Sustainability Assessment of Residential Skyscrapers Based on Multi-criteria Decision-making Method: 9 Dubai Case Studies

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Abstract

Residential skyscrapers play a vital role in all aspects of sustainable developments as an integral component of the built environment. The need for tall buildings first arose in Chicago in the late 19th century while today more and more skyscrapers are built to accommodate many occupants in the small available land plots of the world's megacities. In this paper, after reviewing previous studies, a series of effective indicators are prioritized so that a method for analysing the sustainability performance of residential skyscraper buildings relating to the three dimensions of sustainability is presented. Residential skyscrapers should be designed to respond to all different requirements during their life cycle. Inclusion of economic, social and environmental dimensions of sustainable development in the initial design results in a higher quality of life in residential skyscraper buildings. The method used in this paper is the Integrated Value Model for Sustainable Assessment (MIVES) - a multi-criteria decision-making method for assessing sustainability. In this regard, nine residential skyscrapers as case studies have been evaluated in Dubai. Based on the multi-criteria approach

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used in this paper, the analysed residential skyscrapers in Dubai have a sustainability performance in range of 0.29 < SI < 0.62.

***Keywords*:** Residential skyscraper, quality of life, life cycle, Sustainability assessment, MIVES.

Practical Applications

This paper aims to evaluate the sustainability of residential skyscrapers based on the use of MIVES, a decision-making approach. Based on the literature review, there are not high-rise buildings design and construction studies covering all the pillars of sustainability. Due to that, nine case studies were selected in the city of Dubai and evaluated by means of the MIVES approach. MIVES integrates three requirements of sustainability (economic, environmental and social) by using the concept of value functions and indicators based on the weight assignment.

In this regard, the formulae for the sustainability index were defined in this model, and each of these case studies has been quantitatively assessed and the degree of sustainability of each tower was determined. All these data and results provided a framework and reference to establish a minimum sustainability index that future residential skyscrapers constructed in Dubai should achieve. In addition, the evaluation of residential skyscrapers may be reviewed from other dimensions of sustainability, for example, landscape for the design of outdoor spaces and so forth.

Introduction

Given the technological, historical, climatic and social conditions, housing is the establishment of economic and cultural vitality and it is a critical factor in the quality of life for the residents. (Hudgins 2009; Yeang 2006; Modi 2014). Residential skyscrapers (RS) buildings have been considered as a suitable way to restructure busy city centres in order to reduce the impact on the use of land (Lau 2014). Advances in architecture, engineering and construction (AEC) industries have made possible an increase in size, height, and complexity of RS buildings while simultaneously reducing CO2 footprint.

The Malaysian architect, Yeang (2012) who is the father of sustainable skyscrapers and bioclimatic buildings, has claimed that a tall building can be defined as a "vertical city" which requires designers to consider the various sustainability dimensions such as social, environmental and economic. Ali and Armstrong (2008) have highlighted some critical design factors and strategies that need to be considered to achieve sustainability in high-performance tall buildings using innovative technologies. Jin et al (2013), identified the prototype for sustainable high rise design trends for the future towers align with the Dubai Government's strategy based on a number of case studies. Begec and Hamidabad (2015) noted the sustainable concepts in some case examples of high-rise buildings. The concepts including ecological environment, active energy using and energy saving of ecological and sustainable architectural concepts, green construction and sustainable building principles. An extensive literature review on the topic of residential high-rise building has been performed and published in Maleki et al (2022).

RS buildings have a major impact on the carbon footprint during the construction, use and deconstruction stages. (Cowlard et al. 2013). Some of the reasons that RSs continue to be constructed and used can be summarized as follows: maximum utilization of land, provision of complete set of amenities, aesthetic qualities, high density, and reduction in the volume of urban infrastructure networks causing a general reduction in carbon footprint.

The main design factors that are necessary to achieve high-performance of RS are the structure, site context, energy usage, water consumption, materials, environment, and community development (Ali and Armstrong 2008). In general, sustainable development is classified in three aspects of social, environment and economic, which can affect each other as shown in Fig. 1.

This paper aims to present a new model for assessing the sustainability of RS and in particular, consider the effective factors in design. The developed model is based on a multi-criteria analysis method, the so-called Integrated Value Model for Sustainable Assessment (MIVES). This method makes it possible to consider the three main pillars of sustainability and the various stakeholders can use it as a decision-making model (Al-Jokhadar and Jabi 2016).

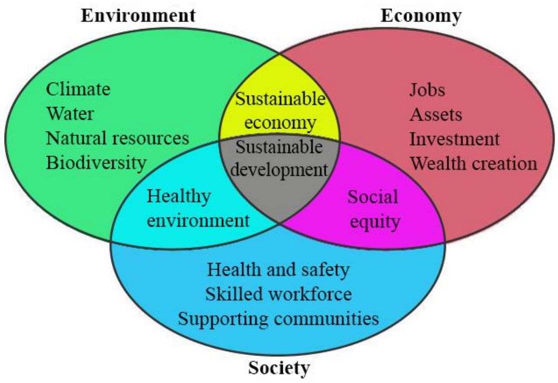


Fig. 1. Sustainable development aspects (International Monetary Fund 2014).

MIVES multi-criteria decision-making method

Multi-criteria decision-making (MCDM) is a good tool to achieve the best decision when choosing from various options in building construction or operation management and it helps decision-makers (Mosalam et al. 2012). There are a few studies on the development of a method to assess the global sustainability of the RS. This section aims to review and analyse the existing literature in order to identify previous methods used to assess the sustainability of RS. Table 1 summarizes the different methods used for sustainability assessment of RS. After evaluating different methods, the features, advantages and disadvantages of each method were examined as shown in Table 2.

Table 1. Summary of different methods used for sustainability assessment of RS buildings

Method	Area of study	Reference
Analytical Hierarchy Process (AHP)	High-rise building construction	Kia & Adeli, (2014).
Strengths, Weaknesses, Opportunities and Threats (SWOT)	Project management	Zavadskas *et al*., (2013)
Elimination and Choice Expressing Reality (ELECTRE) + Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE)	Structural systems	Balali *et al*., (2014)
Elimination and Choice Expressing Reality (ELECTRE)	Energy efficient retrofitting	Carapeto *et al*., (2016)
Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	Evacuation capability assessment	Mei *et al*., (2012)

VIsekriterijumsko KOmpromisno Rangiranje (VIKOR)	Response to risk	Katebi & Teymourfar, (2017)
Complex Proportional Assessment (COPRAS)	Structural systems	Tamošaitienė & Gaudutis (2013)
Choquet Integral (CI)	Residential heating system	Ozdemir & Ozdemir (2019)
Simple Additive Weighting (SAW)	Assessment of high-rise timber buildings	Tupėnaitė *et al*., (2019)
Integrated Value Model for Sustainable Assessment (MIVES)	Sustainability assessment	Maleki & Casanovas Rubio (2019); Maleki et al., (2019; 2022)

Table 2. Strengths, weaknesses and other relevant information of the various sustainability assessment methods

Abbreviation	Description	Methodology	Software	Applications	Strengths	Weaknesses
AHP	The AHP is a theory of measurement concern with quantifiable and/or intangible criteria in decision-making and conflict resolution developed by Saaty (1980).	Comparison of evaluation criteria and alternatives. The decision applications of the AHP are carried out in two phases: hierarchic design and evaluation of design.	MultCSync Expert Choice Logical Decisions, Web-HIPRE (HIPRE 3+, HIVIEW	Construction Environmental planning Energy design Social sciences Agriculture Marketing	Its applicability to the weighting of fuzzy criteria, along with solid ones, through ratio scales and scoring. Decomposing a problem or process in its components and combining these in a rational way. Its ability to handle both quantitative and qualitative judgements.	The number of comparisons to be made may become very large increasing significantly the uncertainty of the process. Its inability to reflect the human cognitive process because it does not cope with the uncertainty and ambiguity, which occurs in decision maker's judgments.
SWOT	The SWOT as a method of analysis for instrument formulating management strategies is recommended.	It is constructed according to the four factors of decision-making: alternatives, criteria, performance, and weight. Alternatives refer to objects to be compared (e.g., the criteria of company A and B refer to the key factors of external assessment). Performance structure refers to weights of the key factors. Performance refers to the performance of the object put into comparison under the evaluation of all the key factors.	Smart Draw SWOT Map Gliffy Creately SWOT Analysis Generator	Business Land-resource Planning Urban strategy planning Tourism planning	The algorithm helps to select the most preferable strategies based on the expert judgment and permutation method of feasible alternatives. It helps find a sustainable opportunity in the market. When used in a personal context, it helps develop career in a way that takes best advantage of talents, abilities and opportunities. It helps focus on strengths, minimizing threats and take the greatest possible advantage of opportunities available.	There is not any weighting factors (ambiguity).
ELECTRE	Bernard Roy developed ELECTRE in the mid-1960s. Today there exist several variations of the	ELECTRE involves a systematic analysis of the relationship between all the different options,	CSMAA software	Engineering and Infrastructure Investments studies Environmental	The comparison of the alternatives can be achieved even if there is not a clear preference for each one.	It is a rather complex decision making method and requires many primary data.

	first method, namely ELECTRE I, ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE IS and ELECTRE TRI. All methods use an outranking methodology to solve problems.	based on each option's scores on a set of common criteria of evaluation.		Renewable energy Waste management	It has the ability to handle both quantitative and qualitative judgements. The tradeoffs among multiple attributes are compensatory, and the information contained in the decision matrix is fully utilized.	Sometimes ELECTRE is difficult to identify the preferred alternative.
PROMETHEE	PROMETHEE uses the outranking principle to rank the alternatives like ELECTRE. PROMETHEE I is used for partial ranking of the alternatives and PROMETHEE II for their complete ranking. There are also PROMETHEE III, IV, V and VI.	PROMETHEE is based on mutual comparison of each alternative with respect to each of the selected criteria.	D-Sight Visual PROMETHEE	Urban infrastructures Medicine Chemistry Tourism	PROMETHEE supports group−level decision making and it constitutes a useful platform for debate and consensus building. PROMETHEE as an all-outranking method can simultaneously deal with qualitative and quantitative criteria. These scores of criteria can be expressed in their own units. PROMETHEE can deal with uncertain and fuzzy information.	PROMETHEE suffers from the rank reversal problem when a new alternative is introduced. PROMETHEE does not provide the possibility to structure a decision-making problem in the cases of many criteria and options. It thus may become difficult for the decision maker to obtain a clear view of the problem and to evaluate the results. Until now, PROMETHEE does not provide any formal guidelines for weighing, but assumes that the decision maker is able to weigh the criteria appropriately.
TOPSIS	It is a simple ranking method in conception and application technique based on the concept that the best alternative to a MCDM problem is the one, which is closest to its ideal solution.	TOPSIS helps to evaluate the objectives in terms of multidimensional economic phenomena based on the set of detailed economic attributes.	Excel	Human resources management Energy management Supply chain Management and logistics design, engineering and manufacturing systems	It has a simple process and it is easy to use and it is programmable. The number of steps remain the same regardless of the number of attributes.	Euclidean distance, does not consider the correlation of attributes. It is difficult to weight attributes and keep consistency of judgment, especially with additional attributes.

VIKOR	The VIKOR method was developed for multi-criteria optimization of complex systems. It determines the compromise-ranking list and the compromise solution obtained with the initial weights.	VIKOR method includes a multi criteria optimization of complex systems that focuses on ranking and selecting from a set of alternatives among conflicting criteria.	MATLAB Trapezoidal Fuzzy VIKOR Software	Design and manufacturing management Environmental resources & energy management Construction management Health care and risk management Supply chain and logistics management	This method focuses on ranking and selecting from a set of alternatives, and determines compromise solution for a problem with conflicting criteria, which can help the decision makers to reach a final solution.	It needs some modifications, as it is sometimes difficult to model a real-time solution. Difficulty of dealing with conflicting situations. Lack of consideration and interactions among criteria.
COPRAS	Ranking alternatives based on several criteria by using weights in alternatives. The selection of the best alternative is based on considering ideal and worst case scenario solutions.	*COPRAS* method is based on multi criteria evaluation of maximum and minimum values of each criteria.	Excel	Construction locating of roads Manufacturing of systems Risk analysis Intelligent environment	Evaluating both maximizing & minimizing criteria values separately. Simple computation process with less computational time. Ranking alternatives in terms of significance.	Less stable than other methods in cases of data variation. Results obtained by COPRAS depend on the number of minimizing criteria and the values.
Choquet Integral	Choquet Integral is an aggregation function defined with respect to the fuzzy measure. It is capable of representing interactions between the criteria.	Choquet Integral is based on sort of general averaging operator that can represent the notions of importance of a criteria and interactions among criteria.	Excel	Capacity identification Construction Data modelling Risk assessment	Can be used for both single & multifaceted decision making problems. Considers the interaction among criteria. Can deal with qualitative & quantitative criteria. Mathematically not demanding.	Time consuming and difficulty of Assigning weights. This depends on the subjective input from a panel of experts. It is almost impossible to assign weights when the number of criteria increases.
SAW	Earliest and most commonly used MCDM approach. In SAW, a value function is established based on a simple addition of scores that represent the goal achievement under each criteria, multiplied by the particular weights.	SAW is based on weighted summation of rating the performance of each alternative on all alternative criteria.	Excel	Energy efficiency Geographic research Construction	Simple computation and easily understandable. Ability to compensate among criteria for decision-makers.	Estimates revealed do not always reflect the real situation. Difficulty in multi-dimensional problems where the criteria units are different and their numerical values are occasionally several orders of magnitude apart.

						Illogical results may be obtained.
MIVES	It is a methodology, which combines two concepts as MCDA and Value Engineering to synthesize any type of criteria in a value index.	MIVES method is a combination of techniques based on a requirement tree, value functions, and the Analytic Hierarchy Process (AHP).	Excel	Industrial buildings Underground infrastructures Hydraulic structures Wind towers Sewerage systems Post-disaster site and housing selection Construction projects	Ability to compare design alternatives. MIVES allows comparing and prioritizing alternative solutions while minimizing the subjectivity in the decision-making process.	Allocating weights in the tree branches with up to four indicators does not generate problems. With more than four, one often loses the overall view and this can lead to inconsistencies, among other potential problem.

After analysing the various MCDM, the method selected in this paper is MIVES. MIVES is a multi-criteria decision model that integrates the basic requirements of sustainability (economic, environmental and social) and includes the concept of value functions that is used as an assessment tool. Some of the novelties of MIVES in this paper are that it considers the most representative sustainability indicators of the process/system under assessment. The proposed set of weights are aligned with the priorities and sensitivities of all the involved stakeholders. Another innovation of this paper is that is the first study to implement MIVES to evaluate all the aspects of sustainability of the design and construction of RSs.

For the below reasons MIVES method is preferred to other methods:

- Using MIVES method, alternatives can be compared in determining criteria and sub-criteria. Concerning the subject design of RS, using the weighting capability of the criteria, it is possible to identify the importance of the criteria and prioritize these. As a result, the decision-making process can be simply completed. MIVES also enables the identification and optimization of RS based on the satisfaction performance of stakeholders.
- MIVES can be combined with other decision-making methods such as, Analytical Hierarchy Process (AHP), Detector with Lepton, Photon, and Hadron Identification (Delphi), Multi-Criteria Search (MCS), and Performance-Based Engineering (PBE). MIVES is used to transform different types of variables, measured with different units, in the same dimensional unit to measure value (del Caño et al. 2015).
- MIVES reduces the subjectivity in decision-making, while integrating economic, environmental and social factors (Pardo-Bosch and Aguado 2016).

In MIVES, evaluations are carried out based on the following steps:

i. First, the problem is defined, for example, the fact that social factors have not been properly identified in some of the RS (Al-Jokhadar and Jabi 2016). One of the solutions to this problem is for instance, the provision of social interaction facilities (e.g. adding a community hall).

ii. In the second step, the requirement tree is designed. The tree is a hierarchical scheme in which the different characteristics of the process to be assessed are defined in an organized way. MIVES process includes the requirement tree, weights assignment for requirement tree, quantification of the indicators and value function for indicators.

iii. In the next stage, different alternatives are evaluated by means of the model and a sustainability index (*SI*) is obtained for each of them.

iv. In final step, the alternatives are ranked according to their index and the best one is selected.

MIVES-based approach to assessing the sustainability of RS

Requirement tree

In the approach used in this paper, MIVES quantifies the indicators that typically involve social, economic and environmental measures in sustainability. These indicators have different units for this purpose and they are normalized using value functions. Different indicators are measured in units pertinent to the particular metric system and having a common unit of measurement is useful for comparison and synthesis of indicators. Combining measurements of multiple indicators produce the sustainability scores. In this way, composite indicators or aggregates can provide a single holistic value for general sustainability. MIVES consists of three phases as shown in Fig. 2. These phases include the following:

i. Phase 1: Data collection

In this phase, previous research is considered and the problem areas are identified in the studies. The main goal is to achieve the best sustainability solution, which can be reached by the use of a decision-making tree. This tree is based on a theoretical structure for identifying the most representative indicators.

ii. Phase 2: Data evaluation

In this phase, the definition of the indicators, that may be quantitative or qualitative, is investigated at the same time as the databases. This is because there is a need to know what information is available in order to define the indicators accordingly. In addition, it is possible to find a very precise indicator but without the necessary data, it will not be very useful, as it can not be calculated correctly. Value functions are calibrated to normalize the measure of the indicators. Thus, a scale between 0 to 1 is considered, zero, indicates the minimum satisfaction (S_{min}) and one, indicates the maximum satisfaction (S_{max}).

iii. Phase 3: Assessment of sustainability index

In this phase, the Sustainability Index (*SI*) of each project alternative is assessed to evaluate the application of this approach. *SI* is based on a formula presented in the following sections. The *SI* value of each alternative can ultimately be used to prioritize and assist stakeholders in the decision-making process.

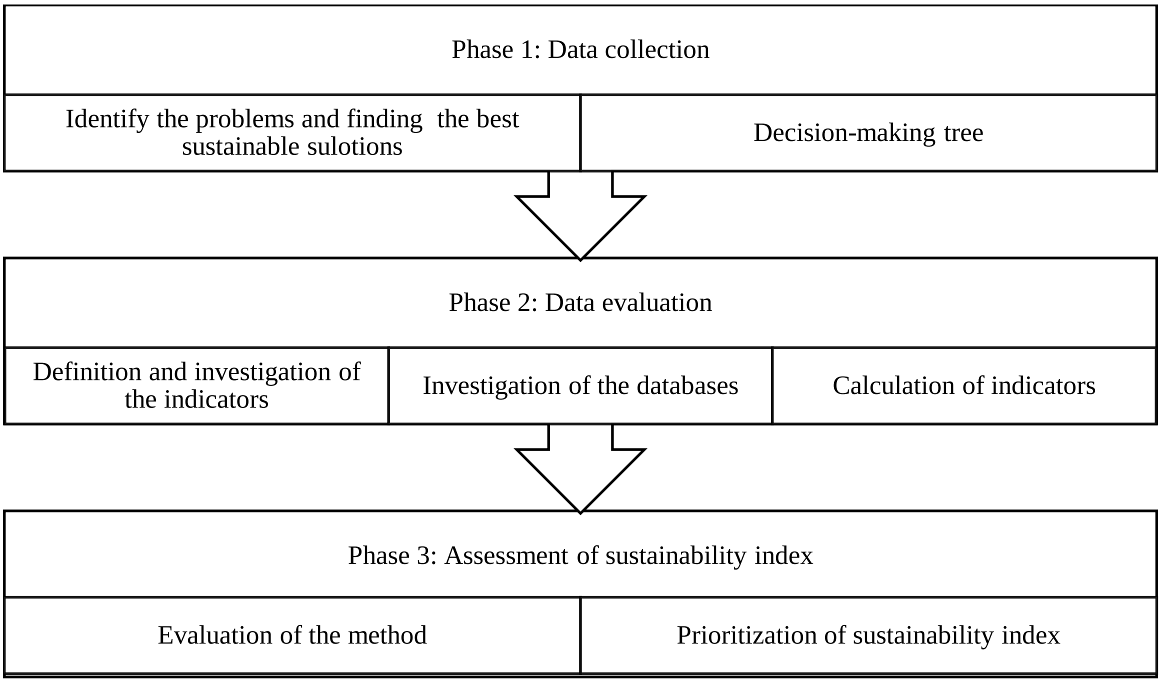
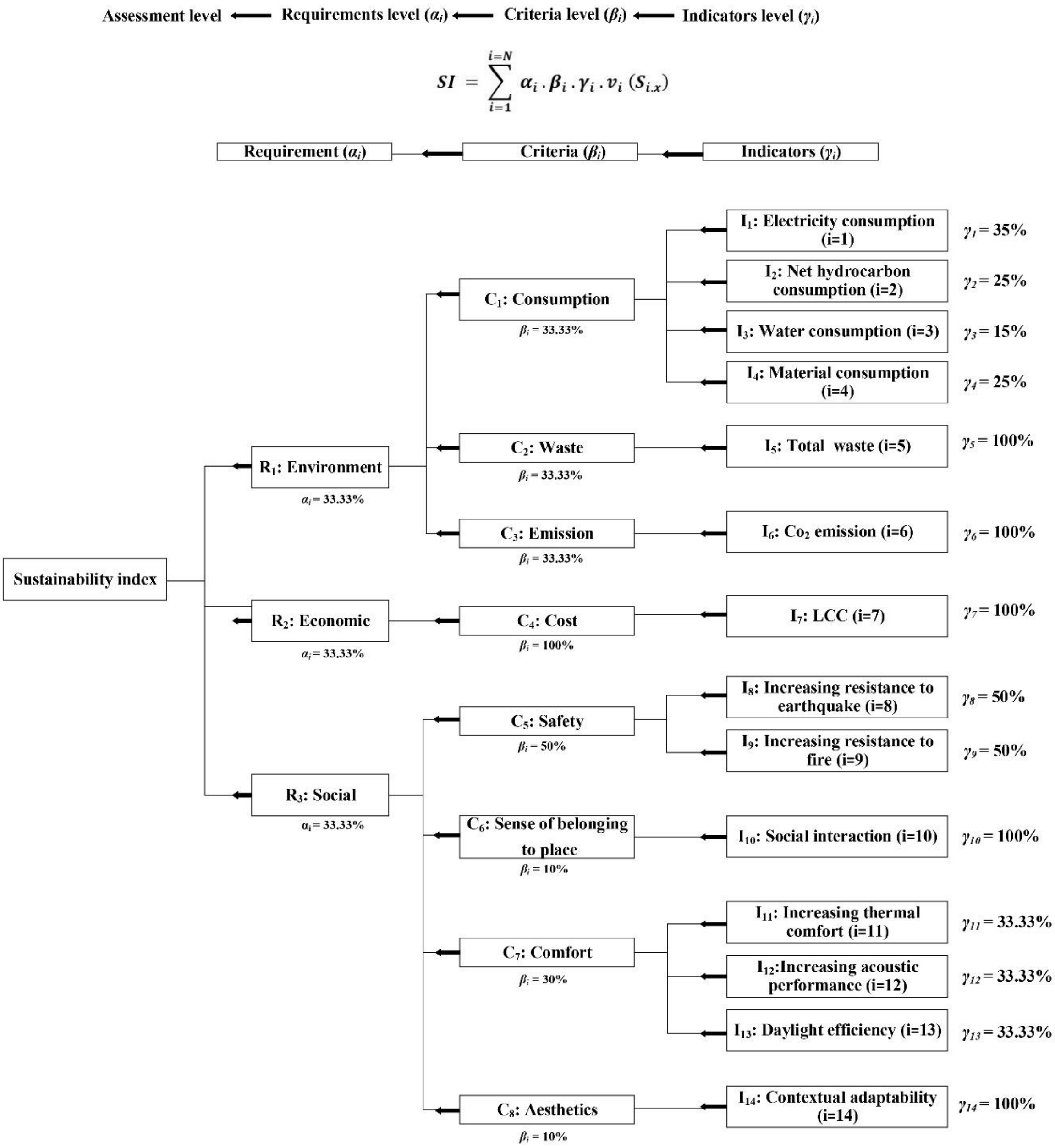


Fig.2. Three phases for sustainability assessment based on MIVES.

Requirement tree consists of the criteria and indicators that are relevant to the decision-making. This tree enables the evaluation and level of satisfaction obtained in sustainability and decision-making for a specific process. This tree is a hierarchical diagram in which the most significant aspects of the options are organized. This is typically defined at three levels: requirements, criteria and indicators. The indicators should be independent of each other to avoid overlaps in the evaluation process. Similarly, the indicators included are those considered most representative in terms of assessing the *SI*. Fig. 3 presents the decision-making tree for sustainability assessment of RS. The initial set of indicators was previously identified through an extensive literature review and consisted of nineteen indicators. From this, five indicators were discarded which include security against crime, safety of public space, user's flexibility, façade design and well-being. The reason, which these were discarded, was that these indicators were not quantifiable in MIVES calculation. The remaining fourteen indicators were selected and which were most applicable and these are presented in Fig. 3.



$$SI = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot v_i \, (S_{i.x})$$

Fig. 3. Decision-making tree for sustainability assessment of RS.

Environmental requirement

Environmental requirement (R_1) assesses the environmental effects of RS on the entire life cycle. It assesses both the positive and negative impacts that can be generated on the global and local environment of RS. R_1 is based on four life cycle phases of the building: (i) manufacturing; (ii) construction and assembly; (iii) use and maintenance (iv) demolition and disassembly.

Manufacturing phase includes the manufacture and transportation of building materials and technical installations used in the erection and renovation of buildings. The method of construction, use of resources and assembly phase should be clearly defined for the smooth management of all activities. This is particularly important in relation to activities such as production, collection, transportation, storage and utilization of materials. Use and maintenance phase encompasses all activities related to the use of the buildings over its life span. These include maintaining suitable condition inside the buildings such as water use and power appliances. Demolition and disassembly phase includes destruction of the building and transportation of dismantled materials to landfill sites and/or recycling plants (Ramesh et al. 2010). The life cycle stages of a building are all intensively involved, in the use of natural resources, energy and water are consumed in each of them (Ngwepe and Aigbavboa 2015).

Economic requirement

The *economic requirement* (R_2) measures the economic impact of RS both direct and indirect, during the entire life cycle. R_2 aims to minimize the cost of construction into two periods, the time of project construction and project maintenance.

Social requirement

The *social requirement* (R_3) assesses the effects on residents as well as third parties involved. The health and welfare of people are prioritized above any other consideration.

Weights assignment

Different methods can be used for assign the weights, such as direct assignment or AHP (Saaty 1990) and for the aggregation of experts' opinions: seminars, mean, Delphi method, etc. (Casanovas-Rubio and Armengou 2018; Pons et al. 2016; Hopfe et al. 2013; Del Caño et al. 2012). In this paper, MIVES has been used instead of other methods such as BREEAM, because the latter has some limitations that made it difficult to weight the criteria and indicators.

Some of the limitations are: complex weighting system (this complex process makes the calculation less transparent), market oriented, cost of compliance (BSRIA, 2020; Freitas & Zhang, 2018). In addition, LEED did not seemed to be a good method for this research due to its limitations, such as weakness in weighting the criteria and lack of attention to the economic aspect.

The use of MIVES for the assignment of weights and evaluation of 9 case studies is recommended because of advantages such as: it is accessible to all stakeholders (i.e., researchers, consultants, designers, authorities), the sets of weights are aligned with the priorities and sensitivities of all the involved stakeholders, and it considers the most representative sustainability indicators of the process/system under assessment (Umer et al., 2016).

For the research presented in this paper, the weights were assigned based on an extensive literature review and seminar discussions. The weights assigned to the indicators (γi) of each criterion, to the criteria (βi) of each requirement and to the three requirements (αi) of the decision tree establish their relative importance and are presented in Fig. 3.

The weightings of the requirements α (R_i) were assigned from the point of view of the sustainability as a balance between the three requirements α (R_i) = 0.33; i = 1, 2, 3, aligned with the Rio Declaration (UN 1992). The following literature was considered to assign the weights of the criteria and indicators (Alarcon et al. 2010; De la Fuente et al. 2017; Pardo-Bosch and Aguado 2016). Consequently, these weights reflect the importance of the aspects considered within the system boundaries and customize the general tree requirements to the specific conditions of the case study. *SI* of each alternative is calculated using (Eq. 1):

$$\boldsymbol{SI} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{i=N}} \boldsymbol{\alpha_i \,.\, \beta_i \,.\, \gamma_i \,.\, v_i \,(S_{i.x})} \qquad (1)$$

$\boldsymbol{\alpha_i}$, $\boldsymbol{\beta_i}$ and $\boldsymbol{\gamma_i}$: The weights of each requirement, criteria and indicator, respectively.

v_i ***($S_{i.x}$)***: The value of the alternative *x* with respect to a given indicator *i*.

N: The total number of indicators.

The *SI* value of each alternative can ultimately be used to prioritize and assist stakeholders in the decision-making process.

Value function and indicators

Value function

In this paper, a value function that transforms the units of each indicator into a non- dimensional value between 0 and 1 was proposed for each of the indicators. These represent the valuation from zero to maximum satisfaction, respectively. This scale of non-dimensional values is necessary to even out the sum of the values of each indicator, the physical units of which will depend on the nature of the evaluation.

To determine the satisfaction value for an indicator, MIVES consists of a procedure, which includes the following four steps (MIVES 2005; Reyes et al.2014; Martínez-Santos et al.2008):

- Stage 1: definition of the tendency (increase or decrease) of the value function.
- Stage 2: definition of the points corresponding to the minimum (S_{min}, value 0) and maximum (S_{max}, value 1) satisfaction.
- Stage 3: definition of the shape of the value function (linear, concave, convex, and S-shaped).
- Stage 4: definition of the mathematical expression of the value function.

Definition of the mathematical expression of the value function

MIVES uses (Eq. 2) as basis for defining individual value functions *Vi*.

$$v_i = M.\left[1 - e^{-j.\left(\frac{|s_{i.x} - s_{min}|}{R}\right)^q}\right] \quad (2)$$

In (Eq. 3) variable *M* is a factor that ensures that the value function will remain within the range of (0.0 -1.0) and the best response is associated with a value equal to the unit.

$$M = \frac{1}{\left[1 - e^{-j \cdot \left(\frac{|S_{max} - S_{min}|}{R}\right)^{q}}\right]} \quad (3)$$

In (Eq. 2 and Eq. 3):

***S**$_{max}$* **&** ***S**$_{min}$*: Maximum & minimum points in the scale of the indicator under consideration.

***S**$_{i.x}$*: The score of alternative *x* that is under assessment, with respect to indicator *i* under consideration, which is between S_{min} and S_{max}. This score generates a value that is equal to *Vi* ($S_{i,x}$), which has to be calculated.

q: The shape factor that defines approximation, in this case, whether the curve is *concave* ($q < 1.0$), or whether it tends to be a *straight line* ($q \approx 1.0$), or whether it is *convex* or *S-shaped* ($q > 1.0$).

R: The value that is used, if $q > 1.0$, to build *convex* or *S-shaped* curves as it coincides approximately with the value of the abscissa on which the inflection point occurs.

j: the value of the ordinate for point *j*, in the former case where $q > 1.0$.

The value functions for the fourteen indicators are shown in Table 3 and the requirement tree shown in Fig. 3 are sustainability analysis models for RS. Parameters and shapes of value functions were also defined in the experts seminars, using the references presented in the final column of Table 3. DCv functions were chosen for indicators that the client demand maximum satisfaction.

From the fourteen indicators, 5 increase concavely (ICv), 2 decrease convexly (DCx), 3 decrease S-shape (DS), 1 decrease linear (DL), 2 increase S-shape (IS), 1 decrease concavely (DCv). DCx function is suitable when there is hardly any increase for small changes around the point that creates the minimum satisfaction. This type of relationship is selected when approaching the maximum satisfaction point is greater than moving away from the minimum satisfaction point. This type of function is often used for economic or environmental indicators.

The goal is to ensure that the alternatives are as close to the maximum possible satisfaction point as possible.

This is also used when most alternatives are close to maximum satisfaction. In this case, as in the previous case, discrimination of alternatives is better and the motivation for improvement is greater. DCx functions show indicators that stakeholders will be prepared to accept partial satisfaction. Indicators with DL functions fall somewhere in between. The linear function represents a steady increase in the satisfaction generated by the alternatives. There is a proportional relationship in the whole range. This function is the default option when there is not a specific criterion, which can be defined.

ICv functions show the indicators that can increase the satisfaction of the decision makers. S-shaped function shows indicators with a combination of concave and convex functions. A significant increase in satisfaction is detected at central values, while satisfaction changes little as the minimum and maximum points are approached. DS functions present indicators that can increase in measurements and may cause a decrease in satisfaction. In contrast, IS functions present an increase in the measurements and may cause an increase in satisfaction.

DCv concave curve is used when, starting from the minimum satisfaction with the indicator firstly increasing rapidly. In this case, small changes around the point that creates the minimum satisfaction are highly valued. This type of relationship is chosen when moving away from the minimum satisfaction point, is more important than approaching the maximum satisfaction point. This is also used when most alternatives are close to the minimum satisfaction. In this case, the discrimination between the alternatives is better and the motivation for improvement is greater.

Table 3. Value function parameters for each indicators

Indicator	Unit	x_{max}	x_{min}	R	j	q	Shape	Ref.
I1. Net electricity consumption	kWh/m^2/year	187.85	1036.29	387	0.19	3.64	DS	Barros et al. (2015)
I2. Hydrocarbon consumption	litre/m^2/year	133006.56	733722.55	435000	0.009	3.64	DCx	Pons and de la Fuente. (2013)
I3.Water consumption	litre/m^2/year	96.28	531.22	815	0.009	0.97	DL	Aguado et al. (2012)
I4. Material consumption	tons/m^2	1.40	2.68	4250	0.000009	1.89	DCx	Casanovas-Rubio and Ramos, (2017)
I5. Total waste	kg/m^2/year	10.88	60.03	1250	3753	2.35	DS	del Caño et al. (2012)
I6. CO2 emission	kg/m^2/year	380.17	2097.19	3740	34.45	2.85	DS	de la Fuente et al. (2016)
I7. LCC	Currency/m^2/ year	39.44	295.06	55.46	0.52	0.84	DCv	de la Fuente et al. (2017)
I8. Increased resistance to earthquake	Richter	7	6	354	10	0.7	ICv	de la Fuente et al. (2017)
I9. Increased resistance to fire	hour	3	2	13	4	0.8	ICv	Pons and Aguado (2012)
I10. Social interaction	Points	5	1	4.21	4.50	3.10	IS	Lombera et al. (2010)
I11. Increased thermal comfort	w/m^{2}k	0.307	0.124	2.1	0.5	0.6	ICv	Pons and de la Fuente.(2013)
I12. Increased acoustic performance	*dB*	0.952	0.044	9.246	1.79	0.3	ICv	Mosalam et al. (2012)
I13. Daylight efficiency	%	5	2	2.1	1.6	3.5	IS	de la Fuente et al. (2017)
I14. Contextual adaptability	Points	5	3	4.55	4.31	3.08	ICv	Jato-Espino et al. (2014)

x_{max}: the lowest amount of consumption obtained from the case studies has led to the maximum satisfaction.
x_{min}: the maximum amount of consumption obtained from the case studies has resulted in a minimum of satisfaction.

Indicators

Net electricity consumption (kWh/m^2/year)

The indicator *net electricity consumption (**I_1**)* assesses the electrical power consumption over the gross area of the RS lifecycle and it is calculated as the energy consumed per gross square meter per year minus the energy produced in the building per gross square meter per year. This is the total energy in the two phases of manufacturing/construction and use/maintenance. The direct and indirect energy demand throughout the life cycle of the building is considered. Direct energy refers to the energy used to build, operate, rehabilitate and demolish buildings, while indirect energy consumption refers to the energy consumed to manufacture the construction materials and its facilities (Sartori and Hestnes 2007). Fig. 4 shows the value function of net electricity consumption indicator. In Fig. 4, the amount between 187.85 to 1036.29 ($kWh/m^2/year$) is related to the amount calculated from nine case studies. The added value for net electricity consumption of RS is evaluated through (Eq. 4):

Net energy consumption (kWh/year) = the number of residents × annual energy consumption per capita using the building.

According to World Bank organization, 11088.35 kWh energy per capita consumed in UAE in 2014 (Juaidi et al. 2016).

I_1= Net energy consumption per square meter ($kWh/m^2/year$) = net energy consumption/ gross floor area (GFA). (4)

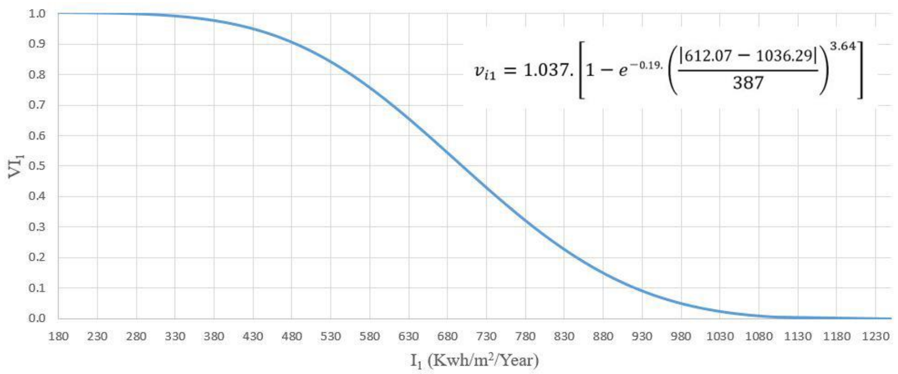


Fig. 4. Value function of net electricity consumption indicator (I_1).

Hydrocarbon consumption (litre/m^2/year)

The indicator *hydrocarbon consumption* (***I_2***) includes the hydrocarbon consumption during the RS life cycle, in manufacturing, construction, use and maintenance. Fig. 5 shows the value function of hydrocarbon consumption indicator. In Fig. 5, the amount between 133006.56 to

733722.55 (litre/m^2/year) is related to amount of nine case studies. The added value for hydrocarbon consumption of RS is suggested to be evaluated through (Eq. 5):

I_2= Hydrocarbon consumption (litre/year) = the number of residents × annual fuel consumption per capita. (5)

Hydrocarbon consumption per square meter (litre/m^2/year) = hydrocarbon consumption/GFA.

The United Arab Emirates's Natural Gas per capita per year is 7850845.72 (litre/year) (Khondaker et al., 2016).

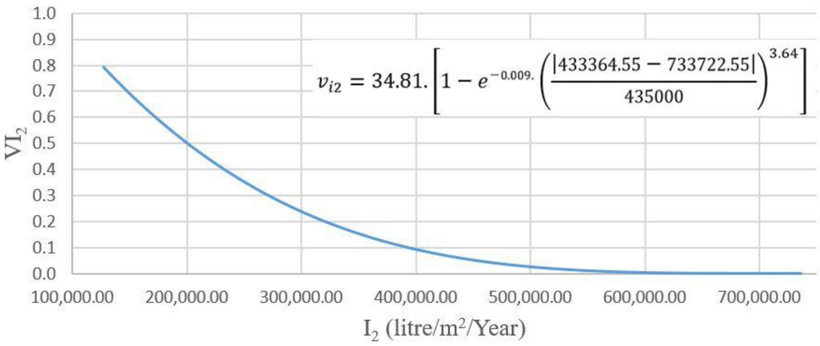


Fig. 5. Value function of hydrocarbon consumption indicator (I_2).

Water consumption (litre/m^2/year)

The indicator *water consumption* (***I_3***) covers the water consumption in the three phases: manufacturing, construction, use and maintenance. Fig. 6 shows the value function of net water consumption indicator. In Fig. 6, the amount between 96.28 to 531.22 (litre/m^2/year) is related to amount of nine case studies which is calculated by the following equation. The added value for net water consumption of RS is suggested to be evaluated through (Eq. 6):

I_3= Net water consumption (litre/year) = the number of residents × annual water consumption per capita.

Net water consumption per sqmeter (litre/m^2/year) = net water consumption /GFA. (6)

The United Arab Emirates's water consumption per capita per year is 200,705 (litre/year). (Yagoub et al. 2019).

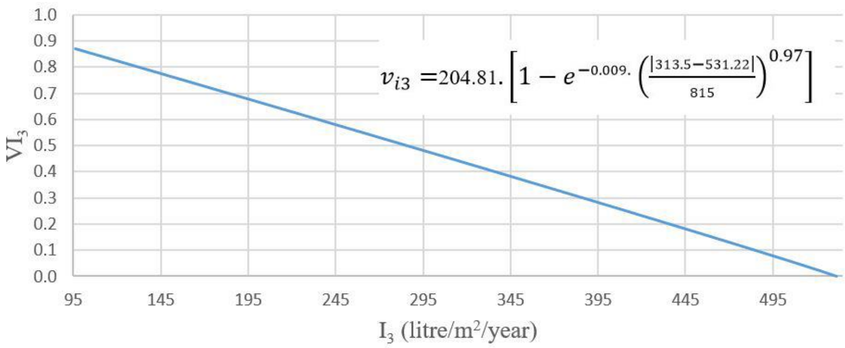


Fig. 6. Value function of net water consumption indicator (I_3).

Material consumption (tons/m^2)

The indicator *material consumption* **(I_4)** evaluates the consumption of material resources for the RS construction. Table 4 shows the material consumption for nine case studies. The added value for material consumption of RS is suggested to be evaluated through (Eq. 7):

I_4= Material consumption per sqm (tons/m^2) = material consumption/GFA (7)

Table 4. The material consumption for nine case studies

Building name	Gross floor area (GFA)	Material	Residents	material consumption (tons)	Material consumption per Sqmeter (ton/m^2)
Burj Khalifa	309,473	steel/concrete	6,335	831,000	2.68
Princess tower	171,175	steel/concrete	2,900	241,000	1.40
23 Marina	139,596	concrete	8,734	263,836.44	1.89
Elite Residence	140,013	concrete	9,267	225,000	1.60
Uptown Tower	107,000	steel	10,000	202,230	1.89
The Torch	94,306	concrete	3,000	178,238.34	1.89
DAMAC Heights	89,579	concrete	2,700	169,304.31	1.89
Ocean Heights	113,416	concrete	2,301	214,356.24	1.89
21st Century Tower	86,000	steel/concrete	3,353	162,540	1.89

Fig. 7 shows the value function of material consumption indicator. In Fig. 7, the amount between 1.40 to 2.68 (tons/m^2) is related to amount of nine case studies.

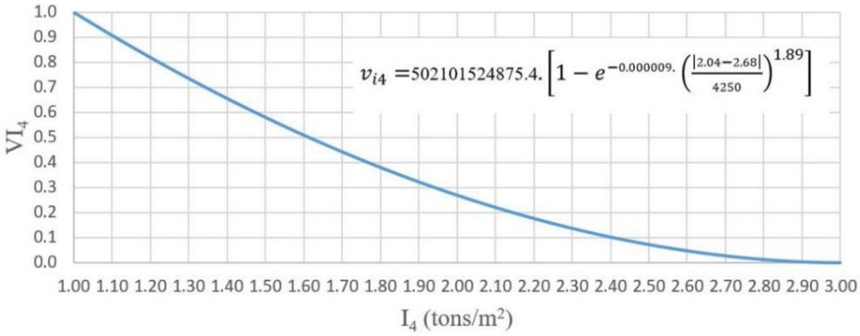


Fig. 7. Value function of material consumption indicator (I_4).

Total waste (kg/m²/year)

The indicator *total waste* (***I₅***) accounts for the total amount of waste material remaining from the manufacturing, construction, use and maintenance. The use of waste is one of the ways to integrate a sustainable approach to the construction industry (Barker 2000). Fig. 8 shows the value function of net waste generation indicator. Net waste generation indicates the result of multiplication of the number of inhabitants in the annual waste generation per capita in Dubai. In Fig. 8, the amount between 10.88 to 60.03 (kg/m^2/year) is related to amount of nine case studies. The added value for net waste generation of RS is suggested to be evaluated through (Eq. 8):

Net waste generation (kg) = the number of residents × annual waste generation per capita.

I_5= Net waste generation per sqm (kg/m^2/year) = net waste generation / GFA. (8)

The yearly per capita municipal waste was approximately 470.85 (kg/year) by 2017 (Paleologos et al. 2016).

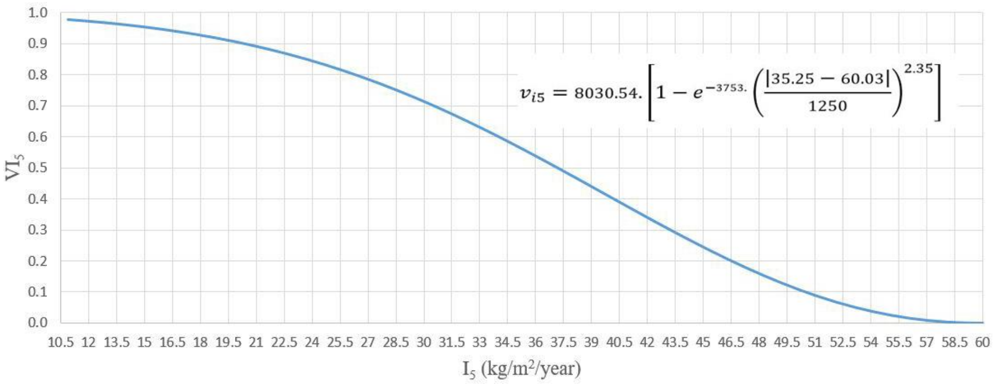


Fig.8. Value function of net waste generation indicator (I_5).

CO2 emission (kg/m²/year)

The indicator *CO2 emission* (***I_6***) considers the CO2 emission for the RS emissions over its lifecycle. Building construction causes high-energy consumption and CO2 emissions during construction, use and demolition (Pons and Wadel 2011). Therefore, indicators should be designed to assess the impact of RS on the environment in terms of CO2 emissions and energy consumption based on life cycle assessment (LCA). Fig. 9 shows the value function of CO2 emission indicator. In Fig. 9, the value between 380.17 to 2097.19 (kg/m²/year) is related to the value of nine case studies which is calculated by the following equation. The added value for net CO2 emission of RS is suggested to be evaluated through (Eq. 9):

I_6= Net CO2 emission (kg) = the number of residents × annual CO2 emission per capita.

CO2 emission per sqm (kg/m²/year) = net CO2 emission/GFA. (9)

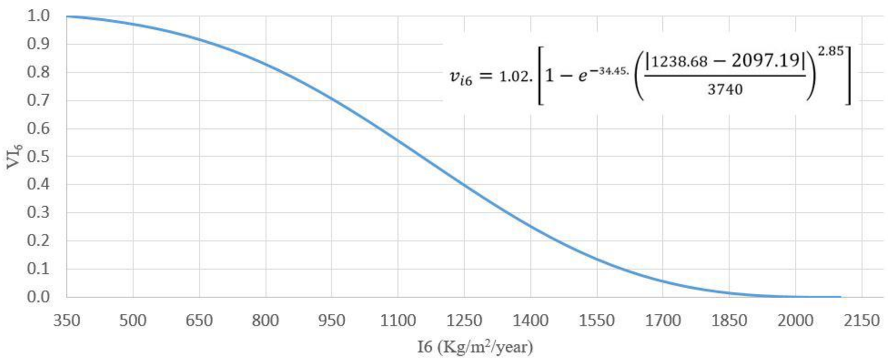


Fig. 9. Value function of net co2 emission indicator (I_6).

LCC (Currency/m^2/ year)

The indicator *LCC* (***I_7***) considers the construction and maintenance costs in one Life cycle costing (LCC) indicator. The construction cost include both direct and indirect cost. Direct cost include the cost of land, the cost of construction per square meter. Indirect cost include the cost of renting machinery and the cost of transporting materials. The maintenance cost covers the expected cost during the life span of RS. In this paper, the life cycle of RS is assumed as 50 years long. Fig. 10 shows the value function of LCC indicator. In Fig. 10, the amount between 39.44 to 295.06 (\$/m^2/ year) is related to the nine case studies which is calculated by the following equation. The added value for LCC of RS is suggested to be evaluated through (Eq. 10):

$$I7 = \text{LCC indicator (monetary unit/m}^2\text{/year)} = \frac{\text{Construction costs}}{\text{Life time}} + \text{Maintenance costs per year} \qquad (10)$$

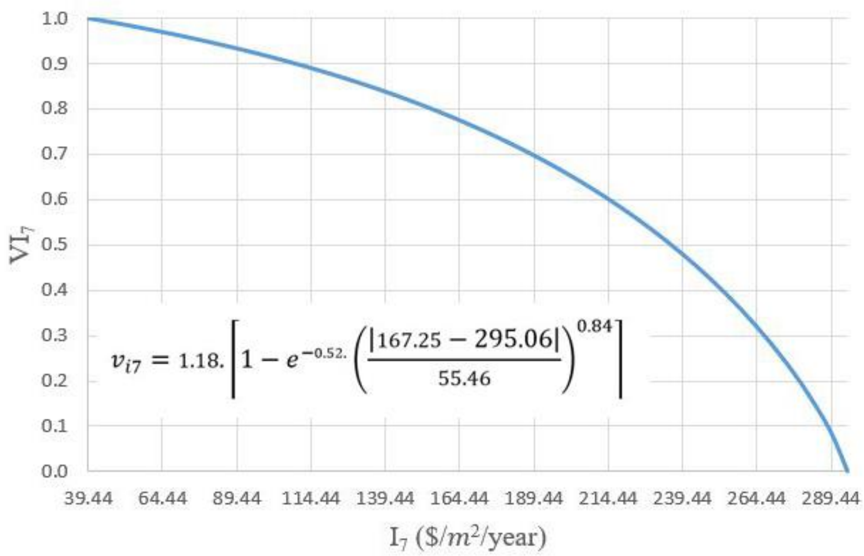


Fig. 10. Value function of LCC indicator (I_7).

Increased resistance to earthquake (Richter)

The indicator *increased resistance to earthquake* (***I_8***) evaluates the strength of the building against earthquake. In RS, normal vertical loads, dead or alive, do not cause much of a problem, but lateral loads due to wind or earthquake vibration should be given special attention in the design of buildings (Wakchaure et al. 2012). Fig. 11 shows the value function of increased resistance to earthquake indicator. In Fig. 11, the amount between 6 to 7 (Richter) is related to the nine case studies.

The added value for increased resistance to earthquake of RS is suggested to be evaluated through (Eq. 11). Legislation for earthquake resistance in Dubai for RS is considered 6.00 (Richter) (El-Arab 2016). Earthquake resistance for Burj Khalifa is considered 7.00 (Richter) and for other case studies are considered 6.25 (Richter). Since the *SI* of each indicator is a number between 0.0 and 1.0, the results of Equation (11) are taken into account in calculating the *SI*. While the value function of indicator 8.0 is based on the range of between 6.00 and 7.00 (Richter).

$$\boldsymbol{I_8} = \frac{\text{Earthquake resistance of the building } (Richter)}{Earthquake \text{ resistance in the legislation } (Richter)} \quad (11)$$

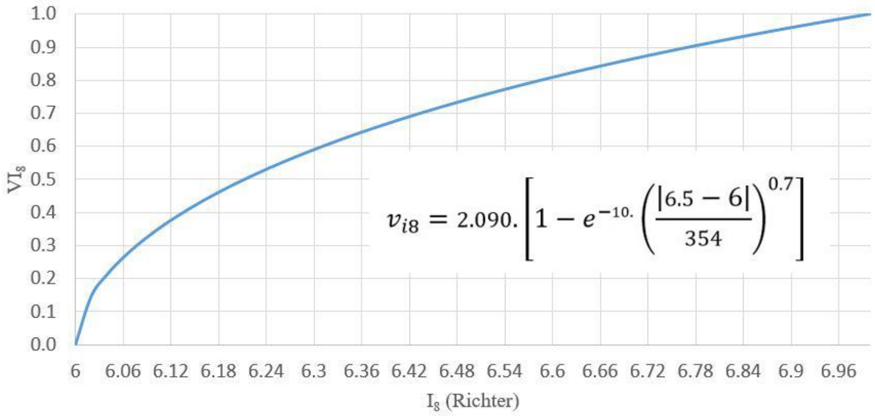


Fig. 11. Value function of increased resistance to earthquake indicator (I_8).

Increased resistance to fire (hour)

The indicator, *increased resistance to fire* **(*I*$_9$)** assesses the durability of the material subject to fire, based on comparing minimum fire resistance times in Dubai. Fig. 12 shows the value function of increased resistance to fire indicator. In Fig. 12, the amount between 2 to 3 (hour) is related to amount of nine case studies. Legislation for fire resistance in Dubai for RS is consider 2 (hour) (Yuen et al. 2021). Fire resistance for Burj Khalifa is consider 3 (hour) and for other case studies are consider 2.5 (hour). Since the *SI* of each indicator is a number between zero to one, so in calculating the *SI*, the results of (Eq. 12) are considered. While the value function of indicator 9 is based on the range of between 2 to 3 (hour). The added value for increased resistance to fire of RS is suggested to be assessed through Equation (12):

$$I_9 = \frac{\text{Fire resistance of the building }(hour)}{Fire\text{ resistance in the legislation }(hour)} \quad (12)$$

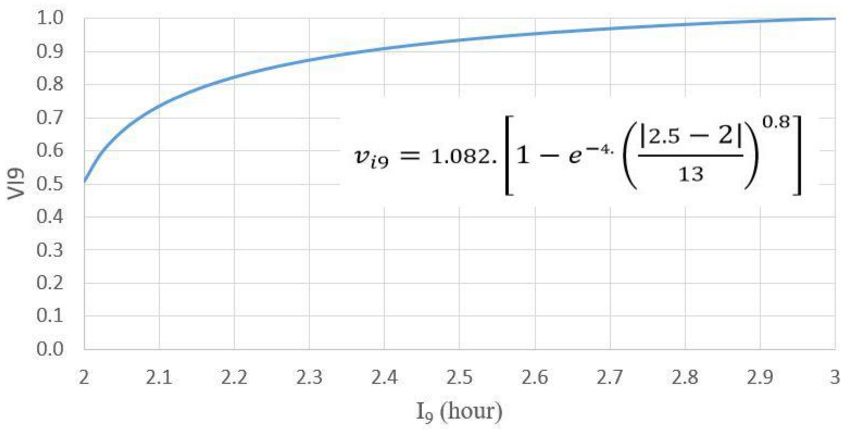


Fig. 12. Value function of increased resistance to fire indicator (I_9).

Social interaction (Points)

The indicator *social Interaction* (***I₁₀***) evaluates the social relations and neighbor's interactions in RS and social interaction between family members. In order to evaluate this indicator, the following survey was proposed based on seminars with multidisciplinary professionals who collaborate in the construction sector, including architects, engineers, contractors, project managers and psychologists. A measurable scale of 1 to 5 has been used to rate the need for social interaction. Table 5 indicates the survey that helps decision-makers to make the correct assessment in the shortest time. Fig. 13 shows the value function of social interaction indicator.

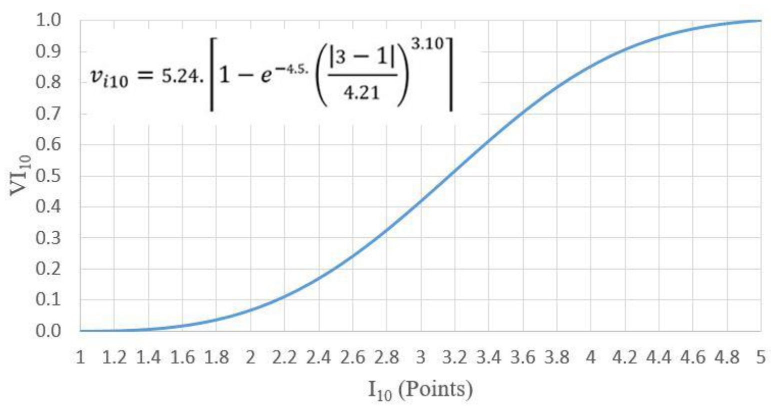


Fig. 13. Value function of social interaction indicator (I_{10}).

Table 5. Proposed survey for assessing the social interaction (Adapted from: Lee et al. 2011; Yao 2020)

Building name	Amenities	Residential unit	Objective parameters that can affect the social interaction	Evaluation of parameters in buildings (score of each parameter 0.56)									Potential to socialize	Points
				1	2	3	4	5	6	7	8	9		
Burj Khalifa	Sky lobbies, fitness and spa, swimming pool, recreational room, observation deck, Library, Health club.	900, 304 hotel room	1. Creating recreational and social spaces	×	×	×	×	×	×	×		×	Very high	5
Princess tower	Gym, spa, indoor-outdoor swimming pools, event space, kids' play area, games room.	763	2. Good community and social planning	×		×			×	×		×	Medium	3
23 Marina	Spas, health club, Steam and Sauna, Gymnasium, Aerobics, Landscaped gardens, Jogging track, Indoor and outdoor swimming pools, Bubble Bath.	291	3. Improve level of safety such as good lighting	×	×	×		×	×	×		×		4.5
Elite Residence	Gym and fitness, tennis, indoor and outdoor swimming pool, sauna, Jacuzzi and sundeck-lounges, children's playroom, air hockey, billiards.	697	4. Providing public spaces, including natural and green spaces	×	×	×		×	×			×		4
Uptown Tower	Restaurants, conference facilities, Cinema, Residents' Lounge, Exclusive Pool & Spa, fitness.	237 plus 130 hotel room	5. Community circulation ways	×	×			×	×			×	Medium	3
The Torch	Sauna and steam room, swimming pool, gym.	676	6. Orientation of building	×				×	×			×		2
DAMAC Heights	Gymnasium with aerobics room, steam room, saunas, Jacuzzis, swimming pool, children's pool, children's playroom, residents' lounge, games room, barbecue area, cinema room.	640	7. Effective management of social spaces	×	×	×		×	×	×		×		4.5
Ocean Heights	Indoor and an outdoor swimming pool, sauna, massage, room, Kids' play area, gym and fitness.	672	8. Design of sky bridge	×		×			×			×	Low	2
21st Century Tower	Gym and fitness, rooftop swimming pool, outdoor playing area for children.	400	9. Social Interaction and community involvement	×		×		×				×	Low	2

Increased thermal comfort (w/m^2k)

The indicator *increased thermal comfort* (***I_{11}***) reflects the temperature in the building and it is related to the comfort of residents inside. Temperature control systems in RS should maintain indoor temperature at an appropriate level. The added value for increased thermal comfort of RS is evaluated through (Eq. 13):

$$I_{11} = \text{percentage of façade material (\%)} \times \text{U-value of façade materials (w/m}^2\text{k)} \quad (13)$$

It should be noted that for each city, the permitted U-value is defined according to the legislation. U-value obtained from this equation should not exceed the allowable value of that standard. The allowed level of U-value varies according to the regulations for walls, roof and floors. In this paper, the criteria of this U-value is considered for exterior walls of the façade in the buildings. Table 6 indicates U-value for different materials. For example, U-value for solid aluminium is 221(w/m^{2}k), but the aluminium used in the façade in the form of sheets has a different value. This also applies to other materials. Fig. 14 shows the value function of increased thermal comfort indicator.

Table 6. The U-value for different materials (Mirrahimi et al. 2016; O'Brien and Bennet 2016)

Material	U-value for façade material (w/m^{2}k)
Glass wool insulation	0.042
Aluminum	0.43
Silicone	0.66
Stainless steel	0.35
Concrete	0.8

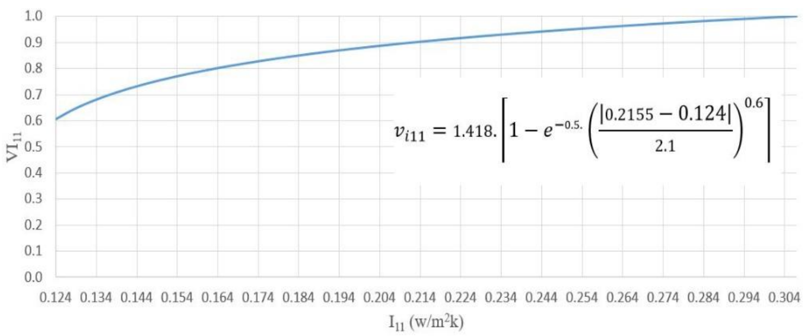


Fig. 14. Value function of increased thermal comfort indicator (I_{11}).

Increased acoustic performance (dB)

The indicator *increased acoustic performance (**I_{12}**)* evaluates the noise pollution and its impact on RS. The additional value for this indicator is calculated from (Eq. 14 and Eq. 15):

$$I_{12} = \frac{\text{Noise reduction of alternative} - \text{Required noise reduction}}{\text{Required noise reduction}} \quad (14)$$

Noise reduction of alternative = estimated noise outside – estimated noise inside (*dB*).

Required noise reduction = estimated noise outside – maximum allowed noise inside based on standard (*dB*).

Usually, the permissible amount of noise outside, for day and night, varies according to the standards of every city. In this study, to estimate the noise outside of each case study, several factors such as the height of the building, the amount of vehicle traffic in the streets around the building and the analysis of the environment around the building are considered. In addition, the maximum allowed noise inside is based on the legislation and is different for each city. (Eq. 14), is used to calculate the estimated noise inside:

Noise reduction of the alternative = Estimated noise outside – (percentage of façade material × noise reduction coefficient of material) × Estimated noise outside. (15)

Noise reduction coefficient (NRC) is a measure of a material's ability to absorb sound within the frequency range of speech. A material with an NRC of 0.0 will reflect all sound that hits to it. A material with an NRC of 1.0 will theoretically absorb all sound that hits to it. Table 7 presents the noise reduction coefficient for some materials in the façade. It should be noted that the NRC in Table 7 is defined based on 250, 500, 1000 and 2000-Hertz (Hz) frequencies test. Table 8 shows the NRC values of most useful materials for noise barriers. Fig. 15 shows the value function of increasing acoustic performance indicator.

Table 7. The noise reduction coefficient for some materials in façade. (Adapted from: Fatima and Mohanty 2011)

Material	NRC
Aluminum	0.05
Glass	0.02
Silicone	0.20
Stainless steel	0.23
Concrete	0.35

Table 8. The NRC values of materials for noise barriers (Adapted from: Arenas and Asdrubali 2018)

Material	Frequency				NRC
	250 Hz	500 Hz	1000 Hz	2000 Hz	
Stainless steel (1.5mm)	0.34	0.25	0.19	0.15	0.23
Glass (6mm)	0.02	0.01	0.01	0.02	0.02
Plywood (10mm)	0.34	0.25	0.19	0.15	0.23
Concrete (150mm)	0.3	0.4	0.6	0.09	0.35
Exposed ground (1500mm)	0.01	0.01	0.02	0.03	0.02
Pool water (1500mm)	0.04	0.06	0.09	0.09	0.07
Plastic (3mm)	0.34	0.25	0.19	0.15	0.23

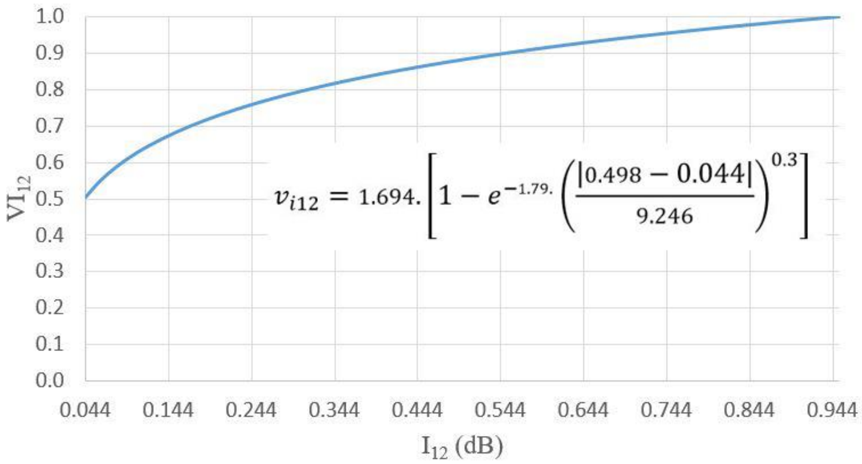


Fig. 15. Value function of increased acoustic performance indicator (I_{12}).

Daylight efficiency (%)

The indicator *daylight efficiency* (I_{13}) assesses the utilization of natural light by utilizing sustainability techniques. Fig. 16 shows the value function of daylight efficiency indicator. The added value for day light efficiency of RS is evaluated through (Eq. 16): (Zhen et al. 2019; Baker and Steemers 2014):

$$\boldsymbol{I_{13} = ADF = \frac{T\, AW\, \theta}{A \times (1 - P^2)}\ \%} \qquad (16)$$

T: Diffuse visible transmittance of the glazing.

AW: Net glazed area of the window (m^2).

θ: The angle of visible sky (°).

A: Total area of the room surfaces: ceiling, floor, walls and windows (m^2).

P: The average reflectance of room surfaces i.e. walls, floors, ceilings.

ADF is measured as a percentage and is classified into 3 parts:

Below 2% - not bright enough and, as a result, requires artificial light.

Between 2 and 5% - sometimes light may be enough, but artificial light is needed.

More than 5% - Proper and artificial light is usually not needed, except between dusk and dawn (Yarham and Wilson, 1999).

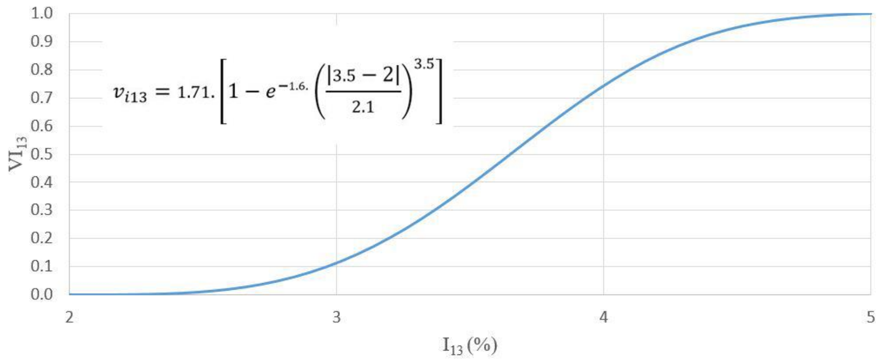


Fig. 16. Value function of daylight efficiency indicator (I_{13}).

Contextual adaptability (Points)

The indicator *contextual adaptability* (***I*$_{14}$**) considers the contextual adaptability between RS and its surrounding. To this end, Table 9 provides a survey to identify the parameters that are effective in adapting the RS to their surroundings.

The survey was defined based on seminars with architects, engineers and city planners. A measurable scale of 3.0 to 5.0 is used to rate the compatibility of RS with its built neighbourhood. The higher the score, the more compatibility is established between the RS alternative and its nearby buildings. This survey helps decision-makers to assess the rate of harmony between the alternatives of RS and their surroundings. Adaptability is also classified as a capability of competence, where capabilities are derived from lower-level competencies (Swafford 2006). Fig. 17 shows the value function of contextual adaptability indicator.

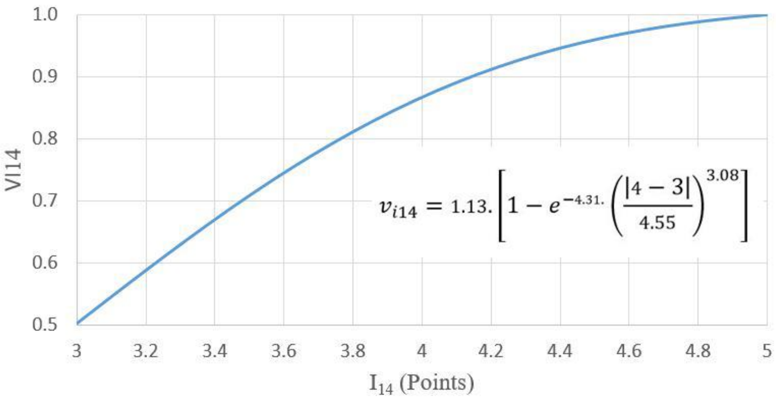


Fig. 17. Value function of contextual adaptability indicator (I_{14}).

Table 9. Proposed survey for assessing the contextual adaptability between RS building and its surrounding (Adapted from: Manewa et al. 2016)

Building name	Objective parameters that can affect the contextual adaptability between RS building and its surrounding	Definitions of parameters	Evaluation of parameters in buildings (score of each parameter 0.42)												Potential to harmony	Points
			1	2	3	4	5	6	7	8	9	10	11	12		
Burj Khalifa	Effective aesthetic factors	1. Harmony between the existing building and the surrounding buildings in terms of color, texture, facade style and skyline.	×	×	×	×	×	×	×	×	×	×	×	×	Very high	5
Princess tower		2. Proportion and aesthetics on visual integration between the existing building and other buildings in terms of height, human scale, dimensions and size.	×	×	×	×	×	×	×	×	×	×	×	×	Very high	5
23 Marina		3. Adaptability of the existing building with its surroundings in terms of building materials and attention to local characteristics of the area.	×	×	×	×	×	×		×	×	×	×	×	high	4
Elite Residence	Proper interventionist factors	4. Projective unity of the landscape.	×	×	×	×	×	×	×		×	×	×	×	high	4
Uptown Tower		5. Easy access to the site and routes.	×	×	×	×	×	×	×	×	×	×	×	×	Very high	4
The Torch		6. Functional architectural forms and combination of structure and architectural form.	×	×	×	×	×	×			×	×	×	×	Medium	4
DAMAC Heights		7. Ability to convert or dismountable the part of the building form to	×	×	×		×	×	×		×	×	×	×	High	3

		change the function of the building.														
Ocean Heights		8. Ability to overcapacity and moving the building elements.	×	×	×		×	×	×	×	×	×		×	Medium	3
21st Century Tower	Relevant anthropological factors	9. Cultural unity of the landscape.	×	×	×	×	×	×		×	×		×	×	Medium	3
		10. To revive the urban identity.														
		11. Interaction of natural and cultural issues.														
		12. The integration of the building with the cultural landscape.														

Dubai case study results

In this paper, nine RS in Dubai have been chosen as case studies. All indicators are evaluated for these case studies. The authors have used a value per capita for the whole of UAE average and this is used in general in case-by-case studies. However, this is a limitation in this paper.

MIVES-based approach in this paper could also be used for other buildings with different function such as commercial, offices, sports, cultural and so forth. It is usually common to define the important criteria based on sustainability and assign a weight to each indicator so that the result of the evaluation can be the correct solution for decision makers in various situations.

Table 10 examines the design and construction specifications of the case studies. Table 11 shows the indicators result for the case studies and this result is consider for the entire buildings. Table 12 presents the *SI* for case studies and this is for a better understanding, as to how to calculate each indicator for the case studies. In Table 10, the weights of requirements (α_i), the weights of criteria (β_i) and the weights of indicators (γ_i) were specified that these weights were distributed differently as previously shown in Fig. 3.

Table 10. Characteristic of case studies (Adapted from: Arul et al. 2020; Emrem et al. 2008)

Building name	Height (m)	Height (ft)	Floors	Gross floor area (GFA)	Floor above ground floor	Floor below ground floor	Number of Elevator	Elevator speed (m/s)	Completion	Function
Burj Khalifa	828	2,717	163	309,473	163	2	58	10	2010	Office / residential/ Hotel/ retail/ communication/fitness
Princess tower	413.4	1,356	101	171,175	101	6	13	6	2012	Residential/ fitness
23 Marina	392.4	1,287	89	139,596	89	4	62	8	2012	Residential/ fitness
Elite Residence	380.5	1,248	91	140,013	87	4	12	6	2012	Residential/ fitness/ commercial/ office/retail
Uptown Tower	370	1,214	78	107,000	78	-	14	6	2022	Residential/ hotel/office
The Torch	352	1,155	86	94,306	86	4	8	6	2011	Residential
DAMAC Heights	335.1	1,099	88	89,579	88	5	12	6	2018	Residential /retail
Ocean Heights	310	1,017	83	113,416	83	3	6	6	2010	Residential/ fitness
21st Century Tower	269	883	55	86,000	55	4	7	6	2003	Residential

Table 11. Result of the indicators for case studies

Indicator	Names of buildings								
	Burj Khalifa	Princess tower	23 Marina	Elite Residence	Uptown Tower	The Torch	DAMAC Heights	Ocean Heights	21st Century Tower
I_1 ($kWh/m^2/year$)	1003.23	187.85	693.75	733.90	1036.29	352.73	334.21	224.96	432.31
I_2 ($Litre/m^2/year$)	160708.8	133006.5	491197.3	519620.9	733722.5	249745.4	236631.8	159278.8	306091.3
I_3 ($Litre/m^2/year$)	116.38	96.28	355.66	376.33	531.22	180.94	171.32	115.25	221.72
I_4 (ton/m^2)	2.68	1.40	1.89	1.60	1.89	1.89	1.89	1.89	1.89
I_5 ($kg/m^2/year$)	13.15	10.88	40.19	42.51	60.03	20.43	19.36	13.03	25.04
I_6 ($Kg/m^2/year$)	459.35	380.17	1,403.98	1,485.22	2,097.1	713.84	676.36	455.26	874.89
I_7 ($\$/m^2$/ year)	128.95	39.44	63.00	51.38	138.89	295.06	158.70	96.11	190.52
I_8 (Richter)	7	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
I_9 (hour)	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
I_{10} *(Points)*	5	3	4.5	4	3	2	4.5	2	2
I_{11} (w/m^2k)	0.124	0.274	0.307	0.293	0.158	0.197	0.138	0.236	0.177

I_{12} (*dB*)	0.836	0.368	0.084	0.422	0.044	0.152	0.952	0.26	0.098
I_{13} (%)	2	5	5	5	5	3.5	2	5	2
I_{14} (Points)	5	5	4	4	4	4	3	3	3

Table 12. Values and *SI* for case studies

Values	Burj Khalifa	Princess tower	23 Marina	Elite Residence	Uptown Tower	The Torch	DAMAC Heights	Ocean Heights	21st Century Tower
SI	0.499	0.291	0.380	0.375	0.622	0.611	0.451	0.358	0.418
V_{R1}	0.41	0.13	0.28	0.28	0.99	0.20	0.19	0.16	0.22
V_{R2}	0.31	0.10	0.16	0.13	0.32	1	0.36	0.23	0.42
V_{R3}	0.78	0.63	0.69	0.70	0.56	0.63	0.78	0.35	0.60
V_{C1}	1	0.27	0.61	0.61	1	0.41	0.40	0.34	0.46
V_{C2}	0.07	0.06	0.14	0.14	1	0.09	0.09	0.07	0.10
V_{C3}	0.08	0.07	0.10	0.10	1	0.09	0.09	0.08	0.09
V_{C4}	0.31	0.10	0.16	0.13	0.32	1	0.36	0.23	0.42
V_{C5}	0.95	0.9	1	1	0.98	0.98	0.95	0.98	0.92
V_{C6}	0.36	0.06	0.84	0.14	0.06	0.02	0.21	0.02	0.25
V_{C7}	0.85	0.55	0.34	0.62	0.17	0.29	0.94	0.43	0.23
V_{C8}	0.13	0.13	0.09	0.09	0.13	0.5	0.09	0.5	0.5
V_{I1}	0.08	0.24	0.08	0.08	0.5	0.14	0.15	0.21	0.12
V_{I2}	0.08	0.08	0.08	0.08	0.5	0.08	0.08	0.08	0.08
V_{I3}	0.51	0.51	0.51	0.51	0.4	0.51	0.51	0.51	0.51
V_{I4}	1	0.26	0.27	0.26	0.27	0.27	0.27	0.27	0.27
V_{I5}	0.34	0.36	0.21	0.2	1	0.29	0.30	0.34	0.26
V_{I6}	0.37	0.41	0.15	0.15	1	0.28	0.29	0.38	0.23
V_{I7}	0.71	0.76	0.75	0.75	0.7	1	0.68	0.73	0.66
V_{I8}	0.41	0.6	0.4	0.55	0.5	0.48	0.42	0.36	0.45
V_{I9}	0.54	0.3	0.6	0.45	0.48	0.5	0.53	0.62	0.47
V_{I10}	0.36	0.12	0.97	0.19	0.12	0.10	0.25	0.10	1
V_{I11}	1	0.88	0.88	0.88	0.86	0.87	0.85	0.88	0.86
V_{I12}	0.87	0.85	0.79	0.85	1	0.81	0.87	0.85	0.84
V_{I13}	0.04	0.08	0.08	0.08	0.08	0.06	0.04	0.08	0.04
V_{I14}	0.13	0.13	0.12	0.12	0.13	1	0.12	1	1

Table 13 shows some of the sustainable strategies that have been effective in assign weight of indicators. In Table 13, the marks (x) indicate that the building performs well in the relation to sustainability. This table shows which of the sustainability indicators performed better in the case studies.

Table 13. Some of the sustainable strategies for nine case studies

Building name	Environment requirement						Economic requirement	Social requirement						
	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}
Burj Khalifa			×	×							×			

Princess tower			×				×	×					×	
23 Marina			×										×	
Elite Residence			×										×	
Uptown Tower	×	×			×	×						×	×	
The Torch			×				×							×
DAMAC Heights			×											
Ocean Heights			×						×				×	×
21st Century Tower			×							×				×

Following the measurement of the *SI* for case studies with the MIVES approach, the results are analysed to prove the reliability and the accuracy of the results as well as *SI* quantification of each case study. For this purpose, the sustainability and performance requirement for each alternative is presented in Fig. 18.

From Figure 18 and Table 12, it can be concluded that *SI* of the alternatives ranged from 0.29 for case 2 with the lowest *SI* and 0.62 for case 5 with the highest *SI* is a balanced requirement weight set (α (R_i) = 0.33; i = 1, 2, 3). The results demonstrate the potential for further improvement of sustainability performance in RS in Dubai under this investigation.

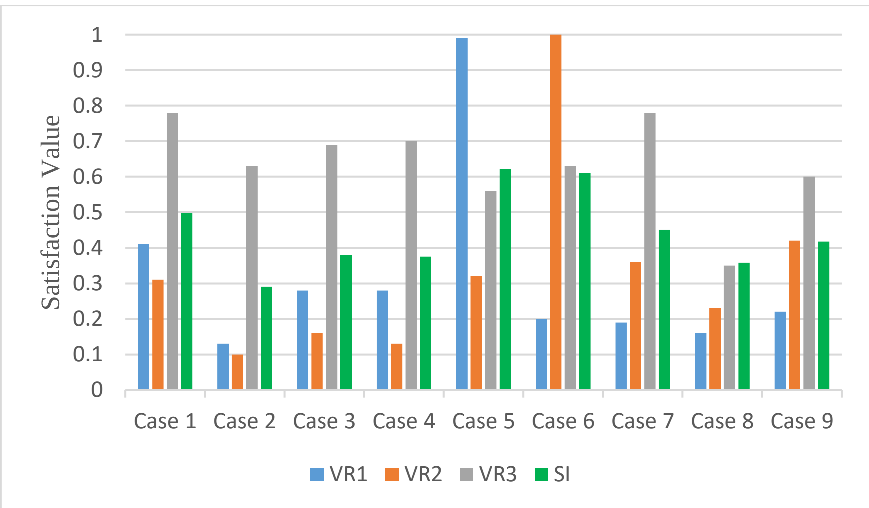


Fig.18. Requirements values and *SI* for the case studies.

In detailed, it was attempted to investigate the MIVES-based assessment method to evaluate the sustainability of nine RSs in Dubai to confirm the appropriateness and strength of the method. In this evaluation, the following results have been identified:

- Sustainability assessment of nine case studies were analyzed by this approach and it was concluded that the social indicator should be further improved and developed. It is also possible to add new criteria to the decision-making tree relating to the design and construction aspects.
- In this paper, social indicators have been given the highest weights and case study 5 performed better in terms of sustainability. In general, the results of case studies have shown that the multi-criteria approach for the majority of RSs in Dubai have a sustainability performance in the range of $0.29 < SI < 0.62$.
- Case study 2 (Princess Tower) obtained the lowest *SI* (0.291) and case study 5 (Uptown Tower) the highest *SI* (0.622) as case study 2 was mainly designed and constructed in 2012 but case study 5 was built in 2022. Since case study 2 was constructed in 2012, the dimensions of sustainability were less important than in recent years however, this building was built with all the usual design and structural considerations.
- The results of the above-studied assessments can be a useful tool for the construction and maintenance of existing and future RSs. This is especially important in Dubai, as it has seen an increase in population and construction of RS in recent years. It should be noted that some indicators, for instance, in the economic field, have included cost estimates in this paper. This was required for the application of the method and the latest data were considered.
- Since amongst other factors, designers should consider buildings to meet the social needs of residents, the use of surveys and interviews in identifying the essential social

needs of residents is considered an important step. It is therefore important to focus on the shortcomings, main gaps and the disadvantages of previous RS in this regard.

- Some of the limitations of this paper include the following: the demolition phase of the building life cycle is not considered for the case studies and this phase can be considered for future buildings. In addition, the value functions in this research are defined based on the case studies. This can be adapted by modifying the graph shape of value function for other buildings.

Conclusion

This paper has focused about evaluation of RS considering the three dimensions of sustainable development. Previous studies have examined RS in most cases from the two aspects of sustainability namely the environmental and economic dimensions but less on the social aspect. Thus, in the literature review there are limited sources, which have used a coherent, systematic and flexible method to evaluate all sustainability criteria of RS.

In this paper, a model based on the MIVES method was presented for sustainability analysis and decision-making. This model will help decision-makers to design and construct more sustainable RS for the future in Dubai. There is room for improving the sustainability of future HRBs. In order to achieve this, the multi-criteria approach used in this research, can be a useful tool to use for the design and construction of future RS. The model can be used to evaluate the overall sustainability of RS using the strategy of value functions. The objective of this paper was to investigate the MIVES-based assessment method to evaluate the sustainability of nine HRBs in Dubai. This was to confirm the appropriateness and strength of the method used and the evaluation and results of the nine case studies in Dubai show that the majority of HRBs in this paper have a sustainability performance in the range of $0.29 < SI < 0.62$.

In order to create a balance of sustainability, a requirement tree with eight criteria and fourteen indicators with different weightings has been used. This tree defines different indicators of products or process to be assessed. The important point is that while the weights reflect a specific evaluation but at the same time, these weights can also be used for the calibration and simulation of different social, economic and environment conditions without changing the tree structure. In later studies, more criteria and indicators can be defined for the requirement tree.

It is concluded that the same process can be carried out with the value functions and this model can be applied to most RS's evaluation. The proposed model can also be used reliably with other boundary conditions to achieve similar results. This can be carried out by adapting the weight distribution and value function parameters. To this end, some indicators and weights should be adjusted to different location's characteristics and requirements. Therefore, this paper presents a flexible and customizable model as a specific approach to the design and evaluation of RS for future research. Finally, MIVES model can also be reliably used with other boundary conditions to obtain better results by adapting the weights distribution and the value function parameters.

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Data Availability Statement

- Some or all data, models, or code generated or used during the study are available in a repository online as shown below in accordance with funder data retention policies (https://www.mdpi.com/2071-1050/3/1/35; https://www.sciencedirect.com/science/article/pii/S095006181200222X; https://ascelibrary.org/doi/epdf/10.1061/%28ASCE%29CO.1943-7862.0000419).

Notation list

The following symbols are used in this paper:

A = Total area of the room surfaces: ceiling, floor, walls and windows (m^2);

ADF = Azure data factory;

AW = Net glazed area of the window (m^2);

dB = Decibel;

DCv = Decrease concavely;

DCx = Decrease convexly;

DL = Decrease linear;

DS = Decrease S-shape;

GFA = Gross floor area;

ICv = Increase concavely;

IS = Increase S-shape;

j= the value of the ordinate for point j, in the former case where q > 1.0;

M = Variable M is a factor that ensures that the value function will remain within the range of (0.0 -1.0);

N= The total number of indicators;

P = The average reflectance of room surfaces i.e. walls, floors, ceilings;

q = The shape factor that defines approximation;

R =The value that determines the shape of the value function;

R_1 = Environmental requirement;

R_2 = Economic requirement;

SI = Sustainability index;

$S_{i.x}$ = The score of alternative x that is under assessment, with respect to indicator i under consideration, which is between S_{min} and S_{max};

S_{max} = Maximum satisfaction;

S_{min} = Minimum satisfaction;

T = Diffuse visible transmittance of the glazing;

V_C = The total weights assigned to the criteria;

V_I = The total weights assigned to the indicator;

v_i ($S_{i.x}$) = The value of the alternative x with respect to a given indicator i;

V_R = The total weights assigned to the requirement;

αi= The weights assigned to the requirement;

βi = The weights assigned to the criteria;

γi = The weights assigned to the indicators;

θ =The angle of visible sky (°);

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