-criterion of this group is indoor hygiene, the main concern of which is to eliminate adverse effects on users' health conditions. Indoor hygiene also includes sub-criteria; e.g., refuse disposal, water supply, pest control, and cleaning (DGNB, 2009).

### c) Job Opportunities

Job opportunities is divided into two: c1) direct employment and c2) indirect employment. Construction laborers, specialists, and engineers are included in local labor market (Shen et al., 2007). Indirect employment is defined by Shen et al. (2007) as employment generated by the up-and-down-stream industries and services to construction.

### d) Safety Issues

Safety issues include d1) design considerations towards safety and d2) management considerations towards safety. Design considerations towards safety includes architectural features (e.g., height and disposition, means of escape, means of access, and amenities), building services (e.g., fire service installations, electrical installations, and fuel supply), and the external environment (e.g., proximity to special hazards and proximity to fire station) (Ho et al., 2008). Management considerations towards safety includes operations and maintenance issues (e.g., structural condition, building services condition, exit routes condition, and fire compartmentation) and management approaches (e.g., owners' duties, documentation, emergency preparedness, and financial arrangements) (Ho et al., 2008).

### e) Stakeholders' Relationship

The stakeholders' relationship criterion is classified as either e1) communication to the public or e2) public participation. Communication to the public emphasizes increasing public awareness about the project and possible effects on the public of project demolition (Shen et al., 2007). Public participation aims to generate improved decisions around multiple challenges regarding risks to well-being, health, and the environment (Sharifi & Murayama, 2013; Kasemir, 2003; Sahely et al., 2005).

### f) Architectural Issues

Architectural issues include either f1) architectural heritage considerations or f2) architectural functionality and flexibility considerations. Architectural heritage considerations focus on prevention

of negative impact of project development on any kind of cultural heritage (Ding, 2005). Furthermore, buildings should provide proper functionality to residents and be able to be altered based on residents’ needs (Zavrl et al., 2009). The criteria and sub-criteria in social sustainability are summarized in Table 2.

Table 2: Social Criteria and Sub-Criteria in Sustainability

Level 1	Level2	Level 3	Author
Social sustainability	1.1. Site and Equipment Considerations	1.1.1. Quality of Infrastructure	(Newell et al., 2013), (Shen et al., 2007), (Ceron-Palma et al., 2013)
		1.1.2. Security of the Site	(Buys et al., 2005), (Maria & Stella, 2006)
		1.1.3. Quality of Facilities	(Ceron-Palma et al., 2013), (Maria & Stella, 2006),
		1.1.4. Barrier-free Built Environment considerations	(Maria & Stella, 2006),
		1.1.5. Land use considerations	(Shen et al., 2010)
	1.2. Health and Comfort considerations	1.2.1. Thermal Comfort	(Ceron-Palma et al., 2013), (DGNB, 2009)
		1.2.2. Visual Comfort	(DGNB, 2009)
		1.2.3. Acoustical Comfort	(Mötzl & Fellner, 2011), (DGNB, 2009)
		1.2.4. Indoor Air Quality	(Lee et al., 2002)
		1.2.5. Daylight and Exposure to Sunlight	(Shen, et al., 2007)
		1.2.6. Indoor Hygiene	(DGNB, 2009)
	1.3. Job Opportunities	1.3.1. Direct Employment	(Shen, et al., 2007)
		1.3.2. Indirect Employment	(Shen, et al., 2010)
	1.4. Safety Issues	1.4.1. Design Considerations towards safety	(Ho et al., 2008)
		1.4.2. Management considerations towards safety	(Ho et al., 2008)
		1.4.3. Communication to the Public	(Shen et al., 2007)
	1.5. Stakeholders’ Relationship	1.4.4. Public Participation	(Sahely et al., 2005), (Kasemir, 2003), (Sharifi & Murayama, 2013)
	1.6. Architectural Issues	1.6.1. Architectural heritage considerations	(Ding, 2005),
1.4.5. Architectural Functionality and flexibility considerations		(Zavrl et al., 2009)	

### 2.3 Economic criteria in sustainability

Economic criteria for sustainability are classified into four major sub-criteria: a) Expenditure; b) Revenue; c) Investment in innovation, research and development; and, d) Improvement of local economic environment.

#### a) Expenditure

The expenditure criterion consists of a1) capital costs; a2) lifecycle costs; and, a3) environmental costs. Capital costs are the expenses relating to construction clients. Capital costs are the construction

costs, associated legal and design fees, property acquisition, site preparation costs, VAT (Value Added Tax), and financing costs (Mohamed et al., 2002). Lifecycle costs are costs to owners and building users after the completion of projects; e.g., maintenance and facilities management costs, operational costs, and replacement and disposal costs (Quigley et al., 2007). Environmental costs are imposed on the community in the form of pollution; e.g., from the production of concrete, the use of harmful materials, and other impacts from construction such as traffic due to the location of the building (Quigley et al., 2007).

#### b) Revenue

The revenue criterion consists of: b1) value stability; b2) lifecycle profit; and, b3) distribution of project income. A building intended for sustainability could be effortlessly modified to altering needs. Changes in the use of the building can come about from tenant or user alterations or by reorganization of tenants. An excellent level of flexibility and adaptability of buildings under the aim of sustainability occurs in the event that the changes could be achieved with few resources (DGNB, 2009). Profit assessments ought not to be emphasized on stage or even sectional earnings and profits, but it should include total revenue and profit from operating a building project across its whole lifecycle (Shen et al., 2007). The final sub-criterion of this category is the distribution of project income defined by Shen et al. (2007) as reinvestment, dividends, and paybacks.

#### c) Investment in Innovation, Research and Development

This criterion include both c1) expenditure on R&D and c2) reserve funds. Expenditure on R&D indicates the amount of investment allocated to R&D activities toward sustainability. In addition, sustainable construction companies need to ensure there are accessible reserve funds to support survival during sustainable development (Sahely et al., 2005).

#### d) Improvement of Local Economic Environment

This criterion is classified to four main sub-criteria: d1) local material choice; d2) utilization of local infrastructure; d3) improvement of local labor market; and, d4) improvement of local businesses. Choosing to use local materials for construction as much as possible is the main concern of the first sub-criterion. A project needs to assist local economy by taking advantage of the infrastructure in

order to produce economic profits (Shen et al., 2010). Improvement of the local labor markets highlights the importance of recruiting a range of local laborers (e.g., construction workers, engineers, managers, and janitors) over the different stages of the building lifecycle. Local authorities should encourage the involvement of citizens, local institutions, and private companies and promote thinking globally but acting locally (Pulselli et al., 2006). Finally, consideration should be given to business opportunities for local suppliers, contractors, and consultants as this will improve economic development locally. The economic criteria for sustainability are summarized in Table 3.

Table3: Economic Criteria for Sustainability

Level 1	Level2	Level 3	Author
Economic sustainability	1.1. Expenditure	1.1.1. Capital costs	(Quigley et al., 2007), (Mohamed et al., 2002)
		1.1.2. Life-cycle costs	(Quigley et al., 2007), (Mohamed et al., 2002)
		1.1.3. Environmental costs	(Quigley et al., 2007)
	1.2. Revenue	1.2.1. Value stability	(DGNB, 2009)
		1.2.2. Life-cycle profit	(Shen et al., 2007)
		1.2.3. Distribution of project income	(Shen et al., 2007)
	1.3. Investment in innovation, research and development	1.3.1. Expenditure on R &D	(Sahely et al., 2005)
		1.3.2. Reserve funds	(Sahely et al., 2005)
	1.4. Improvement of local economic environment	1.4.1. Local material choice	(Shen et al., 2007), (Shen et al., 2010)
		1.4.2. Utilization of local infrastructure	(Shen et al., 2007), (Shen et al., 2010)
		1.4.3. Improvement of local labor market	(Pulselli et al., 2006)
		1.4.4. Improvement of local businesses	(Shen et al., 2007)

### 3.0 FUZZY-AHP FOR DECISION MAKING

Decision making is a crucial element in many different careers and daily life. Construction practitioners and scholars must give priority to some options and devote less attention to others. A well-known tool for prioritizing effective criteria and sub-criteria in the realm of decision making is Analytic Hierarchy Process (AHP).

Residential buildings are prone to many uncertainties and vagueness. The utilization of fuzzy reasoning techniques offers an effective tool to manage the doubts, uncertainties, and subjectivities associated with construction initiatives (Zeng et al., 2007). Promentilla et al. (2008) proposed the integration of fuzzy principles in a hierarchical network and asserted that human judgment declared in natural language is usually vague and uncertain, so using Fuzzy principles the vagueness can be limited significantly. The strength of AHP is that it can be simply integrated with other techniques.

As a prioritizing tool, the judgment of experts plays a crucial role and is normally expressed in numerical scales. By applying fuzzy principles in comparison scale in AHP, the uncertainty in judgments can be controlled appropriately. In order to apply fuzzy principles in AHP, the fuzzy numbers should be considered rather than real numbers. Triangular fuzzy numbers are used for pairwise comparison scale of AHP in most of the studies. Fuzzy averaging is applied to aggregate the experts' opinions and judgments and the fuzzy average numbers will be transferred into crisp numbers. Afterwards, the eigenvector of the crisp matrix is calculated (Chang, 1996).

One stage of AHP relates to pairwise comparisons which should be conducted by experts and specialists. In this stage, experts give scores to paired criteria. However, due to nature of construction initiatives, experts will face difficulties in allocating absolute numbers to each of these criteria, making the relative comparison pragmatic. The approach can be further enhanced in AHP applications for construction activities by integrating Fuzzy set theory as this can better capture the vagueness of decision making. Therefore, instead of proposed point scale in AHP, language variables will be used which can be interpreted as fuzzy numbers is a great assistance. Fuzzy operations are applied to fuzzy numbers to further improve the results.

#### **4.0 RESEARCH METHODS AND PROCEDURES**

The aim of this research is to develop a Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS) for residential buildings. The research is principally a descriptive study assisted by quantitative approaches, to systematically explain a situation, issue, and phenomenon and explains attitudes regarding an issue. To prioritize categorized sustainable criteria, the AHP tool was selected and in the stage of pairwise comparison, where each set of two criteria were compared due to the relative weights of the criteria. Psychologists have demonstrated that it is less complicated and more precise to show your viewpoint on merely a couple of options compared to concurrently on almost all the choices using interview or questionnaire survey (Ishizaka & Labib, 2011).

This study employed a structured interview approach among carefully selected industry experts. The questionnaire form developed for this structured interview consists of three sections addressing each of environmental, social, and economic criteria. A pilot survey was conducted to determine the contemplated criteria and to choose those specialists with related qualification and expertise to join the Fuzzy-AHP survey.

As the goal of the research was to determine and prioritize performance criteria over a range of factors that may not be well-understood by laypeople or building residents, it was decided that the respondents that would be able to provide the most support for the research would be experts (either industry-based or academic). These individuals must have substantial experience with sustainability development in residential building projects. Their experience and immersion in the industry would allow them to understand contemporary practices and trends in the global construction industry. An initial list of experts was constructed based on personal contacts of the research group and by conducting an extensive internet-based search. The initial list was filtered by peer recommendation and published biographies. There were 64 building practitioners and 31 academic scholars were shortlisted and invited from 29 nations and regions. Finally, 17 building practitioners and eight academic scholars from 16 nations agreed and participated in the expert-based structured interview (participant profiles are presented in Table 4). These participating experts were interviewed by the research team using the same research instrument either in their office or through appointments when they attending international conferences during 2013. A pilot study was conducted to examine the relevance of the suggested criteria and to check the comprehensibility of terms. Some terms were unclear to all participants and so were changed, using feedback from the respondents involved in the pilot study. Finally, at any point, the respondents in the final interviews were able to clarify with the researchers the meaning of any term used during the process so that appropriate decisions were made.

The integrated Fuzzy-AHP tool was employed as a decision making approach for prioritizing relevant criteria and sub-criteria. Priority weights are achieved based on experts’ judgment and selection. The application of fuzzy numbers for weighting scores instead of real numbers mitigates the associated fuzziness and uncertainty. The fuzzy rule was applied for averaging experts’ judgments. After fuzzy averaging, defuzzification of fuzzy numbers was conducted to generate crisp numbers for determining priority weights. The following seven steps were conducted in this research.

Table 4: Demography of Experts

Experts	Type	Working Country	Expertize	Total Working Experience	Experience in Building Sustainability	Position	Qualification	Gender
A	Practitioner	UK	Environmental Sustainability	27	23	Senior Director	PHD	M
B	Practitioner	UK	Economic Sustainability	31	25	Senior Director	Master	M
C	Practitioner	Australia	Environmental	24	24	Project Director	Master	M



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			Sustainability						
D	Academia	NZ	Environmental Sustainability	29	21	Professor		PHD	M
E	Practitioner	US	Economic Sustainability	32	13	Senior Engineer	Project	PHD	M
F	Academia	NZ	Social Sustainability	24	20	Professor		PHD	F
G	Academia	Australia	Social Sustainability	18	17	Associate Professor		PHD	F
H	Practitioner	HK	Economic Sustainability	22	14	Senior Engineer	Project	Master	M
I	Practitioner	China	Environmental Sustainability	26	25	Senior Engineer	Project	Bachelor	M
J	Academia	Malaysia	Fuzzy-AHP	33	11	Professor		PHD	F
K	Practitioner	Denmark	Environmental Sustainability	23	19	Senior Engineer	Project	Master	M
L	Academia	India	Social Sustainability	34	17	Professor		PHD	F
M	Practitioner	Singapore	Social Sustainability	27	20	General Manager		Master	M
N	Practitioner	Germany	Environmental Sustainability	19	18	Senior Engineer	Project	Master	M
O	Academia	Malaysia	Social Sustainability	28	16	Professor		PHD	M
P	Practitioner	China	Social Sustainability	30	22	Senior Director		Master	F
Q	Practitioner	Thailand	Social Sustainability	26	19	General Manager		Master	M
R	Practitioner	Malaysia	Environmental Sustainability	21	18	Senior Director		Master	M
S	Academia	HK	Economic Sustainability	25	13	Professor		PHD	M
T	Practitioner	Japan	Economic Sustainability	22	20	Senior Director		PHD	M
U	Practitioner	Iceland	Environmental Sustainability	20	17	Senior Engineer	Project	Master	F
V	Practitioner	Thailand	Economic Sustainability	31	22	General Manager		PHD	M
W	Practitioner	Argentina	Economic Sustainability	34	19	General Manager		PHD	M
X	Practitioner	Singapore	Social Sustainability	27	16	Senior Director		PHD	F
Y	Academia	Netherlands	Environmental Sustainability	22	14	Professor		PHD	M

### **Step 1: Establishment of hierarchy:**

In this step, the decision making problem was divided to relevant criteria, sub-criteria, and alternatives. The linear hierarchy entailing several elements were depicted and determined in this stage. The first level is the goal of the hierarchy. The second and third levels consist of criteria, sub-criteria, and the alternatives which decision should be made over. In order to determine priority weights of each criterion, relevant criteria and sub-criteria were categorized in three different categories (viz., environmental sustainability, social sustainability and economic sustainability) which formed a triquetrous sustainability. It needs the weights of each criterion or sub-criterion in comparison with all the rest of criteria and sub-criteria in three categories. Hence, by multiplying the weight of each criterion with the weight of relevant category, the exact weights were attained. In Figure 1 the environmental hierarchy was depicted. In the second level, six criteria of environmental sustainability are outlined. In the third level, the sub-criteria of each criterion are presented. Likewise,

the social sustainable hierarchy and the economic sustainable hierarchy are presented in Figure 2 and Figure 3, respectively.

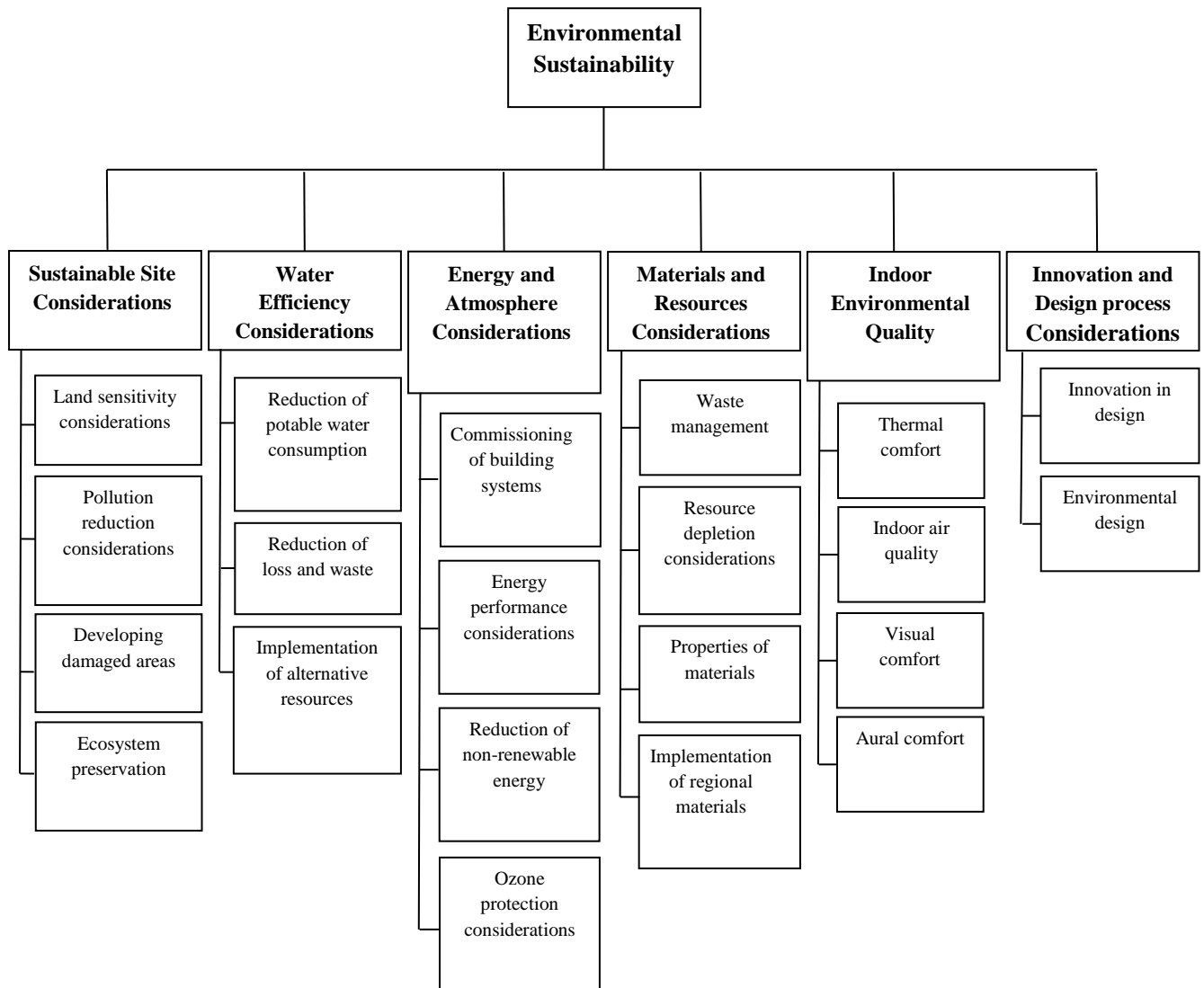


Figure 1: Environmental criteria for sustainability

**Step 2: Establishment of pairwise comparison matrices**

Step 2 in this study differs from the original AHP step in two ways. Firstly, there is no alternative in the setting of this study. Secondly, there are a greater number of indicators in this study than is usual. The dimension of each matrix is equal to  $n(n-1)/2$ ; since the number of indicators in this study is 52, the dimensions of comparison matrix are as high as 1326. Hence, a modification was made to the original AHP approach. Each block of factors was compared then the eigenvector of each group was

calculated. By multiplying eigenvector of upper levels to lower levels the final weights of criteria were computed. In this step, the related pairwise comparison matrices were constructed based on the experts’ judgment. Experts provided judgments on pairwise comparison toward sustainability criteria and were requested to give fuzzy scales when they were uncertain about the precise numerical values.

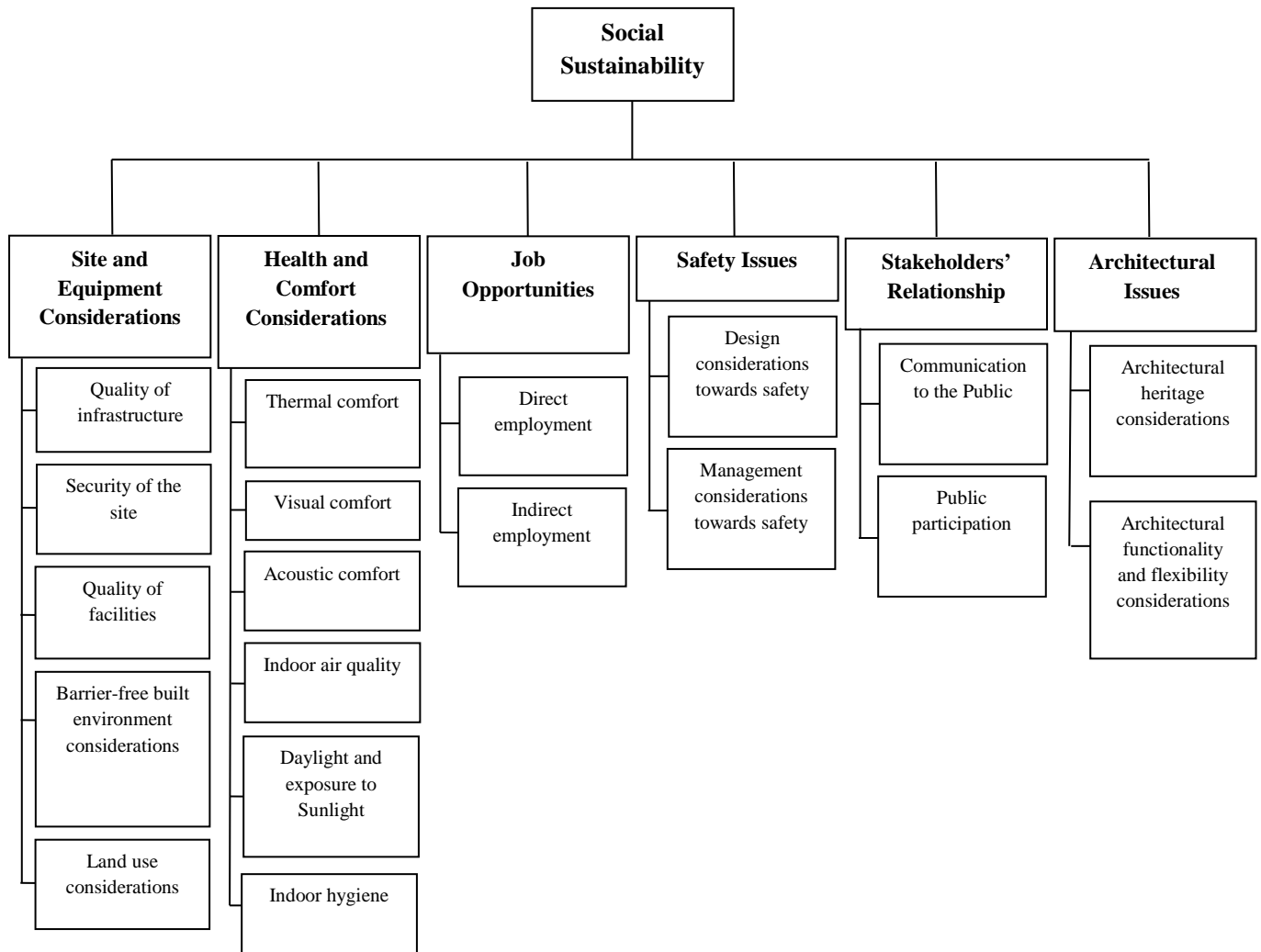


Figure 2: Social criteria for sustainability

**Step 3: Calculating the consistency ratio of questionnaires**

Each related consistency ratio in the comparison matrices was calculated for the four levels. Whenever the related consistency of a group was not acceptable, the expert was requested to redo the

judgments for the same questions but in a purposely changed order to prevent prejudice. This process was repeated until all the consistency ratios became acceptable.

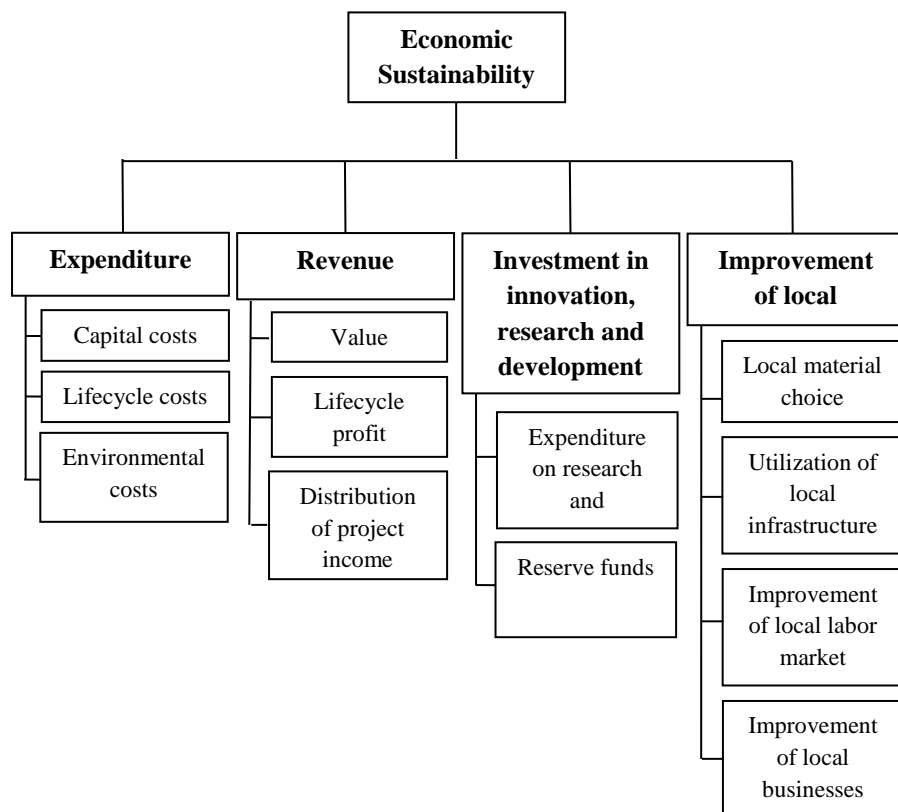


Figure 3: Economic criteria for sustainability

**Step 4: Converting linguistic judgment variables to fuzzy numbers**

Linguistic variables were converted to fuzzy numbers using Table 5. Triangular fuzzy numbers were utilized for pairwise comparison scale of AHP for the conversion of linguistic variables. Since in the comparison matrix in AHP all the elements were reversed with respect to the diagonal of matrix, the reverse of the fuzzy number was shown in the column named ‘reciprocal scale’; these values represent the reverse of a number in fuzzy space.

Table 5: Fuzzy comparison scale (Tiryaki & Ahlatcioglu, 2009)

Linguistic importance	Fuzzy scale	Reciprocal scale
Equally important	(1,1,1)	(1,1,1)
Weekly more important	(1/2,1,3/2)	(2/3, 1, 2)
Strongly more important	(3/2,2,5/2)	(2/5, 1/2, 2/3)

Very strongly more important	(5/2,3,7/2)	(2/7, 1/3, 2/5)
Absolutely more important	(7/2,4,9/2)	(2/9, 1/4, 2/7)

### ***Step 5: Combining experts’ views***

In this step the experts’ views were combined. Fuzzy averaging was applied to combine the fuzzy matrices.

### ***Step 6: Converting fuzzy numbers to crisp numbers***

The combined fuzzy matrices were defuzzified to real matrices using the maximum formula as presented in Eq. 1

$$x_{max}^{(3)} = \frac{m_1 + 4m_M + m_2}{6} \quad (1)$$

This formula has been applied for every member of the combined matrices.

### ***Step 7: Extraction of eigenvectors***

The eigenvector of each matrix were calculated using Microsoft Excel 2012. Firstly, the “matrix.xla extension” was added to the Excel software then the MEigenvecMax function was used. This function computes eigenvector of a matrix regarding its maximum eigenvalue. This vector determines the importance weighting of each level. Finally, the weight of each criterion was computed by multiplying the weights of each level. The detailed calculations of Fuzzy-AHP are presented in the next section.

## **5.0 DATA INTERPRETATION AND ANALYSIS**

The seven steps using Fuzzy-AHP were conducted and the relevant matrices were depicted and analysed to determine priority weights of each criterion and sub-criterion.

### **5.1 Hierarchy and Matrices**

#### **Step 1: Establishment of hierarchy**

The original hierarchy consists of three sub-hierarchies: Environmental Sustainability, Social Sustainability, and Economic Sustainability, which were depicted earlier in Figures 1, 2, 3, respectively.

## Step 2: Establishment of pairwise comparison matrices

The pairwise comparisons were conducted using linguistic variables for each pair of criteria. There were 20 blocks of factors. For each block a comparison matrix was established. Table 6 is the comparison matrix of Level 1 which consists of the three principal sustainability criteria; i.e., environmental, economical, and societal factors. Table 7 and Table 8 are the comparison matrices of the Level 2 and Level 3 under the environmental category, respectively. Likewise, Table 9 and 10 are for the social criteria, and Table 11 and 12 are for the economic criteria in respective levels.

Table 6: Level 1- Comparison Matrix of Sustainability Criteria

Sustainability Criteria	EnS	EcS	ScS
EnS	1	0.333333	2
EcS	3	1	3
ScS	0.5	0.333333	1

Note: EnS = Environmental sustainability; EcS = Economic sustainability; ScS = Social sustainability

Table 7: Level 2- Comparison Matrix of Environmental Criteria

Environmental Criteria	SSC	WEC	EAC	MRC	IEQ	IDPC
SSC	1	0.333333	0.5	0.5	0.5	0.5
WEC	3	1	1	0.5	1	2
EAC	2	1	1	0.5	0.5	1
MRC	2	2	2	1	1	2
IEQ	2	1	2	1	1	2
IDPC	2	0.5	1	0.5	0.5	1

Note: SSC = Sustainable Site Considerations; WEC = Water Efficiency Considerations;  
 EAC = Energy and Atmosphere Considerations; MRC = Materials and Resources Considerations;  
 IEQ = Indoor Environmental Quality; IDPC = Innovation and Design Process Considerations

Table 8: Level 3- Comparison matrix of Sub-criteria in Environmental Sustainability

Matrix SSC: Comparison matrix of Sustainable Site Considerations				
Sustainable Site Considerations	LSC	PRC	DDA	EP
LSC	1	1	2	2
PRC	1	1	1	2
DDA	0.5	1	1	2
EP	0.5	0.5	0.5	1

LSC=Land Sensitivity Considerations;  
 PRC=Pollution Reduction Considerations;  
 DDA = Developing Damaged Areas;  
 EP = Ecosystem Preservation

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Matrix WEC: Comparison matrix of Water Efficiency Considerations

Water Efficiency Considerations	RPWC	RLW	IAR	
RPWC	1	0.5	0.5	RPWC=Reduction of Potable Water Consumption; RLW = Reduction of Loss and Waste; IAR=Implementation of Alternative Resources
RLW	2	1	1	
IAR	2	1	1	

Matrix EAC: Comparison matrix of Energy and Atmosphere Considerations

Energy and Atmosphere Considerations	CBS	EPC	RNE	OPC	
CBS	1	0.5	0.5	2	CBS=Commissioning of Building Systems; EPC=Energy Performance Considerations; RNE=Reduction of Non-renewable Energy; OPC=Ozone Protection Considerations
EPC	2	1	3	3	
RNE	2	0.333	1	2	
OPC	0.5	0.333	0.5	1	

Matrix MRC: Comparison matrix of Materials and Resources Considerations

Materials and Resources Considerations	WM	RDC	PM	IRM	
WM	1	0.5	2	1	WM = Waste Management; RDC = Resource Depletion Considerations; PM = Properties of Materials; IRM = Implementation of Regional Materials
RDC	2	1	2	2	
PM	0.5	0.5	1	2	
IRM	1	0.5	0.5	1	

Matrix IEQ: Comparison matrix of Indoor Environmental Quality

Indoor Environmental Quality	TC	IAQ	VC	AC	
TC	1	3	2	3	TC = Thermal Comfort; IAQ = Indoor Air Quality; VC = Visual Comfort; AC = Aural Comfort
IAQ	0.333	1	2	2	
VC	0.5	0.5	1	2	
AC	0.333	0.5	0.5	1	

Matrix IDPC: Comparison matrix of Innovation and Design process Considerations

Innovation and Design process Considerations	ID	ED	
ID	1	2	ID = Innovation in Design; ED = Environmental Design
ED	0.5	1	

Table 9: Level 2- Comparison matrix of Social criteria

Social criteria	SEC	HCC	JO	SI	SR	AI
SEC	1	2	1	1	1	0.5
HCC	0.5	1	2	0.333	0.333	2
JO	1	0.5	1	0.333	0.5	0.5
SI	1	3	3	1	2	2
SR	1	3	2	0.5	1	2
AI	2	0.5	2	0.5	0.5	1

Note: SEC = Site and Equipment Considerations; HCC = Health and Comfort Considerations;  
 JO = Job Opportunities; SI = Safety Issues; SR = Stakeholders’ Relationship; AI = Architectural Issues

Table 10: Level 3- Comparison Matrix of Sub-criteria in Social Sustainability

Matrix SEC: Comparison matrix of Site and Equipment Considerations							
Site and Equipment Considerations	QI	SS	QF	BBEC	LUC		
QI	1	2	1	2	2	QI = Quality of Infrastructure; SS = Security of the Site; QF = Quality of Facilities; BBEC = Barrier-free Built Environment Considerations; LUC = Land Use Considerations	
SS	0.5	1	1	3	2		
QF	1	1	1	3	2		
BBEC	0.5	0.333	0.333	1	0.5		
LUC	0.5	0.5	0.5	2	1		
Matrix HCC: Comparison matrix of Health and Comfort Considerations							
Health and Comfort considerations	THC	VIC	ACC	INAQ	DES	IH	
THC	1	3	3	0.5	0.333	0.333	THC = THERmal Comfort; VIC = VIsual Comfort; ACC = ACoustical Comfort; INAQ = INdoor Air Quality; DES = Daylight and Exposure to Sunlight; IH = Indoor Hygiene
VIC	0.333	1	2	0.5	0.333	0.333	
ACC	0.333	0.5	1	0.333	0.333	0.333	
INAQ	2	2	3	1	0.333	0.333	
DES	3	3	3	3	1	3	
IH	3	3	3	3	0.333	1	
Matrix JO: Comparison matrix of Job Opportunities							
Job Opportunities	DE		IE				
DE	1		0.5		DE = Direct Employment; IE = Indirect Employment		
IE	2		1				
Matrix SI: Comparison matrix of Safety Issues							
Safety Issues	DCS		MCS				
DCS	1		3		DCS = Design Considerations towards Safety; MCS = Management Considerations towards Safety		
MCS	0.333		1				
Matrix SR: Comparison matrix of Stakeholders’ Relationship							
Stakeholders’ Relationship	CP		PP				
CP	1		2		CP = Communication to the Public; PP = Public Participation		
PP	0.5		1				
Matrix AI: Comparison matrix of Architectural Issues							
Architectural Issues	AHC		AFFC				
AHC	1		1		AHC = Architectural Heritage Considerations; AFFC=Architectural Functionality and Flexibility Considerations		
AFFC	1		1				

Table 11: Level 2- Comparison Matrix of Economic Criteria

Economic Criteria	EX	REV	IIRD	ILEE
EX	1	2	2	1
REV	0.5	1	1	1
IIRD	0.5	1	1	0.5



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ILEE	1	1	2	1
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Note: EX = EXpenditure; REV = REVenue; IIRD = Investment in Innovation, Research and Development; ILEE = Improvement of Local Economic Environment

Table 12: Level 3- Comparison matrix of Sub-criteria in Economic Sustainability

Matrix EX: Comparison matrix of Expenditure				
Expenditure	CC	LC	EC	
CC	1	2	2	CC = Capital Costs; LC = Lifecycle Costs; EC = Environmental Costs
LC	0.5	1	1	
EC	0.5	1	1	

Matrix REV: Comparison matrix of Revenue				
Revenue	VS	LP	DPI	
VS	1	1	1	VS = Value Stability; LP = Lifecycle Profit; DPI = Distribution of Project Income
LP	1	1	1	
DPI	1	1	1	

Matrix IIRD: Comparison matrix of Investment in Innovation, Research and Development				
Investment in Innovation, Research and Development	ERD	RF		
ERD	1	0.5		ERD = Expenditure on Research and Development; RF = Reserve Funds
RF	2	1		

Matrix ILEE: Comparison matrix of Improvement of local economic environment					
Improvement of local economic environment	LMC	ULI	ILLM	ILB	
LMC	1	0.5	2	0.5	LMC = Local Material Choice; ULI = Utilization of Local Infrastructure; ILLM = Improvement of Local Labor Market; ILB = Improvement of Local Businesses
ULI	2	1	2	2	
ILLM	0.5	0.5	1	0.5	
ILB	2	0.5	2	1	

### Step 3: Calculating the consistency ratio of each comparison matrix

This step ensures all experts have given consistent responses to the questions. The consistency ratios of all block of criteria were perfectly under 0.1 level therefore acceptable.

### Step 4: Converting linguistic judgment variables to fuzzy numbers

The linguistic variables to which experts referred for comparisons of pair criteria were converted to fuzzy numbers.

### Step 5: Combining experts’ views

The experts’ views were combined. Fuzzy averaging operations were conducted for each block of criteria. Table 13 to Table 19 present the averages of each block of criteria.

Table 13: Fuzzy Averaging of Sustainability Criteria Block

Sustainability Criteria	EnS	EcS	ScS
EnS	( 1, 1, 1 )	( 1.741, 2.119, 2.510 )	( 0.986, 1.071, 1.167 )
EcS	( 0.792, 0.976, 1.181 )	( 1, 1, 1 )	( 0.737, 0.857, 1.005 )
ScS	( 0.986, 1.071, 1.167 )	( 1.684, 2.048, 2.414 )	( 1, 1, 1 )

Table 14: Fuzzy Averaging of Environmental Criteria Block

IDPC	(0.893, 1.190, 1.605)	(1.350, 1.762, 2.271)	(1.667, 2, 2.429)	(1.667, 2.143, 2.714)	(1.367, 1.786, 2.310)	(1, 1, 1)
IEQ	(0.522, 0.690, 0.986)	(0.836, 0.976, 1.224)	(1.129, 1.357, 1.595)	(1.310, 1.571, 1.929)	(1, 1, 1)	(0.555, 0.762, 1.010)
MRC	(0.569, 0.655, 0.860)	(0.505, 0.667, 0.948)	(0.914, 1.214, 1.524)	(1, 1, 1)	(0.677, 0.810, 1.043)	(0.403, 0.571, 0.862)
EAC	(0.428, 0.488, 0.584)	(0.701, 0.726, 0.765)	(1, 1, 1)	(0.805, 1, 1.405)	(0.836, 0.976, 1.224)	(0.544, 0.655, 0.788)
WEC	(0.839, 0.952, 1.090)	(1, 1, 1)	(1.643, 1.857, 2.071)	(1.452, 1.857, 2.357)	(1.129, 1.357, 1.595)	(0.727, 0.964, 1.327)
SSC	(1, 1, 1)	(1.469, 1.762, 2.057)	(2, 2.429, 2.857)	(1.643, 2, 2.357)	(1.310, 1.714, 2.214)	(1.136, 1.476, 1.914)
Environmental Criteria	SSC	WEC	EAC	MRC	IEQ	IDPC

Table 15: Fuzzy Averaging of Sub-criteria in Environmental Sustainability

Sustainable Site Considerations	LSC	PRC	DDA	EP
LSC	( 1, 1, 1 )	( 0.710, 0.738, 0.781 )	( 0.627, 0.762, 0.938 )	( 0.824, 1.024, 1.257 )
PRC	( 1.500, 1.714, 1.929 )	( 1, 1, 1 )	( 0.781, 1, 1.333 )	( 1.003, 1.262, 1.724 )
DDA	( 1.414, 1.786, 2.167 )	( 0.938, 1.214, 1.595 )	( 1, 1, 1 )	( 0.955, 1.262, 1.867 )
EP	( 1.455, 1.833, 2.224 )	( 0.955, 1.262, 1.581 )	( 0.884, 1.262, 1.652 )	( 1, 1, 1 )
Water Efficiency Considerations	RPWC	RLW	IAR	
RPWC	( 1, 1, 1 )	( 0.521, 0.571, 0.653 )	( 0.665, 0.833, 1.129 )	
RLW	( 1.929, 2.286, 2.643 )	( 1, 1, 1 )	( 1.357, 1.714, 2.071 )	
IAR	( 1.271, 1.643, 2.024 )	( 0.615, 0.738, 1.067 )	( 1, 1, 1 )	
Energy and Atmosphere Considerations	CBS	EPC	RNE	OPC
CBS	( 1, 1, 1 )	( 0.717, 0.833, 1.152 )	( 0.663, 0.881, 1.210 )	( 1.186, 1.429, 1.690 )
EPC	( 1.143, 1.429, 1.714 )	( 1, 1, 1 )	( 1.081, 1.357, 1.738 )	( 1.557, 1.929, 2.310 )
RNE	( 1.295, 1.500, 2.095 )	( 0.765, 0.976, 1.295 )	( 1, 1, 1 )	( 1.414, 1.786, 2.167 )
OPC	( 0.869, 1.048, 1.248 )	( 0.610, 0.738, 0.900 )	( 0.627, 0.762, 0.938 )	( 1, 1, 1 )
Materials and Resources Considerations	WM	RDC	PM	IRM

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WM	(1, 1, 1)	(0.662, 0.857, 1.262)	(0.850, 1.048, 1.343)	(0.638, 0.857, 1.190)
RDC	(0.952, 1.286, 1.714)	(1, 1, 1)	(1.010, 1.357, 1.810)	(0.900, 1.143, 1.405)
PM	(1.010, 1.214, 1.524)	(0.695, 0.929, 1.286)	(1, 1, 1)	(0.844, 1.083, 1.444)
IRM	(1.024, 1.286, 1.643)	(0.924, 1.143, 1.476)	(0.781, 1, 1.333)	(1, 1, 1)
Indoor Environmental Quality	TC	IAQ	VC	AC
TC	(1, 1, 1)	(0.915, 1.095, 1.471)	(0.843, 1.214, 1.595)	(1.295, 1.643, 2.095)
IAQ	(1.184, 1.476, 1.771)	(1, 1, 1)	(1.357, 1.857, 2.357)	(1.429, 1.857, 2.286)
VC	(0.757, 1, 1.548)	(0.482, 0.667, 1.162)	(1, 1, 1)	(1.207, 1.476, 1.843)
AC	(0.663, 0.881, 1.210)	(0.529, 0.667, 1.019)	(0.869, 1.048, 1.248)	(1, 1, 1)
Innovation and Design process Considerations	ID	ED		
ID	(1, 1, 1)	(0.806, 1.048, 1.300)		
ED	(1.622, 1.976, 2.438)			(1, 1, 1)

Table 16: Fuzzy Averaging of Social Criteria Block

AI	(0.813, 1.036, 1.374)	(1.398, 1.762, 2.129)	(1.169, 1.405, 1.652)	(1.738, 2.143, 2.643)	(0.836, 0.976, 1.224)	(1, 1, 1)
SR	(0.624, 0.810, 1.019)	(1.207, 1.619, 2.129)	(0.914, 1.214, 1.524)	(2.071, 2.571, 3.071)	(1, 1, 1)	(1.129, 1.357, 1.595)
SI	(0.415, 0.488, 0.665)	(0.529, 0.667, 1.019)	(0.365, 0.500, 0.671)	(1, 1, 1)	(0.342, 0.417, 0.536)	(0.480, 0.631, 0.893)
JO	(0.387, 0.548, 0.824)	(1.095, 1.571, 2.143)	(1, 1, 1)	(1.810, 2.286, 2.857)	(0.827, 1.048, 1.557)	(1.012, 1.190, 1.390)
HCC	(0.607, 0.750, 0.998)	(1, 1, 1)	(0.512, 0.762, 1.319)	(1.429, 1.857, 2.286)	(0.736, 0.976, 1.343)	(0.791, 0.952, 1.233)
SEC	(1, 1, 1)	(1.843, 2.214, 2.595)	(1.810, 2.286, 2.857)	(2.429, 2.857, 3.286)	(1.438, 1.786, 2.238)	(1.257, 1.571, 1.905)
Social Criteria	SEC	HCC	JO	SI	SR	AI

Table 17: Fuzzy Averaging of Sub-criteria in Social Sustainability

Site and Equipment Considerations	QI	SS	QF	BBEC	LUC	
QI	(1, 1, 1)	(1.107, 1.333, 1.676)	(0.660, 0.821, 1.279)	(0.695, 0.786, 1)	(0.724, 0.929, 1.238)	
SS	(1.089, 1.393, 1.707)	(1, 1, 1)	(0.822, 1.048, 1.390)	(0.365, 0.500, 0.671)	(0.758, 0.940, 1.146)	
QF	(1.214, 1.571, 1.929)	(1.114, 1.429, 1.762)	(1, 1, 1)	(0.701, 0.952, 1.400)	(1.010, 1.357, 1.810)	
BBEC	(1.143, 1.429, 1.714)	(1.810, 2.286, 2.857)	(1.152, 1.500, 1.952)	(1, 1, 1)	(1.5, 1.857, 2.214)	
LUC	(0.905, 1.143, 1.571)	(1.614, 2, 2.405)	(0.695, 0.929, 1.286)	(0.555, 0.619, 0.724)	(1, 1, 1)	
Health and Comfort considerations	THC	VIC	ACC	INAQ	DES	IH
THC	(1, 1, 1)	(0.655, 0.905, 1.462)	(0.631, 0.905, 1.39)	(1.357, 1.714, 2.071)	(1.105, 1.357, 1.81)	(1.786, 2.143, 2.5)
VIC	(1.057, 1.5, 1.952)	(1, 1, 1)	(1.152, 1.357, 1.667)	(1.643, 2.143, 2.643)	(1.024, 1.429, 1.929)	(1.643, 2, 2.357)
ACC	(1.081, 1.5, 2.024)	(0.812, 0.976, 1.152)	(1, 1, 1)	(1.571, 2, 2.429)	(1.098, 1.405, 1.724)	(1.929, 2.429, 2.929)

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INAQ	(0.615, 0.738, 1.067)	(0.434, 0.583, 0.955)	(0.491, 0.595, 0.829)	(1, 1, 1)	(0.931, 1.119, 1.51)	(0.986, 1.214, 1.452)
DES	(0.741, 0.976, 1.224)	(0.598, 0.833, 1.367)	(0.965, 1.190, 1.533)	(1.041, 1.333, 1.629)	(1, 1, 1)	(0.850, 1.190, 1.629)
IH	(0.522, 0.571, 0.648)	(0.590, 0.702, 1.012)	(0.373, 0.476, 0.705)	(0.874, 1.048, 1.414)	(0.876, 1.143, 1.619)	(1, 1, 1)
Job Opportunities	DE			IE		
DE	(1, 1, 1)			(1.200, 1.500, 1.810)		
IE	(0.750, 0.905, 1.176)			(1, 1, 1)		
Safety Issues	DCS			MCS		
DCS	(1, 1, 1)			(1.295, 1.500, 1.810)		
MCS	(0.796, 0.952, 1.114)			(1, 1, 1)		
Stakeholders’ Relationship	CP			PP		
CP	(1, 1, 1)			(0.827, 1.048, 1.271)		
PP	(1.033, 1.214, 1.595)			(1, 1, 1)		
Architectural Issues	AHC			AFFC		
AHC	(1, 1, 1)			(0.648, 0.810, 1.090)		
AFFC	(1.414, 1.786, 2.167)			(1, 1, 1)		

Table 18: Fuzzy Averaging of Economic Criteria Block

Economic Criteria	EX	REV	IIRD	ILEE
EX	(1, 1, 1)	(1.067, 1.286, 1.619)	(0.901, 1.167, 1.638)	(0.648, 0.810, 1.090)
REV	(0.884, 1.119, 1.367)	(1, 1, 1)	(0.822, 1.048, 1.390)	(0.663, 0.881, 1.210)
IIRD	(1.169, 1.548, 1.938)	(1.114, 1.429, 1.762)	(1, 1, 1)	(0.771, 0.929, 1.381)
ILEE	(1.414, 1.786, 2.167)	(1.295, 1.643, 2.095)	(0.857, 1.143, 1.429)	(1, 1, 1)

Table 19: Fuzzy Averaging of Sub-criteria in Economic Sustainability

Expenditure	CC		LC		EC			
CC	(1, 1, 1)		(0.656, 0.845, 1.060)		(0.822, 1.071, 1.338)			
LC	(1.757, 2.143, 2.548)		(1, 1, 1)		(1.169, 1.405, 1.652)			
EC	(1.457, 1.786, 2.143)		(1.012, 1.190, 1.390)		(1, 1, 1)			
Revenue	VS		LP		DPI			
VS	(1, 1, 1)		(0.629, 0.810, 1.186)		(0.701, 0.952, 1.400)			
LP	(1.238, 1.571, 2)		(1, 1, 1)		(1.186, 1.429, 1.690)			
DPI	(1.152, 1.500, 1.952)		(0.869, 1.048, 1.248)		(1, 1, 1)			
Investment in Innovation, Research and Development	ERD			RF				
ERD	(1, 1, 1)			(1.407, 1.690, 2.081)				
RF	(0.915, 1.155, 1.407)			(1, 1, 1)				
Improvement of local economic environment	LMC		ULI		ILLM		ILB	
LMC	(1, 1, 1)		(0.599, 0.631, 0.679)		(0.748, 0.952, 1.257)		(0.576, 0.786, 1.214)	
ULI	(1.857, 2.143, 2.429)		(1, 1, 1)		(0.993, 1.333, 1.771)		(1.152, 1.500, 1.952)	
ILLM	(1.224, 1.500, 1.881)		(0.838, 1.071, 1.429)		(1, 1, 1)		(0.867, 1.071, 1.381)	

ILB	( 1.024, 1.429, 1.929 )	( 0.679, 0.905, 1.248 )	( 0.867, 1.071, 1.381 )	( 1, 1, 1 )
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### Step 6: Converting fuzzy numbers to crisp numbers

The fuzzy numbers in previous matrices were defuzzified into crisp numbers in Table 20 to Table 26.

Table 20: Crisp Matrix of Sustainability Criteria

Sustainability Criteria	EnS	EcS	ScS
EnS	1	2.121	1.073
EcS	0.980	1	0.862
ScS	1.073	2.048	1

Table 21: Crisp Matrix of Environmental Criteria

Environmental Criteria	SSC	WEC	EAC	MRC	IEQ	IDPC
SSC	1	0.956	0.494	0.675	0.712	1.210
WEC	1.762	1	0.728	0.687	0.994	1.778
EAC	2.429	1.857	1	1.216	1.359	2.016
MRC	2	1.873	1.035	1	1.587	2.159
IEQ	1.730	1.359	0.994	0.826	1	1.803
IDPC	1.493	0.985	0.659	0.592	0.769	1

Table 22: Crisp Matrix of Sub-criteria in Environmental Sustainability

Sustainable Site Considerations		LSC	PRC	DDA	EP
LSC		1	0.741	0.769	1.029
PRC		1.714	1	1.019	1.296
DDA		1.787	1.232	1	1.312
EP		1.835	1.264	1.264	1
Water Efficiency Considerations		RPWC	RLW	IAR	
RPWC		1	0.577	0.854	
RLW		2.286	1	1.714	
IAR		1.644	0.772	1	
Energy and Atmosphere Considerations		CBS	EPC	RNE	OPC
CBS		1	0.867	0.899	1.432
EPC		1.429	1	1.375	1.930
RNE		1.565	0.994	1	1.787
OPC		1.051	0.744	0.769	1
Materials and Resources Considerations		WM	RDC	PM	IRM
WM		1	0.892	1.064	0.876
RDC		1.302	1	1.375	1.146
PM		1.232	0.949	1	1.104
IRM		1.302	1.162	1.019	1
Indoor Environmental Quality		TC	IAQ	VC	AC
TC		1	1.128	1.216	1.660

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IAQ	1.477	1	1.857	1.857
VC	1.051	0.718	1	1.493
AC	0.899	0.702	1.051	1
Innovation & Design Process		ID	ED	
ID	1		1.049	
ED	1.994		1	

Table 23: Crisp Matrix of Social Criteria

Social criteria	SEC	HCC	JO	SI	SR	AI
SEC	1	0.767	0.567	0.505	0.814	1.055
HCC	2.216	1	1.587	0.702	1.635	1.762
JO	2.302	0.813	1	0.506	1.216	1.407
SI	2.857	1.857	2.302	1	2.571	2.159
SR	1.803	0.997	1.096	0.424	1	0.994
AI	1.575	0.972	1.194	0.650	1.359	1

Table 24: Crisp Matrix of Sub-criteria in Social Sustainability

Site and Equipment Considerations		QI	SS	QF	BBEC	LUC	
QI	1		1.395	1.571	1.429	1.175	
SS	1.353		1	1.432	2.302	2.003	
QF	0.871		1.067	1	1.517	0.949	
BBEC	0.806		0.506	0.985	1	0.626	
LUC	0.946		0.944	1.375	1.857	1	
Health and Comfort considerations		THC	VIC	ACC	INAQ	DES	IH
THC	1		1.502	1.517	0.772	0.978	0.576
VIC	0.956		1	0.978	0.620	0.883	0.735
ACC	0.940		1.375	1	0.617	1.210	0.497
INAQ	1.714		2.143	2	1	1.334	1.080
DES	1.390		1.444	1.407	1.153	1	1.178
IH	2.143		2	2.429	1.216	1.207	1
Job Opportunities		DE		IE			
DE	1		1.502				
IE	0.924		1				
Safety Issues		DCS		MCS			
DCS	1		1.517				
MCS	0.953		1				
Stakeholders’ Relationship		CP		PP			
CP	1		1.048				
PP	1.248		1				
Architectural Issues		AHC		AFFC			
AHC	1		0.829				
AFFC	1.787		1				

**Table25: Crisp Matrix of Economic Criteria**

Economic Criteria	EX	REV	IIRD	ILEE
EX	1	1.305	1.201	0.829
REV	1.121	1	1.067	0.899
IIRD	1.550	1.432	1	0.978
ILEE	1.787	1.660	1.143	1

**Table 26: Crisp Matrix of Sub-criteria in Economic Sustainability**

Expenditure		CC	LC	EC	
CC		1	0.850	1.074	
LC		2.146	1	1.407	
EC		1.790	1.194	1	
Revenue		VS	LP	DPI	
VS		1	0.842	0.985	
LP		1.587	1	1.432	
DPI		1.517	1.051	1	
Investment in Innovation, Research and Development		ERD		RF	
ERD		1		1.708	
RF		1.157		1	
Improvement of local economic environment		LMC	ULI	ILLM	ILB
LMC		1	0.634	0.969	0.822
ULI		2.143	1	1.350	1.517
ILLM		1.517	1.092	1	1.089
ILB		1.444	0.924	1.089	1

### Step 7: Extraction of eigenvector

Within this step eigenvector of each matrix was computed. These vectors establish the weight of each level that should be normalized. The weight of each criterion was calculated by multiplying the weight for each level. Table 27, 28, and 29 present the final weight of sustainability criteria and sub-criteria for environmental, social, and economic, respectively.

**Table 27: Final Weights of Environmental Criteria and Sub-criteria**

Sustainability objective	Final weight	Sustainability criterion	Relative weights of criteria	Final weights of criteria	Sustainability sub-criterion	Relative weights of sub-criteria	Final weights of sub-criteria
Environmental Criteria	0.371	sustainable Site Considerations	0.114	0.0423	Land sensitivity considerations	0.187	0.0079
					Pollution reduction considerations	0.260	0.0110
					Developing damaged areas	0.276	0.0117
					Ecosystem preservation	0.277	0.0117
		Water Efficiency Considerations	0.152	0.0564	Reduction of potable water consumption	0.229	0.0129
					Reduction of loss and waste	0.457	0.0258

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				Implementation of alternative resources	0.314	0.0177
				Commissioning of building systems	0.223	0.0183
Energy and Atmosphere Considerations	0.221	0.0820		Energy performance considerations	0.304	0.0249
				Reduction of non-renewable energy	0.281	0.0230
				Ozone protection considerations	0.191	0.0157
Materials and Resources Considerations	0.217	0.0805		Waste management	0.220	0.0177
				Resource depletion considerations	0.276	0.0222
				Properties of materials	0.246	0.0198
				Implementation of regional materials	0.258	0.0208
Indoor Environmental Quality	0.173	0.0642		Thermal comfort	0.264	0.0169
				Indoor air quality	0.322	0.0207
				Visual comfort	0.221	0.0142
				Aural comfort	0.193	0.0124
Innovation and Design process Considerations	0.123	0.0456		Innovation in design	0.420	0.0192
				Environmental design	0.580	0.0265

Table 28: Final Weights of Social Criteria and Sub-criteria

Sustainability objective	Final weight	Sustainability criterion	Relative weights of criteria	Final weights of criteria	Sustainability sub-criterion	Relative weights of sub-criteria	Final weights of sub-criteria
Social Criteria	0.365				Quality of infrastructure	0.225	0.0086
		Site and Equipment Considerations	0.105	0.0383	Security of the site	0.265	0.0102
					Quality of facilities	0.181	0.0069
					Barrier-free built environment considerations	0.130	0.0050
					Land use considerations	0.200	0.0077
		Health and Comfort considerations	0.189	0.0690	Thermal comfort	0.142	0.0098
					Visual comfort	0.120	0.0083
					Acoustic comfort	0.127	0.0088
					Indoor air quality	0.209	0.0144
					Daylight and exposure to Sunlight	0.178	0.0123
					Indoor hygiene	0.224	0.0155
		Job Opportunities	0.150	0.0548	Direct employment	0.560	0.0307
					Indirect employment	0.440	0.0241
		Safety Issues	0.275	0.1004	Design considerations towards safety	0.558	0.0560
					Management considerations towards safety	0.442	0.0444
		Stakeholders’ Relationship	0.134	0.0489	Communication to the Public	0.478	0.0234
					Public participation	0.522	0.0255
		Architectural Issues	0.147	0.0537	Architectural heritage considerations	0.405	0.0217
					Architectural functionality and flexibility considerations	0.595	0.0319

Table 29: Final Weights of Economic Criteria and Sub-criteria

Sustainability objective	Final weight	Sustainability criterion	Relative weights of criteria	Final weights of criteria	Sustainability sub-criterion	Relative weights of sub-criteria	Final weights of sub-criteria
Economic Criteria	0.264	Expenditure	0.229	0.0605	Capital costs	0.262	0.0158
					Lifecycle costs	0.391	0.0236



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			Environmental costs	0.348	0.0210
			Value stability	0.274	0.0158
Revenue	0.218	0.0576	Lifecycle profit	0.384	0.0221
			Distribution of project income	0.341	0.0196
Investment in innovation, research and development	0.260	0.0686	Expenditure on research and development	0.549	0.0377
			Reserve funds	0.451	0.0310
			Local material choice	0.186	0.0143
Improvement of local economic environment	0.292	0.0771	Utilization of local infrastructure	0.318	0.0245
			Improvement of local labor market	0.256	0.0197
			Improvement of local businesses	0.241	0.0186

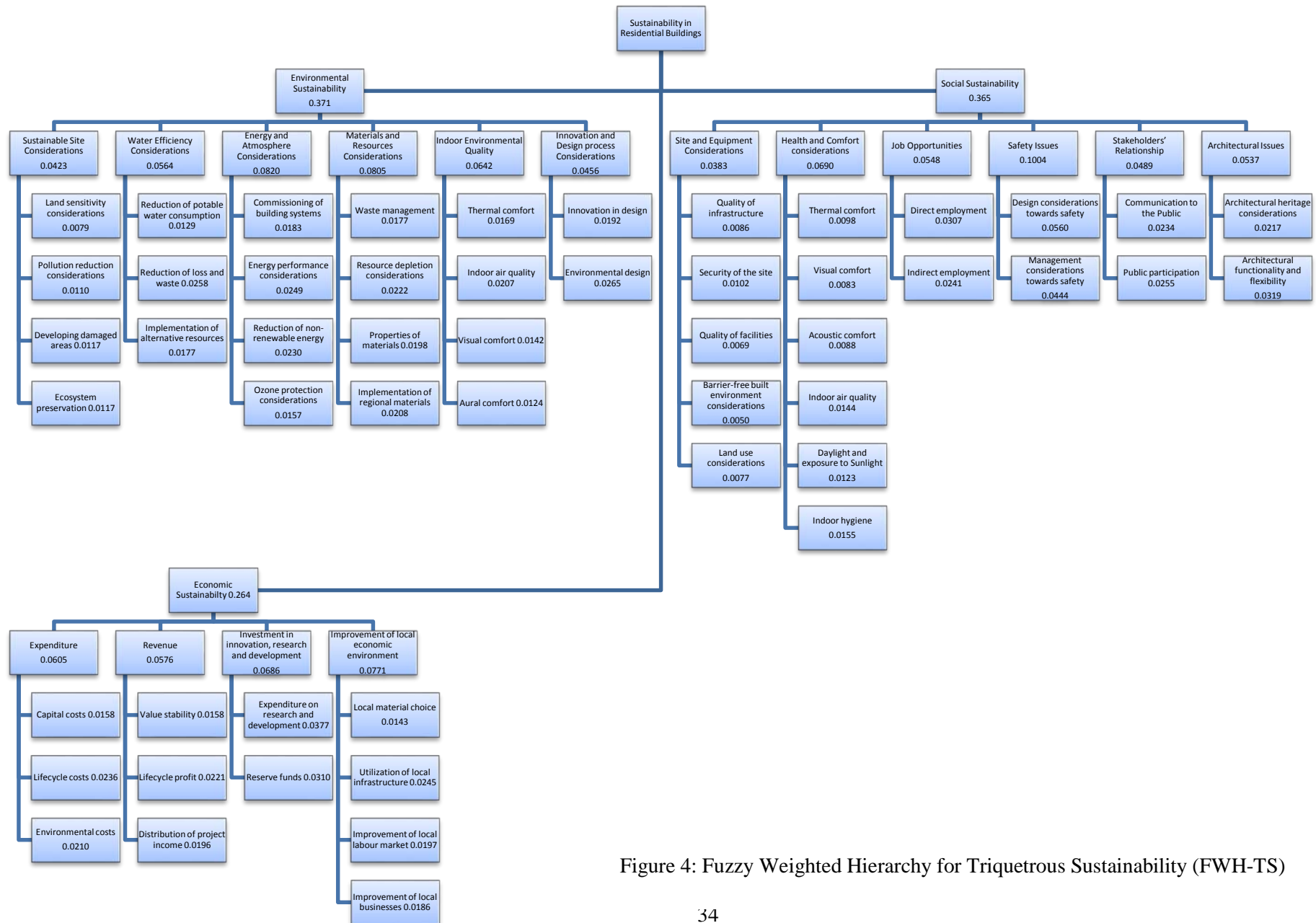


Figure 4: Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS)

The priority weights derived from this study are specifically for residential buildings. The Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS) was developed in Figure 4. Practitioners and scholars can employ these priority weights to simplify complicated decision making process in practicing sustainability.

Figure 4 indicates that the weight of environmental sustainability is slightly higher than social sustainability. The weight of economic sustainability in residential buildings is less than either environmental or social sustainability. Table 30 presents the rank of sustainability criteria, according to which the absolute weight of safety issues related to social sustainability is the highest. Site and equipment considerations are less weighted compared to other criteria.

Table 30: Ranking of Priority Weights of Sustainable Criteria

rank	Sustainability criterion	Priority weight
1	Safety Issues (Social criteria)	0.1004
2	Energy and Atmosphere Considerations (Environmental Criteria)	0.0820
3	Materials and Resources Considerations (Environmental criteria)	0.0805
4	Improvement of Local Economic Environment (Economic criteria)	0.0771
5	Health and Comfort Considerations (Social criteria)	0.0690
6	Investment in Innovation, Research and Development (Economic criteria)	0.0686
7	Indoor Environmental Quality (Environmental criteria)	0.0642
8	Expenditure (Economic criteria)	0.0605
9	Revenue (Economic criteria)	0.0576
10	Water Efficiency Considerations (environmental criteria)	0.0564
11	Job Opportunities (Social criteria)	0.0548
12	Architectural Issues (Social criteria)	0.0537
13	Stakeholders’ Relationship (Social criteria)	0.0489
14	Innovation and Design process Considerations (Environmental criteria)	0.0456
15	sustainable Site Considerations (Environmental criteria)	0.0423
16	Site and Equipment Considerations (Social criteria)	0.0383

The absolute weight of each sub-criterion is presented in Table 31. Design consideration towards safety, which is a social sub-criterion, is the most weighted sub-criterion. The barrier-free built environment considerations under social sub-criterion listed in the bottom.

Table 31: Priority Weights of Sustainable Sub-criteria

Rank	Sustainability sub-criterion	Priority weight
1	Design considerations towards safety (Social sub-criterion)	0.0560
2	Management considerations towards safety (Social sub-criterion)	0.0444
3	Expenditure on research and development (Economic sub-criterion)	0.0377
4	Architectural functionality and flexibility considerations (Social sub-criterion)	0.0319
5	Reserve funds (Economic sub-criterion)	0.0310
6	Direct employment (Social sub-criterion)	0.0307
7	Environmental design (Environmental sub-criterion)	0.0265
8	Reduction of loss and waste (Environmental sub-criterion)	0.0258
9	Public participation (Social sub-criterion)	0.0255
10	Energy performance considerations (Environmental sub-criterion)	0.0249
11	Utilization of local infrastructure (Economic sub-criterion)	0.0245

12	Indirect employment (Social sub-criterion)	0.0241
13	Lifecycle costs (Economic sub-criterion)	0.0236
14	Communication to the Public (Social sub-criterion)	0.0234
15	Reduction of non-renewable energy (Environmental sub-criterion)	0.0230
16	Resource depletion considerations (Environmental sub-criterion)	0.0222
17	Lifecycle profit (Economic sub-criterion)	0.0221
18	Architectural heritage considerations (Social sub-criterion)	0.0217
19	Environmental costs (Economic sub-criterion)	0.0210
20	Implementation of regional materials (Environmental sub-criterion)	0.0208
21	Indoor air quality (Environmental sub-criterion)	0.0207
22	Properties of materials (Environmental sub-criterion)	0.0198
23	Improvement of local labor market (Economic sub-criterion)	0.0197
24	Distribution of project income (Economic sub-criterion)	0.0196
25	Innovation in design (Environmental sub-criterion)	0.0192
26	Improvement of local businesses (Economic sub-criterion)	0.0186
27	Commissioning of building systems (Environmental sub-criterion)	0.0183
28	Waste management (Environmental sub-criterion)	0.0177
29	Implementation of alternative resources	0.0177
30	Capital costs (Economic sub-criterion)	0.0158
31	Value stability	0.0158
32	Thermal comfort (Environmental sub-criterion)	0.0169
33	Ozone protection considerations (Environmental sub-criterion)	0.0157
34	Indoor hygiene (Social sub-criterion)	0.0155
35	Indoor air quality (Social sub-criterion)	0.0144
36	Local material choice (Economic sub-criterion)	0.0143
37	Visual comfort (Environmental sub-criterion)	0.0142
38	Reduction of potable water consumption (Environmental sub-criterion)	0.0129
39	Aural comfort (Environmental sub-criterion)	0.0124
40	Daylight and exposure to Sunlight (Social sub-criterion)	0.0123
41	Ecosystem preservation (Environmental sub-criterion)	0.0117
42	Developing damaged areas (Environmental sub-criterion)	0.0117
43	Pollution reduction considerations (Environmental sub-criterion)	0.0110
44	Security of the site (Social sub-criterion)	0.0102
45	Thermal comfort (Social sub-criterion)	0.0098
46	Acoustic comfort (Social sub-criterion)	0.0088
47	Quality of infrastructure (Social sub-criterion)	0.0086
48	Visual comfort (Social sub-criterion)	0.0083
49	Land sensitivity considerations (Environmental sub-criterion)	0.0079
50	Land use considerations (Social sub-criterion)	0.0077
51	Quality of facilities (Social sub-criterion)	0.0069
52	Barrier-free built environment considerations (Social sub-criterion)	0.0050

## 5.2 Results and Discussion

Our findings reveal that the safety criteria received a high priority which is supported by Ortiz et al. (2009), Kim et al. (2005), and Jensen et al. (2011), from different perspectives. A South African study focused on infrastructure sustainability affirms that the safety indicator is the top sustainability criterion (Ugwu & Haupt, 2007). Vallance et al. (2011) claim that although the concept of sustainable development at the outset enclosed an apparent social mandate, the social dimension has been overlooked in a sustainable approach for about two decades and the economic aspects of sustainability have also received less attention compared to the environmental aspects of sustainability. The three elements of sustainability are included in most studies which focus on

sustainable development in the construction industry. However, the environmental criteria have received more attention relative to the other elements (economic and social sustainability). Social facets of sustainable buildings have not been thoroughly examined due to the complexity of the issues (Lützkendorf & Lorenz, 2005). Jensen et al. (2012) claim that sustainable buildings mainly address energy performance and that not enough attention is accorded to social sustainability. In addition, there is a lack of transference of knowledge from experts to occupants regarding how to utilize low-energy houses more efficiently (Jensen et al., 2012). Therefore, the outputs of our study have successfully filled this gap.

The safety issues were also highlighted by Lee et al. (2011) and Viteikiene and Zavadskas (2007). Further, improvement of local labor market and lifecycle costs were highly weighted in this study, which was supported by Ugwu and Haupt (2007) as key economic criteria. The construction material availability is ranked higher than that in Ugwu and Haupt's (2007) study. The linkage between the sustainable developments along with the construction industry has been apparent, considering the fact that construction is of great economic significance and also includes tough environmental and social effects. Alongside that, the built environment provides the background for the majority of most activities undertaken in today's urbanized environment. The quality of the built environment therefore has a substantial impact on the quality of our existence. Buildings ought to be designed, built, and maintained in a way which fulfils the various requirements of society to provide an appropriate environment, which promotes the development and advancement of individuals and communities. In this research, the implementation of regional materials including the availability of construction materials was ranked as 20 out of 52 sustainability indicators. Energy and atmospheric considerations are ranked as the second most important criterion. This is probably because of the amount of global investment in renewable power generation has been greatly increased relative to investment in fossil fuel energies since 2008 (Oh et al., 2010). The trigger for this change was probably the economic downturn in 2008. Some might argue against a rise of employment as social criteria because it is unclear how relevant this is to residential construction, where most jobs are short-term. However, both Shen et al. (2007) and Shen et al. (2010) fully supported that employment be considered as the level of employment could significantly influence the construction of residences.

The buildings and environment are tightly and symbiotically linked; consequently, as society attempts to provide greater environmental protection, greater concern must be allotted to the

construction industry. In broad terms, the notion of sustainable development is an endeavor to integrate increasing concerns about pressing environmental issues along with socio-economic issues. Practicing sustainability in the construction industry bears noticeable effects on environmental, economic, and social and design practices (Michael et al., 2009). In addition to the environmental aspects in the building lifecycle, other sustainable dimensions (i.e., the social and economic dimensions) should be accounted for; e.g., the interrelation between the building and community-level issues such as evidenced by social segregation and urban design quality (Lützkendorf & Lorenz, 2005). Lee (2011) found that 'health' was the most significant indicator for South Korean sustainable high-rise residential buildings. The priority weights developed in our study extended Lee's (2011) findings from South Korea to a broader global market and we demonstrate the relative importance of health and comfort considerations which we find were weighted as the top fifth criterion.

For some years now, the Happy Planet Organization has published the 'Happy Planet Index (HPI)', measuring the trade-off between ecological footprint data and quality-of-life (Gronwald & Lippelt, 2011); however, HPI did not fit in this study. Due to the lack of country data for some of the variables used in the HPI, it has been necessary to run some missing data estimation procedures. Campus and Porcu's (2010) results show that no country manages to score highly in terms of HPI and economic growth because of countries' incapacity to manage the tensions of maintain high living standards expressed in terms of happy life years and at the same time assure sustainability. Comparing HPI with GDP, no association between the resulting countries' classification has been found, providing evidence that this indicator does not reflect the same reality that GDP illustrates. Tausch (2011) presents some evidence that a wide variety of standard globalization variables have little influence on HPI performance. Big countries with large population resources perform somewhat better, and low military expenditures per GDP are also constraints on HPI performance. Beneficial effects are also closely connected to worker remittances. Efficiency tends to increase and then to decrease with rising development levels.

## **6.0 CONCLUSIONS AND RECOMMENDATIONS**

Construction practitioners including contractors, architects, consultants, developers, and other relevant stakeholders are encouraged to use the developed Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS) for decision making in residential building projects. The

priority weight of each criterion and sub-criterion facilitate decision making for practicing sustainability. Though all aforementioned criteria and sub-criteria are non-negligible, to give all sustainability criteria the same level of attention is not only impossible but also impractical. Therefore, the construction practitioners making decisions need to only take into consideration the top 20% criteria and sub-criteria according to the priority weights to satisfy sustainability objectives. In a way, the developed integrated hierarchy provides a more structured and straightforward framework for stakeholders of the global construction industry. The developed Fuzzy Weighted Hierarchy for Triquetrous Sustainability (FWH-TS) offers the most suitable sustainability criteria and sub-criteria in the three pillars of sustainability, which fills the gap of where, in the case of residential buildings, existing frameworks neglect social and economic sustainability in both theory and practice and do not provide a method to help decision-makers understand relative importance of these factors.

This research has inherent limitations that emerged as we made decisions during the research design process. One limitation was the focus on the use of experts' opinions and judgements to develop the FWH-TS. While we feel that this provides the most comprehensive result, we acknowledge that rankings and prioritizations from the users, or residents, perspectives might provide additional insight and this is an area where the fuzzy AHP process can be extended in future research. The use of some terms may be unclear and while in this case the experts had the opportunity to clarify with the research team what the terms meant, there may have been some misunderstanding. Such misunderstanding of technical terms may be exacerbated when the research is conducted with residents or users. An additional limitation was our focus on residential buildings, which may have significantly different prioritizations than commercial or industrial buildings. This can be addressed with further research that will extend the method to encompass all building types. Further opportunities to apply the method may lead to other derivatives that can be commercialized. Additional work with programmers or software engineers will support the development of software based on FWH-TS in the near future.

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