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Integrated Value Model for Sustainable Assessment of Modular Residential Towers: Case Study: Ten Degrees Croydon and Apex House in London

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Abstract: Modular construction can become sustainable by making all aspects of the design and construction process more effective during all phases. This paper aims to develop and use a sustainability assessment model for modular residential buildings in two case studies. This research uses the Integrated Value Model for Sustainable Assessment (MIVES), which is a multi-criteria decision-making model for sustainability assessment. This model considers all aspects of sustainability, environmental, economic and social, and helps stakeholders make decisions. Few previous studies have assessed all these aspects in full and MIVES make this assessment possible. For assessment purposes, two modular buildings have been chosen, namely "Ten Degrees Croydon" as the tallest high-rise modular residential building in the world and "Apex House" as the second tallest modular building in the world, both in London. These residential towers were assessed using MIVES, demonstrating a very satisfactory sustainability index in all the above aspects.

Keywords: sustainability assessment; MIVES; modular buildings; Ten Degrees Croydon; Apex House

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1. Introduction

Population growth in this century has driven the need for additional land in urban areas, and so also more high-rise buildings. This has led to less horizontal urban construction around the world [1]. According to recent surveys, one third of city-dwellers live in poor conditions [2]. It is estimated that 35 million apartments are required each year to provide adequate housing for people in all the cities throughout the world [3,4].

More modular buildings have been constructed, involving a construction method whereby building components are usually made in a factory and transported to the construction site for assembly [5]. Modular buildings offer significant benefits over traditional onsite construction. Modular construction can boost sustainability by improving resource efficiency at all stages of the construction process [6], such as faster, safer manufacturing of building components, higher-quality building elements due to the controlled factory conditions and less influence from adverse environmental conditions [7–10].

Attributes such as less waste and more flexibility in material reuse, less pollution, reduction in delays during production and construction in variable weather conditions, as well as safer, lean construction, lead to effective, efficient building construction and management. Modular building construction usually provides cheaper housing [11].

Modular buildings are mainly used for facilities such as hotels, student accommodation, military use and social housing, because the module size is suitable for the design and construction of these buildings [12]. However, modular construction can be used for most situations, as highlighted in recent research by the Steel Construction Institute [13]. Research by [14] described how the combined use of modules, panels and steel frames can create more flexible building forms.

Modular buildings have also been constructed for low-rise buildings [15], particularly in the UK [16], North America [17], China [18–20], Singapore [21,22] and Australia [23]. The UK government demonstrates a strong trend and demand to design and construct more modular buildings. Research by [24] highlighted the advantages of offsite manufacturing over a decade ago. Structural methods for these buildings have been used and divided into three different categories: 1D single element, 2D panelized systems and 3D volumetric systems [25,26]. More residential towers are being built due to population growth, land scarcity and prices, climate change and commuting distances. However, these buildings consume vast resources such as energy for heating, ventilation, and air conditioning (HVAC), electricity for lifts and large quantities of materials and have high maintenance and cleaning costs, and so on. These buildings can also have a significant negative impact on the environment, and so it would be useful to assess them. A decision-making model is thereby required to measure the sustainability level for these buildings. The three main sustainability dimensions can be classified as environmental, economic and social aspects. There are various methods which can be used for these assessments and the model chosen in this research project is the Integrated Value Model for Sustainable Assessment (MIVES). This model assesses these three main aspects of sustainability and helps various stakeholders to pick the best alternative option available.

The main objective of this research is to develop an evaluation model for modular residential buildings while considering all aspects of sustainability. The main aspects of sustainability here are environmental, economic and social. This model has helped to achieve the aforementioned objectives and its main features are explored below. In short, this methodology used a new model named MIVES.

The MIVES model was chosen for this paper since it encompasses all aspects of sustainability with particular emphasis on social and environmental aspects as opposed to other methods. In addition, the MIVES model is more suitable and relevant for this research than other methods for reasons such as certainty for decision makers, less difficult weight assignment for the criteria, less time needed, ease of formulation of the indicators and it is more focused on the three main aspects of sustainability.

The MIVES model is also a multi-criteria decision-making method, helping decision-makers to select the most beneficial alternatives for sustainability. In the MIVES model, case studies are ranked according to the indicators [27] which can assist decision-making issues based on a specific set of criteria [28]. MIVES can be applied at the design, construction, renovation and demolition stages. MIVES has not previously been used to assess modular buildings and these buildings in London were selected for this model for the first time. Since modular buildings are more sustainable, they were chosen as a case study for this research.

2. Methodology

2.1. MIVES Model

The MIVES approach combines the fundamental requirements of sustainability (environmental, economic and social) and includes the concept of value function [29]. This also considers representative indicators relating to design and construction including materials and components [30]. MIVES can be coupled with other decision-making methods, such as the analytical hierarchy process (AHP), detector with lepton, photon, and hadron identification (Delphi), multi-criteria search (MCS), performance-based engineering (PBE) and so forth [31].

The MIVES approach intends to reduce subjectivity when making decisions and integrating environmental, economic and social factors simultaneously [32]. MIVES has certain characteristics that are not present in other sustainability assessment methods. As one example, it not only focuses on cost, but also on combining other requirements, such as social and environmental impacts, while also considering most construction lifecycle stages [33]. MIVES enables comparisons to be made according to relevant criteria and subcriteria [34]. Figure 1 presents the different MIVES phases demonstrating how the model works overall.

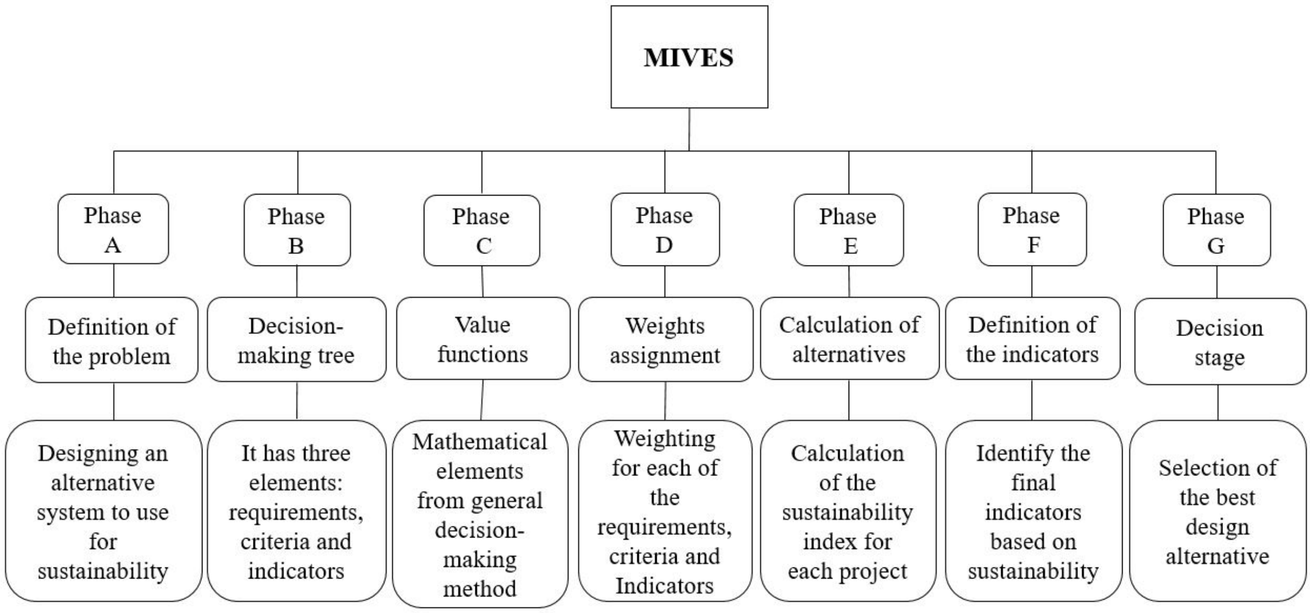

Figure 1. The phases in MIVES.

2.2. Definition of the Decision-Making Tree and the Weight Assessments

The decision-making tree is an important component of MIVES [35], which is part of the decision-making process, and it summarizes the indicators and criteria which represent the technology being assessed. For this paper, a decision-making tree was devised with three requirements: environmental, economic and social (R_1, R_2 and R_3, respectively), eight criteria (C_1–C_8) and sixteen indicators (I_1–I_{16}). The decision-making tree (grouping the indicators, criteria and requirements) is shown in Table 1 along with the assigned weights for requirements, criteria and indicators. The weights affect how all factors are assessed within the system parameters and they comprise the requirements tree for the specific conditions of the case studies. In this paper, the functional unit is considered for the indicators on each square meter of the building. The analytical hierarchy process (AHP) method [36] is used to assign the weights.

To define the value functions, the trend (increase or decrease), shape (concave, convex, linear, S-shaped) and the points that produce minimum and maximum satisfaction (S_{min} and S_{max}) were determined according to [37,38].

Table 1. Criteria and indicators devised for the sustainability assessment on building construction technologies.

Requirement (α_i)	Criteria (β_i)	Indicators (γ_i)	Units
R_1. Environmental (33.33%)	C_1. Consumption (33.33%)	I_1. Net electricity consumption (35%)	kWh/(m^2·year)
		I_2. Hydrocarbon consumption (25%)	l/(m^2·year)
		I_3. Water consumption (15%)	l/(m^2·year)
		I_4. Material consumption (25%)	tons/m^2

	C_2. Waste (33.33%)	I_5. Total waste (50%)	kg/(m²·year)
		I_6. Rate of reused and recycled material in the building (50%)	%
	C_3. Emission (33.33%)	I_7. CO_2 equivalent (100%)	kg/(m²·year)
R_2. Economic (33.33%)	C_4. Cost (100%)	I_8. LCC (100%)	£/(m²·year)
R_3. Social (33.33%)	C_5. Safety (50%)	I_9. Increased resistance to earthquake (33.33%)	Richter
		I_{10}. Increased resistance to fire (33.33%)	hour
		I_{11}. Ease of assembly for components (33.33%)	Points
	C_6. Sense of belonging to a place (10%)	I_{12}. Social interaction (100%)	Points
	C_7. Comfort (30%)	I_{13}. Increased thermal comfort (33.33%)	w/m^{2}k
		I_{14}. Increased acoustic performance (33.33%)	dB
		I_{15}. Daylight efficiency (33.33%)	%
	C_8. Aesthetics (10%)	I_{16}. Contextual adaptability (100%)	Points

Note: percentage values indicate the assigned weights.

The environmental requirement (R_1) comprises three criteria: C_1 (consumption), C_2 (waste) and C_3 (emission), categorized as follows:

- Criteria C_1. Consumption includes four indicators: I_1 assesses the electricity consumption over the building lifecycle. I_2 refers to the hydrocarbon consumption during the building lifecycle. I_3 covers the water consumption in the use phase. I_4 assesses the amount of material resources required to build the tower.
- Criteria C_2. Waste includes two indicators: I_5 considers the total amount of waste material generated during the construction phase and I_6 considers the rate of reused and recycled material in the building.
- Criteria C_3. Emission provides indicator I_7 which quantifies the CO_2 equivalent emissions during the operating phase.
- The economic requirement (R_2) encompasses just one criterion, C_4 (cost), which comprises indicator I_8, quantifying the construction, use and maintenance costs (life cycle costing, LCC).

The social requirement (R_3) consists of five criteria: C_5 (safety), C_6 (sense of belonging to the place), C_7 (comfort) and C_8 (aesthetics). These were configured as follows:

- Criteria C_5. Safety consists of five indicators: I_9 on quantifying the value related to increased bearing capacity against earthquakes over the level required by the legislation (resistance above the target is considered beneficial). I_{10} is increased resistance time against accidental fire action (with respect to the applicable fire safety legislation). I_{11} assesses the components' potential ease of assembly.
- Criteria C_6. Sense of belonging to a place is represented by indicator I_{12}, which quantifies the extent to which the building configuration facilitates social relations and encourages participation and social interactions amongst residents.
- Criteria C_7. Comfort is assessed using three different indicators: I_{13} evaluates the thermal insulation capacity and the resulting thermal comfort of users. I_{14} evaluates the acoustic insulation and its impact on noise pollution and I_{15} assesses the natural light level and its impact on building users.
- Criteria C_8. Aesthetics consists of indicator I_{16} which assesses how the residential towers fit into the context of their surroundings.

It is important to highlight that the criteria and indicators determined in the decision-making tree are those considered to be significantly affected on the building's sustainability index. Therefore, there might be other indicators, although these have since been disregarded: (1) variations of them have negligible impact on the building sustainability index due to its low relative weight compared to the remaining indicators. (2) Reducing the number of indicators to strictly those which are critical and representative facilitates the sustainability analysis and minimizes the source of errors during the quantification phase.

Engineers from various fields performed the weighting assignment of the decision-making tree and this was completed using the AHP method. In this tree, each environmental, economic and social requirement carries a weighting of 33.33% as they each have the same importance. Furthermore, criteria consumption, waste and emission also have the same weighting of 33.33%. Cost criteria have 100% weighting since the economic requirement has only one criterion. Amongst the social requirement criteria, safety has the highest weighting, 50%. For the indicators, the CO2 equivalent and LCC weighting are 100% as the related criterion only has one indicator. The indicators for total waste (5) and for the rate of reused and recycled material in the building (6) have the highest weighting of 50%.

2.3. Definition of Indicators and Value Functions

For each indicator, value functions for quantifying satisfaction/value (between 0 and 1) were defined. This dimensionless value scale is important to normalize the sum of the values for each indicator [39]. Figure 2 shows the various shapes of the value functions.

MIVES utilizes Equation (1) as a guide to interpret each value function (V_i).

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

In Equation (2), variable M is an element that allows the value function to remain within the range of 0 to 1.

$$M = \frac{1}{\left[1 - e^{-j \cdot \left(\frac{|s_{max} - s_{min}|}{R}\right)^q}\right]} \tag{2}$$

In Equations (1) and (2):

S_{max} and S_{min}: These are the maximum and minimum magnitudes of the indicator under review.

$S_{i.x}$: This is the result of alternative x, which is under consideration for the indicator *i* under consideration.

q: This is the element that indicates the properties of the curve, such as concave ($q < 1.0$), straight line ($q \approx 1.0$), convex or S-shaped ($q > 1.0$).

R: The value used when $q > 1.0$ to determine convex or S-shaped curves. It falls approximately within the value of the abscissa on which the inflection point happens.

j: This is the value for point *j* when the previous case is $q > 1.0$.

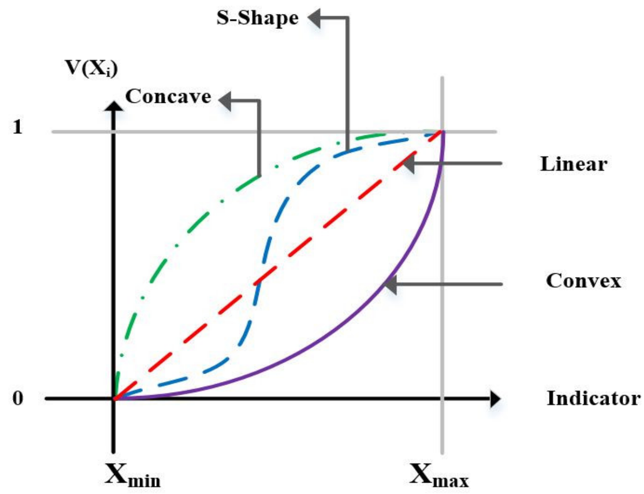

Figure 2. The various shapes of value functions [40].

- Indicators I_1, I_5 and I_7 were modeled using a decreasing S-shaped (DS) function as the level of satisfaction drops quickly to a residual value when a specific value of the indicator is reached [35].
- Indicators I_2 and I_4 were modeled using a decreasing convex (DCx) function. DCx functions are commonly used when there is a significant decrease for minor variations close to the point that gives maximum satisfaction [39].
- Indicator I_3 was modeled using a decreasing linear (DL) function. DL function is used when variations in satisfaction are uniformly (constant slope) dependent on the variation of the indicator's magnitude [41].
- Indicator I_8 was modeled using a decreasing concave (DCv) function. The DCv function is convenient when an increase in the indicator's magnitude from the point of maximum satisfaction causes the satisfaction to decrease sharply. In contrast, small reductions in the indicator's magnitude around the point that creates the minimum satisfaction lead to significant increases in satisfaction [42].
- Indicators I_6, I_9, I_{10}, I_{13}, I_{14} and I_{16} were modeled using an increasing concave (ICv) function since satisfaction increases as the indicator's magnitude increases. The philosophy of this value function shape is the opposite of that for DCv (indicator I_8) [43].
- Indicators I_{11}, I_{12} and I_{15} were modeled using an increasing S-shaped (IS) function as the level of satisfaction is comparatively low when a specific indicator value increases [44].

The ease-of-assembly questionnaire in Table 2 was used to evaluate the components' ease-of-assembly indicator (I_{11}). There were 10 respondents (5 of each gender). A scale from 1 to 5 was defined to rate the need for ease of assembly in tower construction. All the parameters gathered in Table 2 have a direct impact on the assembly and construction of the modular buildings in general. However, the magnitude of each parameter can affect assembly to a different extent. For example, it was assumed that skilled labor affects the speed and quality of construction to a greater extent than other parameters. If all the parameters were met in full, then the building could potentially obtain the best result: 5 points.

The questionnaire devised to assess social interaction (I_{12}) is presented in Table 3. In this table, nine objective parameters were found to influence social interaction in buildings in general. It has been assumed that nine parameters can affect social interaction equally.

A questionnaire devised for the contextual adaptability indicator (I_{16}) is presented in Table 4. The parameters of each of the value functions are presented in Table 5.

Table 2. The questionnaire proposed for ease of assembly.

Number of Respondents in three majors categories			Number of Respondents and qualification		Objective parameters that can affect the ease of assembly	Degree of importance of the parameter Potential for ease of assembly (scale of 1 to 5)					Resulting (1 to 5)	Satisfaction
Architecture	Civil	Construction management	PhD	Master		Very low	Low	medium	High	Very high		
5	3	2	6	4	The accuracy of manufactured components	-	-	*	*****	****	4	0.75
					Workforce Skill	-	*	**	****	***		
					Flexibility of units	*	*	*	****	***		
					Duration of assembly	-	*	****	***	**		
					Level of installation details and information	*	*	**	**	****		
					Collaboration between designer and contractor	-	*	**	***	****		
					Detailed performance information of sections	-	**	****	**	**		
					Simplicity of connections	-	*	**	****	***		

Note: * is the number of respondents who have selected the parameter importance. For example, four respondents gave a very high score to the parameter of "the accuracy of manufactured components". Five respondents gave a high score. One respondent gave a medium score. No one gave a low or very low score. The background is shaded for each score with the highest number of respondents and it represents the scale for the corresponding parameter. For example, the parameters of "the accuracy of manufactured components" has the highest score. Each score that has the greatest number of respondents represents the overall score of the indicator. Potential for ease of assembly (scale from 1 to 5), (1) very low; (2) low; (3) medium; (4) high and (5) very high. Satisfaction level (scale of 0 to 1), 0.00 (very low); 0.25 (low); 0.5 (medium); 0.75 (high); 1 (very high).

Table 3. The questionnaire proposed to evaluate social interaction. Adapted from [45,46].

Responder	Background	Objective parameters that can affect the social interaction and the degree of importance of parameters and potential to social interaction (scale of 1 to 5). 1: very low, 2: low, 3: medium, 4: high, 5: very high.																																											Potential to socialized	Satisfaction
		Creating recreational, sports, friendly routes, spaces for the peers and participation in collective groups.					Community planning (orientation of public spaces)					Level of safety					Design of courtyards public spaces, for social interaction					Community circulation ways					Orientation of building					Good management in social spaces					Design of sky bridge					Social Interaction and solidarity						
		Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high		
1	PhD/ Architecture					*					*					*				*						*				*						*			*							*		
2	Master/ Architecture					*				*						*					*					*					*					*	*									*	5	1
3	PhD/ Architecture					*		*								*				*					*						*			*				*								*		
4	Master/ Civil			*							*				*						*					*					*					*					*				*			
5	Master/ Civil					*				*						*					*					*				*						*					*					*		
6	PhD/ Construction management				*						*				*					*						*					*					*				*						*		
7	PhD/ Architecture					*					*			*						*						*				*						*	*						*					
8	PhD/ Architecture				*						*		*								*				*						*			*					*							*		
9	PhD/ Civil			*						*						*			*							*					*					*		*								*		
10	Master/ Construction management					*				*				*							*					*				*						*			*							*		

Note: Ten respondents participated in this questionnaire and nine parameters for social interaction were considered. In total, 53 respondents gave a very high score, 20 respondents gave a high score, 10 respondents gave a medium score, 5 respondents gave a low score and 2 respondents gave a very low score. * shows the degree each participant has considered for each objective parameters.

Table 4. The questionnaire proposed for contextual adaptability. Adapted from [47].

Responder	Background	Objective parameters that can affect the contextual adaptability and degree of importance of the parameter and potential to contextual adaptability (scale of 1 to 5). 1: very low, 2: low, 3: medium, 4: high, 5: very high.																			
		Harmony between the existing building and surrounding buildings in terms of color, texture, facade style and skyline					Proportion and aesthetics on visual integration between the existing building and other buildings in terms of height, human scale, dimensions and size					Adaptability of the existing building with its surroundings in terms of building materials and attention to local characteristics of the area					Projective unity of the landscape				
		Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high
A	PhD/ Architecture					*					*				*					*	
B	Master/ Architecture				*					*					*						*
C	PhD/ Architecture					*					*			*					*		
D	Master/ Civil					*					*				*						*
E	Master/ Civil				*						*					*				*	
F	PhD/ Construction management				*					*						*					*
G	PhD/ Architecture				*					*					*					*	
H	PhD/ Architecture			*						*						*				*	
I	PhD/ Civil			*					*						*						*
J	Master/ Construction management					*					*				*					*	

Responder	Background	Easy access to the site and routes					Functional architectural forms and combination of structure and architectural form					Ability to convert or dismountable the part of the building form to change the function of the building					Ability to overcapacity and moving the building elements				
		Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high
A	PhD/ Architecture					*				*						*					*
B	Master/ Architecture				*						*					*				*	
C	PhD/ Architecture		*								*				*					*	
D	Master/ Civil					*				*				*							*
E	Master/ Civil				*						*					*					*
F	PhD/ Construction management					*				*						*				*	
G	PhD/ Architecture					*					*					*					*
H	PhD/ Architecture				*					*						*					*
I	PhD/ Civil				*						*				*					*	
J	Master/ Construction management					*					*					*					*

Responder	Background	Cultural unity of the landscape					To revive the urban identity					Interaction of natural and cultural issues					The integration of the building with the cultural landscape					Potential to harmony
		Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	Very low	Low	Medium	High	Very high	
A	PhD/ Architecture					*				*						*					*	5
B	Master/ Architecture				*						*					*					*	
C	PhD/ Architecture					*				*				*						*		
D	Master/ Civil					*			*							*					*	
E	Master/ Civil					*					*				*						*	
F	PhD/ Construction management					*					*					*					*	
G	PhD/ Architecture					*					*					*				*		
H	PhD/ Architecture					*					*				*					*		
I	PhD/ Civil					*					*					*				*		
J	Master/ Construction management					*					*				*						*	

Note: Potential for harmony (scale of 1 to 5), 1 (very low), 2 (low), 3 (medium), 4 (high), 5 (very high). Satisfaction level (scale of 0 to 1), 0.00 (very low), 0.25 (low), 0.5 (medium), 0.75 (high), 1 (very high). * shows the degree each participant has considered for each objective parameters.

Table 5. The parameters of the value functions.

Indicator	Unit	x_{max}	x_{min}	R	J	q
I_1	kWh/(m^2·year)	92.77	104.55	387	0.19	3.64
I_2	litre/(m^2·year)	24,887	26,636.84	435,000	0.009	3.64
I_3	litre/(m^2·year)	2.24	3.42	815	0.009	0.97
I_4	(tons/m^2)	1	2.68	4250	0.000009	1.89
I_5	kg/(m^2·year)	1.36	2.56	1250	3753	2.35
I_6	(%)	50	100	157	18.67	0.68
I_7	kg/(m^2·year)	212.16	272.49	3740	34.45	2.85
I_8	£/(m^2·year)	98.33	106.73	55.46	0.52	0.84
I_9	Richter	6	4	354	10	0.7
I_{10}	hour	3	2	13	4	0.8
I_{11}	Points	5	1	4.12	4.50	3.10
I_{12}	Points	5	1	4.21	4.78	3.26
I_{13}	w/m^2k	0.5	0.2	2.1	0.5	0.6
I_{14}	dB	0.5	0.33	9.246	1.79	0.3
I_{15}	%	5	2	2.1	1.6	3.5
I_{16}	Points	5	3	4.55	4.31	3.08

3. Case Studies

The two tallest modular residential buildings in the world were built in London, "Ten Degrees Croydon" and "Apex House". They are both energy-efficient modular residential towers [48]. These buildings followed the Building Research Establishment Environmental Assessment Method (BREEAM), which is the longest-established method of assessing, rating and certifying the sustainability of buildings.

Both case studies were subjected to a detailed BREEAM sustainability assessment from conception to completion. However, some limitations have been recognized for BREEAM, including very exact requirements, complicated weighting arrangement, marketing relevance, compliance cost and privatization of the Building Research Establishment (BRE) that may have a commercial standpoint [49]. In contrast, the MIVES-based sustainability assessment system has been selected and applied to these case studies as it has some advantages over and above the BREEAM. These advantages include that it is attainable for all stakeholders, plus that weights and priorities align with the sensitivity of all stakeholders. It also considers the most relevant indicators of the system under consideration.

The MIVES method can be integrated with other decision-making methods such as AHP, Delphi, MCS, and PBE, etc. MIVES has been used in previous design and construction studies from various past projects relating to sustainability assessment including environmental, economic and social aspects, making it a proven assessment method. This method reduces subjectivity in decision making and integrates economic, environmental and social factors. The MIVES model has been selected as the most appropriate model for decision making in this paper because of its features such as reducing subjectivity in decision making and increasing flexibility and alternative comparisons. Table 6 shows the characteristics of the two case studies in London

Table 6. Characteristics of two case studies in London. Adapted from [48].

Building Name	Height (m)	Floors	Number of Residents (Capacity)	Gross Floor Area (GFA) m²	Material	Use	Height Ranking for Case Studies
Ten Degrees Croydon	135.0	44 and 38	1365	41,819	Core: Reinforced concrete Columns: Steel Floor spanning: Reinforced concrete	Residential	World's tallest modular tower
Apex House	82.8	29	580	16,602	Steel frames and concrete floors	Student accommodation	Europe's second tallest modular tower

3.1. Case 1: Twin Residential Towers (Ten Degrees Croydon), London

Ten Degrees Croydon is located at 101 George Street, Croydon, London, CR0 1EH, UK. It comprises twin residential tower buildings, 44 and 38 stories high, comprising 546 homes. This development includes the world's tallest residential modular building. Tide Construction and Vision Modular Systems created the 135 m high scheme by manufacturing the buildings in a controlled factory environment. The developer and manufacturer completed project construction in just over two years. This is half the time it would have taken to erect the buildings using traditional construction methods [50]. Figure 3 shows the Ten Degrees Croydon buildings.

Figure 3. Ten Degrees Croydon towers [51,52].

The project took 39 months from conception to completion, and it reduced embodied carbon by 40% with a dramatic drop in construction waste. In addition, quality control was much more effective compared to traditional construction methods [53].

This project produced around 80% less waste than traditional methods, employing fewer onsite workers and providing greater design certainty plus a total cost reduction [54].

The scheme consisted of over 1526 modules, fully completed inside to include kitchens and bathrooms, transported to site, ready for installation.

The buildings were erected as two connected towers that are offset from one another and include a cafe and other spaces that can house small retail outlets, going some way to providing spaces for cultural and social uses. Residents can also enjoy other shared facilities such as a podium garden, lounges and communal spaces, roof top terraces, gym amenities, residents' lounges, games room, yoga room, private dining rooms and event rooms. The homes are a mix of one, two and three bedrooms and other facilities within the buildings include full concierge services.

3.2. Case 2: Apex House, Wembley, London

Apex House is the second tallest modular building in the world. This building is located on Fulton Road, Wembley, London, HA9 0TF, UK. It comprises 679 prefabricated modules with over 560 rooms and most components were fitted prior to arriving on site. Once there, the modules were assembled, and the building was erected within 13 weeks. Apex House was constructed to house students, and it has 28 floors with a total height of 90 m. Prefabrication components with energy efficiency systems were used to obtain an excellent BREEAM rating. The modules were made from steel frames and concrete floors, which were connected to each other and to the slip-formed concrete core after being craned into position; they look like shipping containers.

The modules' weight varies from around 12 to 17 tons and larger modules are fitted at the corners of the tower. Services can be connected between modules, such as the water supply and waste pipes, electrics and so forth. Figure 4 shows Apex House [55,56].

Figure 4. Apex House [57,58].

The module components are mostly filled with fire protection materials and internal finishes. The windows are fitted with external walls which are made of glass-fiber-reinforced concrete (GRC) cladding panels [57]. The units are delivered entirely waterproof so that, once they are assembled in position, further work can take place to complete the units. The modules were then connected to all the site services such as electrical power, water supply and so forth. The commissioning process was then completed to ensure that all services, such as the heating, hot and cold water system, firefighting system and so forth, were all working properly.

Most of the student modules are the correct size and these were delivered outside peak hours because they were so large [54]. The building uses a combined heat and power system [58].

4. Quantification of Indicators and Calculation of Value Functions for the Study Cases

Table 7 shows important features of study case 1 (Ten Degrees Croydon) and study case 2 (Apex House). Results from the parameters of the value functions related to study cases are presented in Table 8.

Table 7. Important features of study case 1 (Ten Degrees Croydon) and study case 2 (Apex House).

Indicators	Unit	Amount for Study Case 1 (Ten Degrees Croydon)	Amount for Study Case 2 (Apex House)
I_1: Net electricity consumption	kWh/(m^2·year)	104.55	92.77
I_2: Hydrocarbon consumption	liter/(m^2·year)	24,887.10	26,636.84
I_3: Water consumption	liter/(m^2·year)	3.42	2.24
I_4: Material consumption	(tons/m^2)	1	1

I_5: Total waste	kg/(m²·year)	2.56	1.36
I_6: Reused and recycled material	(%)	98	96
I_7: CO_2 equivalent	kg/(m²·year)	212.16	272.49
I_8: LCC	£/(m²·year)	106.73	98.33
I_9: Increased earthquake resistance	Richter	4.5	4.5
I_{10}: Increased fire resistance	hour	2.5	2.5
I_{11}: Ease of assembly for components	Points	3	4
I_{12}: Social interaction	Points	5	5
I_{13}: Increased thermal comfort	w/m²·k	0.5	0.2
I_{14}: Increased acoustic performance	dB	0.50	0.33
I_{15}: Daylight efficiency	%	4	3
I_{16}: Contextual adaptability	Points	5	5

Table 8. Results from the parameters of the value functions.

Indicator	Unit	$S_{i.x}$	V_i
I_1	kWh/(m²·year)	98.66	1
I_2	liter/(m²·year)	25,761.97	1
I_3	liter/(m²·year)	2.83	1
I_4	(tons/m²)	1.84	0.5
I_5	kg/(m²·year)	1.96	1
I_6	(%)	75	0.98
I_7	kg/(m²·year)	242.32	1
I_8	£/(m²·year)	102.53	1
I_9	Richter	5	0.3
I_{10}	hour	2.5	0.4
I_{11}	points	3	0.96
I_{12}	points	3	0.25
I_{13}	w/m²k	0.35	1
I_{14}	dB	0.41	0.58
I_{15}	%	3.5	0.08
I_{16}	points	4	1

Regarding the final phase of MIVES, the sustainability index (SI) of each case study is calculated using Equation (3) as follows:

$$\mathrm{SI} = \sum_{i=1}^{i=\mathrm{N}} \alpha_i \, . \, \beta_i \, . \, \gamma_i \, . \, v_i \, (S_{i.x}) \quad (3)$$

α_i, β_i and γ_i: The weights of every requirement, criteria and indicator.
V_i ($S_{i.x}$): The value of the alternative x in relation to a given indicator i.
N: The total number of indicators.

5. Results and Discussion

The results obtained from the sustainability assessment of Ten Degrees Croydon (case study 1) and Apex House (case study 2) are given in this section. This evaluation is illustrated in Table 1. The indicator values and function and weight allocations are as follows. The indicators are quantified for both cases based on the formulas given in Section 2.3. The indicator measurements are presented in Table 5. After quantifying the indicators, the results are presented in Table 9. Excluding the SI value of each case, the satisfaction value of requirements (VR), value of criteria (VC) and value of indicators (VI) were obtained and are shown in Table 9. These values form the factors for the decision-making process.

Table 9. Values of requirement (VR), criteria (VC) and indicator (VI) for each case study.

Values	Ten Degrees Croydon	Apex House
VR_1	0.80	0.74
VR_2	0.6	0.58
VR_3	0.85	0.78
VC_1	1	1
VC_2	1	0.97
VC_3	0.3	0.12
VC_4	0.6	0.58
VC_5	0.98	0.85
VC_6	0.25	0.15
VC_7	0.79	0.82
VC_8	1	0.97
VI_1	1	1
VI_2	1	1
VI_3	1	1
VI_4	0.5	0.4
VI_5	1	0.99
VI_6	0.98	0.98
VI_7	1	1
VI_8	1	1
VI_9	0.3	0.2
VI_{10}	0.4	0.3
VI_{11}	0.96	1
VI_{12}	0.25	0.15
VI_{13}	1	1
VI_{14}	0.58	0.83
VI_{15}	0.08	0.08
VI_{16}	1	0.97

Analysis of the Results

The SI results from the previous section for case study 1 and case study 2 are presented in Figure 5. This section aims to evaluate the sustainability index for the study cases to identify potential strengths and weaknesses. This confirms the properties of MIVES and the sustainability index (SI) including requirement performance for every case study shown in Figure 5.

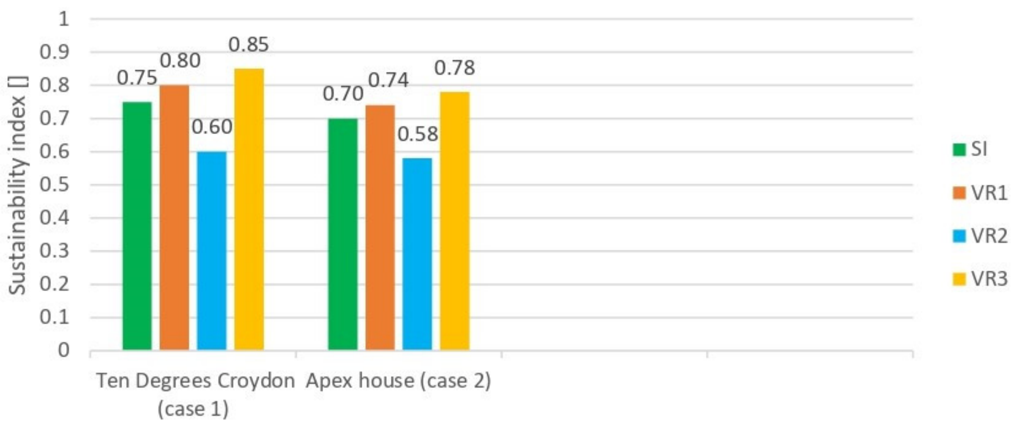

Figure 5. Total sustainability index and requirements value for study cases.

As indicated in Table 9 and Figure 5, case 1 and case 2 generally performed as follows: for case 1, SI = 0.75 and for case 2, SI = 0.70, considering that a balanced requirement's weights are set as follows: αi = 0.33, i = 1 to 3.

The values obtained for SI of these study cases are as follows: SI ≥ 0.75. It is worth mentioning that the value of social requirement (VR_3) for these case studies had a relatively high performance (for case 1, VR_3 = 0.85 and for case 2, VR_3 = 0.78). This result may be due to the design team prioritizing social aspects over other sustainability aspects.

In terms of the environmental requirement (VR_1), the case studies obtained the following values: case 1, VR_1 = 0.80, case 2, VR_1 = 0.74. According to Table 9, the performance was high for some indicators such as VI_1, VI_2, VI_3, VI_7, VI_8, VI_{13} = 1, whilst VI_{15} obtained a very low value (cases 1 and 2, VI_{15} = 0.08).

The performance of the reused and recycled material indicator (I_6) was relatively high for both cases (case 1 and case 2, VI_6 = 0.98). This is because the reuse of components in prefabricated systems is significantly high.

The value of economic requirement (VR_2) for both case studies were as follows: case 1, VR_2 = 0.60 and case 2, VR_2 = 0.58. These results show that both projects are relatively more expensive compared to traditional construction.

There are also some limitations to the MIVES model such as lack of a digital application to assist decision-makers. In addition, when there are a large number of indicators, the weighting and ranking process within the system will be more difficult. Regarding the limitations of this research, it should be highlighted that both case studies were selected in London as these buildings were the tallest modular towers although this does not allow a good comparison with modular residential buildings in other cities.

In general, the results show that the MIVES-based approach has been applied successfully to both case studies and it has the potential and capacity to be employed for a wide variety of other projects. This paper proves that the MIVES-based approach can help decision-makers and allows the design and construction team to quantify various options as objectively as possible and to identify the strengths and weaknesses of all options.

6. Concluding Remarks

The MIVES-based model is adopted in this paper to assess the sustainability index of precast modular high-rise buildings. The model was calibrated to evaluate the sustainability of two residential modular buildings in London. Since these buildings are modular, sustainability results obtained by the MIVES approach differ from results in traditional buildings. Some of the factors, which are different in modular buildings, can be highlighted as follows:

- Modular tower buildings are usually built faster. Typical construction is usually 20 to 60% shorter than traditional construction.
- Design and construction costs are usually lower compared to conventional construction models because most work takes place within a controlled factory environment.
- The quality and precision of products and construction in modular buildings are usually higher.
- General sustainability in modular buildings is usually improved as less waste is generated.
- Site safety is enhanced as most components are made in a controlled factory environment, which is not affected by adverse weather conditions.
- Road congestion is alleviated as the workforce is smaller and fewer materials are delivered onsite. This reduces road traffic and therefore improves local air quality.
- The modular buildings in the case studies demonstrated some of these results compared to traditional buildings. For example, for Ten Degrees Croydon, there was a 30% saving in construction time, 80% reduction in construction waste and 40% reduction in CO_2 equivalent. Apex House obtained savings of 80% in construction time, 90% reduction in construction waste and 40% reduction in CO_2 equivalent.

The MIVES approach for modular case studies proves that it is suitable to be used in this case for the following reasons:

- To quantify the sustainability of modular residential buildings objectively.
- To identify strengths and weaknesses that would allow the design and construction team to implement improvement measures.
- To complete analysis and determine the elements (weights and indicators) that control the sustainability index in these buildings.
- To compare indicators against each other and prioritize them as potential factors affecting sustainability assessments.

Results from applying the MIVES model, developed for both case studies, also highlight the following points:

- Both buildings achieved high social requirement (R_3) performance values ($0.78 < R_3 < 0.85$).
- Both buildings obtained low economic requirement (R_2) performance values ($0.58 < R_2 < 0.60$). This was particularly the case for the economic indicator I8 ($VI_8 = 1$), which accounts for LCC during the design, manufacturing and construction phase.
- The SI performance is 0.75 and 0.70 for Ten Degrees Croydon and Apex House, respectively. In MIVES, the SI performance ranges from very low (0), to low (0.25), medium (0.50), high (0.75) and very high (1.00). This shows that both modular study cases achieved a high value within the SI performance range.
- These results are similar to the results obtained in the BREEAM for these buildings in the case study and received an excellent certification grade.

Therefore, it can generally be concluded that the assessment results for both modular buildings achieved a high-energy efficiency rating plus improved quality standards and high safety levels, with reductions in cost, waste generation, CO_2 emission and construction time.

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Abbreviations

C1	Consumption
C2	Waste
C3	Emission
C4	Cost
C5	Safety
C6	Sense of belonging to a place

C7	Comfort
C8	Aesthetics
dB	Decibel
DS	Decreased S-shape
DCx	Decreased convexly
DL	Decreased linear
DCv	Decreased concavely
ICv	Increased concavely
GFA	Gross floor area
IS	Increased S-shape
I1	Net electricity consumption
I2	Hydrocarbon consumption
I3	Water consumption
I4	Material consumption
I5	Total waste
I6	Rate of reused and recycled material in the building
I7	CO2 equivalent
I8	LCC
I9	Increased earthquake resistance
I10	Increased fire resistance
I11	Ease of assembly for components
I12	Social interaction
I13	Increased thermal comfort
I14	Increased acoustic performance
I15	Daylight efficiency
I16	Contextual adaptability
j	The value of the ordinate for point j, where q > 1.0
M	The M variable is a factor which ensures that the value function will remain within the range of 0.0–1.0
N	The total number of indicators
q	The shape factor that defines approximation
R	The value that determines the shape of the value function
R1	Environmental requirement
R2	Economic requirement
R3	Social requirement
SI	Sustainability index
S_{max}	Maximum satisfaction
S_{min}	Minimum satisfaction
VI	The total weights assigned to the indicator
VR	The total weights assigned to the requirement
VC	The total weights assigned to the criteria
αi	The weights assigned to the requirement
βi	The weights assigned to the criteria
γi	The weights assigned to the indicators
vi ($S_{i.x}$)	The value of the alternative x with respect to a given indicator i
$S_{i.x}$	The score of alternative x that is under assessment, with respect to indicator i under consideration, which is between Smin and Smax

References

1. Maleki, B.; Casanovas-Rubio, M.d.M.; Antequera, A.d.l.F. Sustainability assessment in residential high-rise building design: State of the art. *Arch. Eng. Des. Manag.* **2022**, *18*, 927–940. https://doi.org/10.1080/17452007.2022.2060931.
2. Generalova, E.M.; Generalov, V.P.; Kuznetsova, A.A. Modular Buildings in Modern Construction. *Procedia Eng.* **2016**, *153*, 167–172. https://doi.org/10.1016/j.proeng.2016.08.098.
3. Shah, S.; Mishra, A.K. Review on global practice of housing demand fulfilment for low-income group people. *NOLEGEIN J. Bus. Ethics Ethos CSR* **2018**, *1*, 5–16.
4. Cohen, M.J. New conceptions of sufficient home size in high-income countries: Are we approaching a sustainable consumption transition? *Hous. Theory Soc.* **2021**, *38*, 173–203.
5. Deluxe Modular. The Differences between Prefabricated and Modular Construction. 2019. Available online: https://www.deluxemodular.com/learning-center/modular-vs-prefab (accessed on 18 September 2019).
6. Iacovidou, E.; Purnell, P.; Tsavdaridis, K.D.; Poologanathan, K. Digitally enabled modular construction for pro-moting modular components reuse: A UK view. *J. Build. Eng.* **2021**, *42*, 102820.
7. Lawson, R.M.; Grubb, P.J.; Prewer, J.; Trebilcock, P.J. *Modular Construction Using Light Steel Framing: An Architect's Guide*; The Steel Construction Institute: Ascot, UK, 1999; pp. 1–105.
8. Yu, Y.; Chen, Z. Rigidity of corrugated plate sidewalls and its effect on the modular structural design. *Eng. Struct.* **2018**, *175*, 191–200. https://doi.org/10.1016/j.engstruct.2018.08.039.
9. Stern, D. Steel-Framed Modular Construction for High-Rise Hotels. 2017. pp. 1–12. Available online: https: //www.hotel-online.com/press_releases/release/steel-framed-modular-const ruc-tion-for-high-rise-hotels-what-you-need-to-know (accessed on 29 November 2017).
10. Jin, R.; Hong, J.; Zuo, J. Environmental performance of off-site constructed facilities: A critical review. *Energy Build.* **2020**, *207*, 109567. https://doi.org/10.1016/j.enbuild.2019.109567.
11. Thomson, J. Modular construction: A solution to affordable housing challenges. *Cornell Real. Estate Rev.* **2019**, *17*, 90–97.
12. Lawson, R.M.; Ogden, R.G.; Bergin, R. Application of Modular Construction in High-Rise Buildings. *J. Arch. Eng.* **2012**, *18*, 148–154. https://doi.org/10.1061/(asce)ae.1943-5568.0000057.
13. Lawson, R.M. *Building Design Using Modules*; The Steel Construction Institute, Ascot, UK, 2007.
14. Lawson, R.M.; Ogden, R.G.; Pedreschi, R.; Popo-Ola, S.; Grubb, J. Developments in prefabricated systems in light steel and modular construction. *Struct. Eng.* **2005**, *83*, 28–35.
15. Lawson, R.M.; Ogden, R.G.; Popo-Ola, S. Design Considerations For Modular Open Building Systems. *Open House Int.* **2011**, *36*, 44–53. https://doi.org/10.1108/ohi-01-2011-b0006.
16. Taylor, S. Off-Site Production in the UK Construction Industry—A Brief Overview. *J. Health Saf. Exec.* **2009**. Available online: https://www.buildoffsite.com/content/uploads/2015/04/HSE-off site_production_june09.pdf (accessed on 9 June 2009).
17. Velamati, S. Feasibility, Benefits and Challenges of Modular Construction in High-Rise Development in the United States: A Developer's Perspective. Doctoral Thesis, Centre for Real Estate, Massachusetts Institute of Technology: Cambridge, MA, USA, 2012.
18. Khalfan, M.M.A.; Maqsood, T. Current State of Off-Site Manufacturing in Australian and Chinese Residential Construction. *J. Constr. Eng.* **2014**, *2014*, 164863. https://doi.org/10.1155/2014/164863.
19. Han, Y.J.; Zhu, W.Z. The development of modular building in China. In Proceedings of the International Conference on Applied Mechanics, Electronics and Mechatronics Engineering (AMEME2016), Beijing, China, 24–25 April 2016; pp. 204–207.
20. Jiang, L.; Li, Z.; Li, L.; Gao, Y. Constraints on the Promotion of Prefabricated Construction in China. *Sustainability* **2018**, *10*, 2516–2517. https://doi.org/10.3390/su10072516.
21. Teo Ai Lin, E.; Ofori, G.; Tjandra, I.; Kim, H. Framework for productivity and safety enhancement system using BIM in Singapore. *Eng. Constr. Archit. Manag.* **2017**, *24*, 1350–1371.
22. CIC (Construction Industry Council). Offsite Housing Review. 2013. Available online: http://www.cic.org.uk (accessed on 23 March 2019).
23. Navaratnam, S.; Ngo, T.; Gunawardena, T.; Henderson, D. Performance Review of Prefabricated Building Systems and Future Research in Australia. *Buildings* **2019**, *9*, 38. https://doi.org/10.3390/buildings9020038.
24. Goodier, C.I.; Gibb, A.G.F. Future opportunities for offsite in the UK. *Constr. Manag. Econ.* **2007**, *25*, 585–595.
25. Smith, R.E. *Prefabricated Architecture: A Guide to Modular Design and Construction*; John Wiley & Sons: Hoboken, NJ, USA, 2010.
26. Boafo, F.E.; Kim, J.-H.; Kim, J.-T. Performance of modular prefabricated architecture: Case study-based review and future pathways. *Sustainability* **2016**, *8*, 558.
27. Hosseini, S.A.; de la Fuente, A.; Pons, O. Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: A case study in Bam, 2003. *Sustain. Cities Soc.* **2016**, *20*, 38–51. https://doi.org/10.1016/j.scs.2015.09.012.
28. Liao, H.; Xu, Z.; Zeng, X.J. Distance and similarity measures for hesitant fuzzy linguistic term sets and their application in multi-criteria decision-making. *Inf. Sci.* **2014**, *271*, 125–142.
29. Jato-Espino, D.; Castillo-Lopez, E.; Rodriguez-Hernandez, J.; Canteras-Jordana, J.C. A review of application of multi-criteria decision making methods in construction. *Autom. Constr.* **2014**, *45*, 151–162. https://doi.org/10.1016/j.autcon.2014.05.013.
30. del Caño, A.; de la Cruz, M.P.; Cartelle, J.J.; Lara, M. Conceptual Framework for an Integrated Method to Optimize Sustainability of Engineering Systems. *Energy Power Eng.* **2015**, *9*, 608–615.

31. Maleki, B.; Casanovas Rubio, M.D.M.; De la Fuente, A. The multi-criteria assessment of sustainable residential high-rise building design. In Proceedings of the 19th European Roundtable for Sustainable Consumption and Production (ERSCP 2019) Institute for Sustainability Science and Technology, Universitat Politècnica de Catalunya, Barcelona, Spain, 15–18 October 2019; pp. 375–383.
32. Gibson, R.B. Beyond the pillars: sustainability assessment as a framework for effective integration of social, economic and ecological considerations in significant decision-making. *J. Environ. Assess. Policy Manag.* **2006**, *8*, 259–280.
33. Pardo-Bosch, F.; Aguado, A. Sustainability as the key to prioritize investments in public infrastructures. *Environ. Impact Assess. Rev.* **2016**, *60*, 40–51.
34. Yeap, J.A.; Ignatius, J.; Ramayah, T. Determining consumers' most preferred eWOM platform for movie reviews: A fuzzy analytic hierarchy process approach. *Comput. Hum. Behav.* **2014**, *31*, 250–258. https://doi.org/10.1016/j.chb.2013.10.034.
35. Josa, I.; Tošić, N.; Marinković, S.; de la Fuente, A.; Aguado, A. Sustainability-oriented multi-criteria analysis of dif-ferent continuous flight auger piles. *Sustainability* **2021**, *13*, 7552.
36. Saaty, T.L. How to make a decision: The analytic hierarchy process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. https://doi.org/10.1016/0377-2217(90)90057-i.
37. Alarcon, B.; Aguado, A.; Manga, R.; Josa, A. A Value Function for Assessing Sustainability: Application to Industrial Buildings. *Sustainability* **2011**, *3*, 35–50. https://doi.org/10.3390/su3010035.
38. Lombera, J.-T.S.-J.; Aprea, I.G. A system approach to the environmental analysis of industrial buildings. *J. Affect. Disord.* **2010**, *45*, 673–683. https://doi.org/10.1016/j.buildenv.2009.08.012.
39. Josa, I.; Pons, O.; De la Fuente, A.; Aguado, A. Multi-criteria decision-making model to assess the sustainability of girders and trusses: Case study for roofs of sports halls. *J. Clean. Prod.* **2020**, *249*, 119312.
40. Pons, O.; De la Fuente, A.; Aguado, A. The Use of MIVES as a Sustainability Assessment MCDM Method for Architecture and Civil Engineering Applications. *Sustainability* **2016**, *8*, 460. https://doi.org/10.3390/su8050460.
41. Singh, R.K.; Murty, H.R.; Gupta, S.K.; Dikshit, A.K. An overview of sustainability assessment methodolo-gies. *Ecol. Indic.* **2009**, *9*, 189–212.
42. Berthe, A.; Elie, L. Mechanisms explaining the impact of economic inequality on environmental deteriorati-on. *Ecol. Econ.* **2015**, *116*, 191–200.
43. Joglekar, S.N.; Kharkar, R.A.; Mandavgane, S.A.; Kulkarni, B.D. Sustainability assessment of brickwork for low-cost housing: A comparison between waste based bricks and burnt clay bricks. *Sustain. Cities Soc.* **2018**, *37*, 396–406.
44. Ayres, R.U.; Van Den Bergh, J.C. A theory of economic growth with material/energy resources and demateriali-zation: Interaction of three growth mechanisms. *Ecol. Econ.* **2005**, *55*, 96–118.
45. Lee, J.; Je, H.; Byun, J. Well-Being index of super tall residential buildings in Korea. *J. Affect. Disord.* **2011**, *46*, 1184–1194. https://doi.org/10.1016/j.buildenv.2010.12.010.
46. Yao, Y. *High-Rise Housing and Social Interaction Study under Current Chinese High-Rise Residential Situation*; Rochester Institute of Technology: Rochester, NY, USA, 2020.
47. Manewa, A.; Siriwardena, M.; Ross, A.; Madanayake, U. Adaptable buildings for sustainable built environment. *Built Environ. Proj. Asset Manag.* **2016**, *6*, 139–158. https://doi.org/10.1108/bepam-10-2014-0053.
48. Thai, H.-T.; Ngo, T.; Uy, B. A review on modular construction for high-rise buildings. *Structures* **2020**, *28*, 1265–1290. https://doi.org/10.1016/j.istruc.2020.09.070.
49. Rezaallah, A.; Bolognesi, C.; Khoraskani, R. A. LEED and BREEAM; Comparison between policies, assessment criteria and calculation methods. In Proceedings of the 1st International Conference on Building Sustainability Assessment (BSA 2012), Porto, Portugal, 23–25 May 2012; pp. 23–25.
50. Rajanayagam, H.; Poologanathan, K.; Gatheeshgar, P.; Varelis, G.E.; Sherlock, P.; Nagaratnam, B.; Hackney, P. A-State-Of-The-Art review on modular building connections. *Structures* **2021**, *34*, 1903–1922. https://doi.org/10.1016/j.istruc.2021.08.114.
51. Thomas, L. The Sky's the Limit: See the World's Tallest Modular Tower in Croydon. *Building* **2019**. Available online: https://www.building.co.uk/buildings/the-skys-the-limit-see-the-worldstallest-modular-tower-in-croydon/5101741.article (accessed on 23 September 2021).
52. Al-Sallal, K. (Ed.) *Low Energy Low Carbon Architecture: Recent Advances & Future Directions*; Department of Architectural Engineering, UAE: Al Ain, United Arab Emirates, 2016.
53. Construction News. Croydon's Modular Tower. You Don't Take Chances Building a Skyscraper. 2019. Available online: https://www.constructionnews.co.uk/buildings/project-report s/101-george-street-22-05-2019/ (accessed on 10 November 2020).
54. Hough, M.J.; Lawson, R.M. Design and construction of high-rise modular buildings based on recent projects. *Proc. Inst. Civ. Eng.-Civ. Eng.* **2019**, *172*, 37–44. https://doi.org/10.1680/jcien.18.00058.
55. Gatheeshgar, P.; Poologanathan, K.; Gunalan, S.; Tsavdaridis, K.D.; Nagaratnam, B.; Iacovidou, E. Optimised cold-formed steel beams in modular building applications. *J. Build. Eng.* **2020**, *32*, 101607. https://doi.org/10.1016/j.jobe.2020.101607.
56. Vision Modular Systems. Apex House, Wembley (Student Accommodation). 2019. Available online: https://www.visionmodular.com/portfolio-item/apex-house-wembley-stu dent-accommodation (accessed on 6 August 2021).

57. Pan, W.; Yang, Y.; Yang, L. High-rise modular building: Ten-year journey and future development. In Proceedings of the Construction Research Congress, New Orleans, LA, USA, 2–4 April 2018; pp. 523–532.
58. BREEAM. Building Research Establishment Environmental Assessment Method. Available online: http://www.breeam.org/ (accessed on 23 March 2012).