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Towards a Self- sustained House: Development of an Analytical Hierarchy Process System for Evaluating the Performance of Self-sustained Houses

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Abstract

Nowadays self-sustained buildings have gained a great attention to minimize the ecological impact of buildings on the environment. Houses are one of the building types that have tremendous effect on the environment and need to be self-sustained. Their design need to encounter a holistic approach that deals with a large number of criteria. Most of these criteria are qualitative and are often in conflict with each other making decisions during the preliminary design stage a hard task for architects.

Architects need an easy evaluation method that can deal with multi- criteria and can quantify subjective data into numerical values to give the right decisions. The aim of this paper is to present a comprehensive application of Analytical Hierarchy Process (AHP)-a Multi Criteria Decision Making Method (MCDM). It can aid architects in selecting the most optimal design alternative while taking into account multiple, and even conflicting decision criteria. Herein, it will be applied for evaluating three proposed design alternatives for a self-sustained house and consequently resolving the alternatives' selection problem.

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AHP deals with complex decisions and suits the uncertainty and vagueness that characterize most of the design criteria. It uses math and psychology and can be an easy powerful tool for decision making. Basic AHP calculations will be performed using Python programming language to facilitate and automate the process.

Keywords: sustainability, self-sustained buildings, zero energy buildings, analytical hierarchy process, multi-criteria decision making.

Introduction

We are living in conditions of ecological exhaustion which is obvious in global warming, pollution and over consumption of natural resources. Buildings have massive direct and indirect impact on the environment. They use about 40% of natural resources, consuming virtually 70% of electricity and 12% of potable water, and producing between 45% and 65% of the waste disposed in landfills [1]. This is an alarming issue which needs to be addressed in architecture. Architects need to change their way of thinking regarding our environment. A radical transformation towards the concept of self-sufficient, environmentally friendly and independent living is needed.

The residential buildings have a sizable environmental foot print. The housing sector is one of the highest contributors to the degradation of the environment and the consumption of energy, whether it is from electricity or from natural resources [2]. This paper will discuss the design of self-sustainable houses.

Any architectural design process is formed of a set of decisions [3]. These decisions are sometimes not accurate as they are mostly based on the architect's knowledge, experience, expertise and other factors. In the design of a self-sustained house, decisions are also made throughout the design process. The most critical decisions are those related with the evaluation of design alternatives in the preliminary design stage. They can have far reaching impact on the final results of the building. Developing a decision making tool that evaluates early design alternatives in the design of self-sufficient houses will help to produce the best possible design alternative that can aid in solving the problem of self-sustainability and self-sufficiency in houses.

Evaluation is a complicated process. This complexity is not based only on content and volume of problem, but also uncertainty of information provided for evaluation and on the large number of criteria involved [4]. As stated in many relevant literatures, alternative's selection methods have been evolved with time and conditional changes: from using the single criterion to multi-criteria decision- making (MCDM), weighted-total method, matrix approach, vendor profile analysis (VPA), analytic hierarchy process (AHP), and multiple objective programming (MOP) [5]. Fuzzy logic approach has been recently proposed for evaluating and selection of architectural projects [6,7].

AHP-decision support system is one of multi criteria decision making methods that was originally developed by Thomas L. Saaty [8]. It is used by decision makers and researchers, because it is a simple and powerful tool [9]. It provides a rational framework for a needed decision by quantifying its criteria. In short, it is a method to derive ratio scales from paired comparisons. The input can be obtained from actual measurement or from subjective opinion such as satisfaction feelings.

Analytical Hierarchy Process (AHP) as a powerful and understandable decision making tool can be applied in the initial design phase of self-sustained houses. It deals with any number of criteria whether quantitative or qualitative through the application of mathematical calculations. This approach of AHP had found some previous applications in architecture [10-15].

In this paper the AHP method will be adopted and consequently the programming language Python will be herein used. It facilitates the analysis and selection of architectural design alternatives. Also, an exemplary evaluation and selection process applied on the design of a self-sustained house will be introduced.

1. Applied Methodology

The applied methodology, figure (1), depends on different stages beginning with an introduction of the different principles underlying the design of self-sustained houses, an overview of the analytical hierarchy process and the advantages of using it in architecture, the main and sub-criteria for evaluating self-sustained houses, an introduction to three different design alternatives for self-sustained houses and the application of (AHP) and python programming language to aid architects to select an optimal design solution.

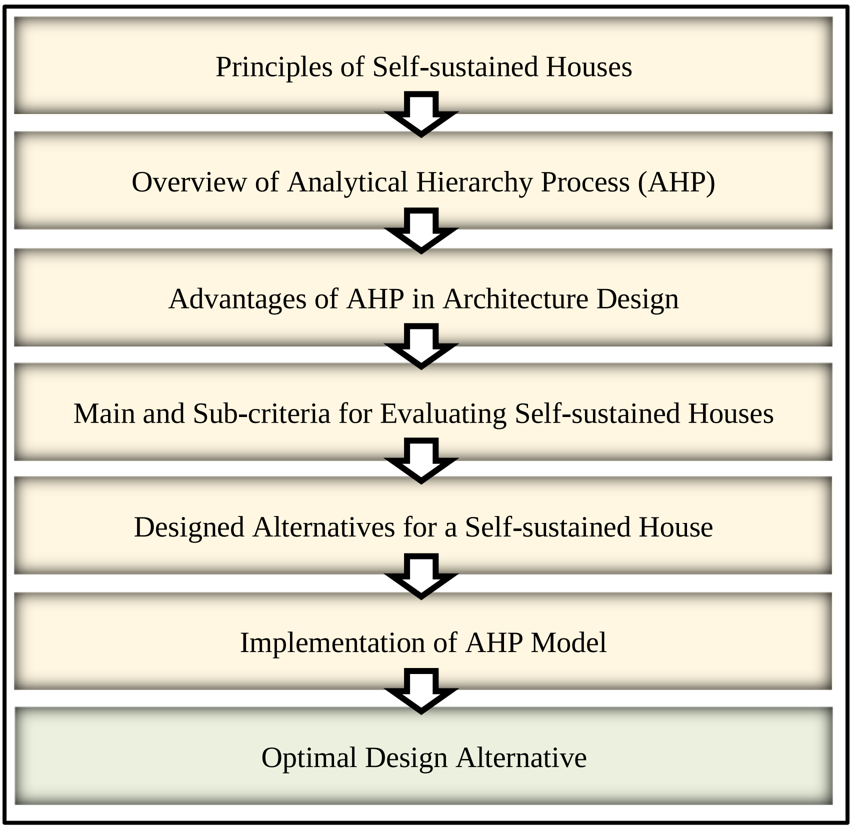


Fig.1: Applied methodology, source: authors

2. Self- sustained Houses

In convenient houses, materials, energy and even food supply comes from large energy consuming systems. On the contrary, the concept of self- sustained houses tap into local resources and recycling of waste. It depends on a closed loop for a building where everything in a building must be locally produced, reused, recycled or returned to nature to complete its natural cycle [16]. Buildings do not rely totally on outsource resources and thus decreasing any dependence on the environment.

By way of example, lighting and ventilation can be controlled by using suitable windows, indoor thermal comfort can be achieved by certain treatments in building envelope and electricity can be produced from wind turbines and solar panels integrated into the building [17-21].

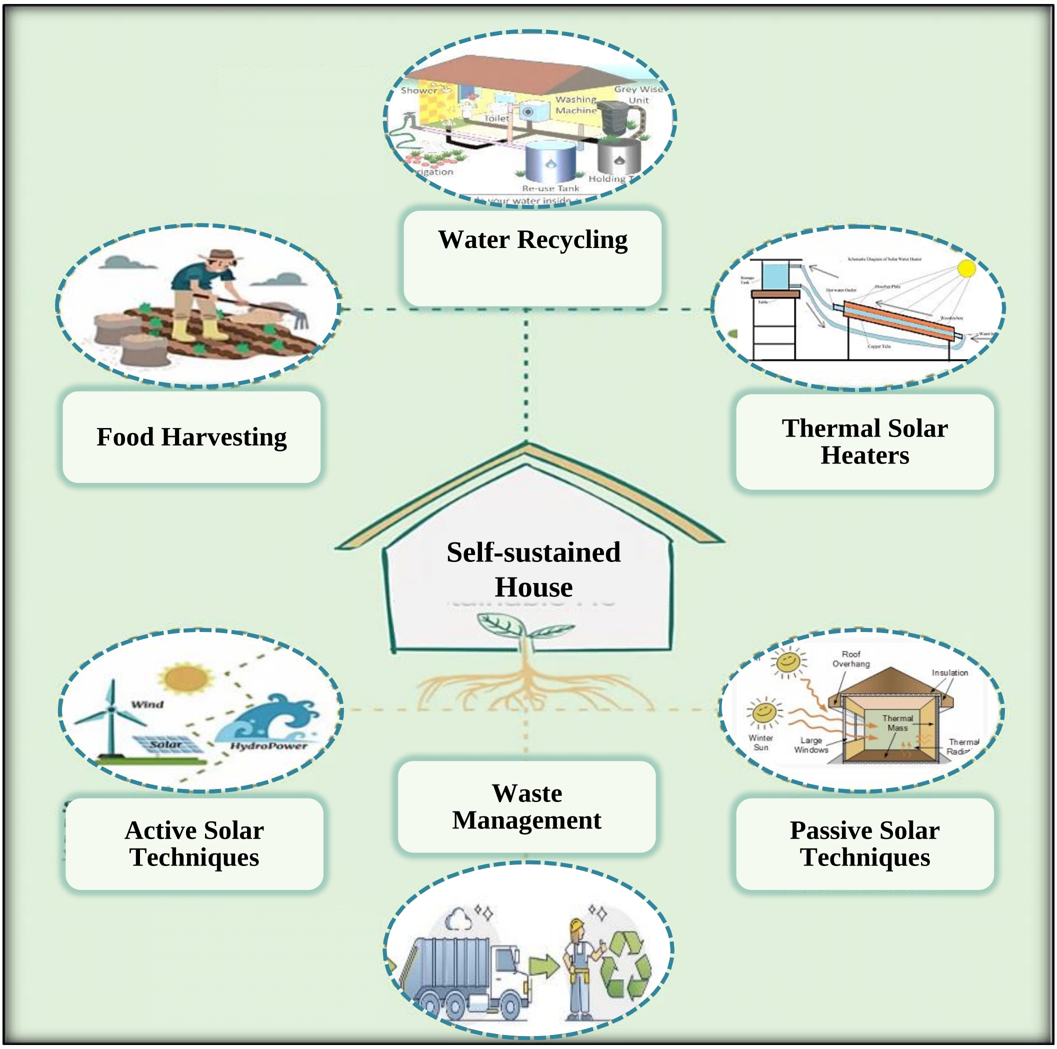


Fig. 2: Features of self-sustained houses, source: [17], modified by authors

3. Features of self-sustained houses

Self-sustained houses, figure (2), derive all inputs for functioning from nature with natural lighting, ventilation and self-generating energy. Also, they use solar thermal heaters and depend on food harvesting, water recycling and waste management. They don't rely on any external system for functioning. A brief description of the main elements in a sustainable house will herein discussed as follows:

3.1. Alternative energy

A very large proportion of the energy is used in the building sector. Also, the gases that are released from this energy use are a result of the building sector [22]. Most of the energy used is for heating-cooling the air, lighting, ventilation, powering devices and heating water. It mainly depends on fossil fuel. It is considered a finite supply of energy; therefore, a shift from fossil fuel to renewable energy sources is essential. They have the ability to renew themselves at an equal or faster rate than the depletion rate of the source. Alternative energy sources are becoming charismatic. They include wind, solar, wave, bio (organic) fuel and geothermal energies. They are safe, clean, economical, and do not harm the environment.

One of the recently applied approaches towards the design of self-sustained buildings is the net and nearly zero energy building approaches. The building does not require or requires a very low amount of energy which is obtained from renewable sources. A pre-condition to achieve this is to maximize energy saving and energy efficiency in buildings [23].

Using alternative energy in buildings can be performed by two different ways, as shown in figure (3).

3.1.1. Passive Techniques

They utilize what nature provides for free to keep buildings comfortable. This depends on the building's envelope itself to receive, store and distribute energy from renewable resources. It can be achieved through many criteria as for example: building orientation, building shape and massing, solar shading, thermal insulation, natural lighting and ventilation, thermal mass. This will be discussed as follows [24]:

- Building orientation: determines the amount of solar radiation received by the building. This can be through the roof and facades. The roof is normally well insulated; the facades have a lot of openings thus façade orientation is of a great importance.
- Building shape and massing: has a great potential to reduce building energy intensity. A compact building shape reduces building energy intensity.
- Solar shading: elements can be applied on windows internally and externally, self-shading smart glass can be used and vertical and horizontal sun screens whether static or dynamic can also be applied.
- Thermal insulation: it depends on the type and thickness of used materials. Poor thermal conductors slow the rate of heat losses and gains to and from the building.

- Natural lighting: through the use of properly designed and oriented windows, skylights and light tubes that can be provided with mirrors.
- Natural ventilation: it can be divided into single sided ventilation, cross ventilation and finally induced ventilation using courts, atria, stack and wind towers.
- Thermal mass: building mass; material of walls, floor and roof; acts as a heat sink, absorbing the heat and slowing its transfer through the building.

3.1.2. Active Techniques

They depend on external additions as photovoltaic panels and wind turbines. A photovoltaic system is composed of an array of solar panels which captures the sun's radiation and converts it into electrical energy. This system needs a controller, batteries and inverter. Wind turbines on the other hand, capture the kinetic energy of the wind through its propellers, transforming it into electrical energy. Batteries store the energy and supply it in the absence of wind. The system needs an inverter to operate [25].

3.2. Solar thermal collectors

Solar collector is a device which absorbs the incoming solar radiation, converts it into heat and transfers this heat to a medium (usually air, water or oil) [26]. It can be classified to solar water heaters and solar space heaters.

3.3. Food harvesting

Growing food is an essential part of being self-sufficient. Being able to produce food is a great way to ensure that there is no need to rely on buying food items from other places.
This can be achieved by converting the backyard of the house, the roof or the facade into a small green area for food production.

3.4. Water recycling

Water can be collected by digging up a well or collecting rainwater to be used for many things. By installing rainwater collecting system with a filtration system, this water can be used for drinking and for shower. Once this water is used, it is called grey water, yet, it is still reusable. It can be filtered and used to water vegetables.

3.5. Waste management

The sources of the environmental impact from buildings fall into two distinct categories, the energy consumption and the production and use of building materials. Self-sustained houses must be designed to minimize waste and encourage recycling to use it again in new buildings. The waste system must be turned into a closed-loop regenerative system.
Residential waste can be divided into two main categories: construction waste, generated during construction and waste from refurbishment actions or demolition of existing building

and occupants waste. The energy produced for the production of some materials from raw resources is much higher than the energy consumed for their production from recycled materials [27].

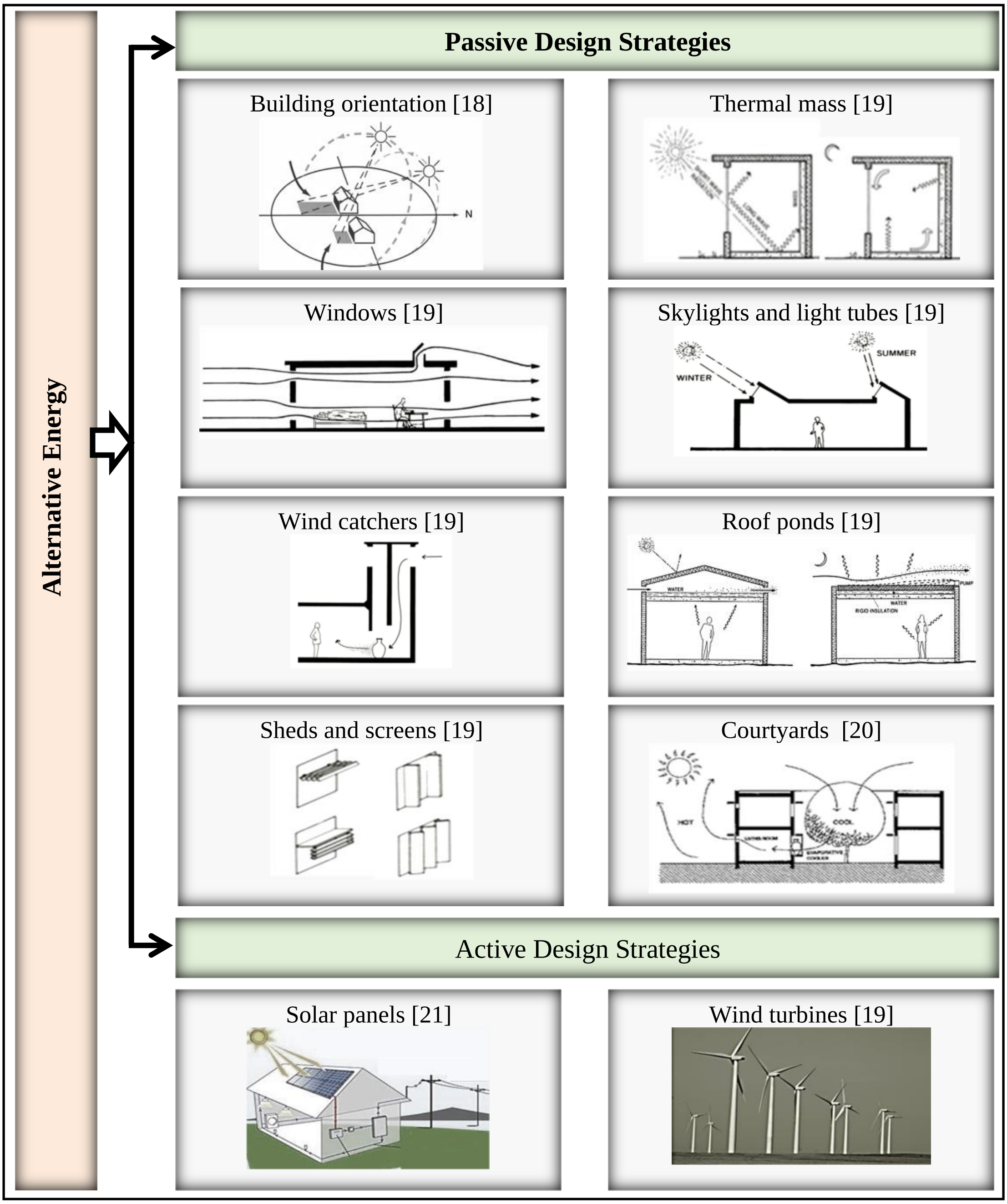


Fig (3): The use of alternative energy in buildings, source: [18-21]

4. AHP Decision Support System

When people make decisions, they provide subjective judgments based on feeling and intuition, as well as their logical understanding. The AHP is a multi-criterion decision making approach which employs a pairwise comparison procedure to obtain a scale of preferences among set of alternatives [8].

4.1. Advantages of AHP in a self-sustained house's design

Multi criteria decision making problem will be herein dealt with in the selection of an optimal design alternative for a self-sustained house. There is a set of criteria gathered in order to achieve this goal. AHP has been used as a tool at the hands of decision makers and it is one of the most widely used multiple criteria decision-making tools [4], [8], [10-15].

It is suitable for selecting the best alternative in architectural work due to the following points:

1. It is easy to understand.
2. It deals with imprecise data and it makes it possible to weight both qualitative and quantitative data in the alternative's evaluation process.
3. It is based on natural language.
4. It can deal with multi- objectives and multi- criteria which suits the case in architecture.

4.2. Developing the AHP- decision support system

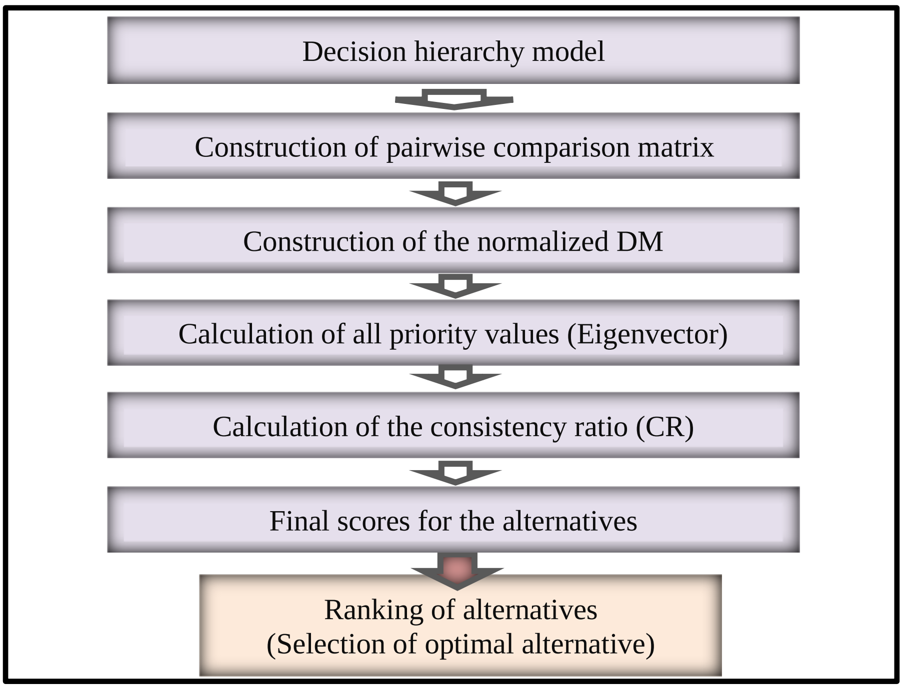


Fig. (4); Procedure of the AHP method, source: author

There are six major steps representing the procedure of implementing AHP in alternative selection process [29] , [30] , namely: development of the decision hierarchical model, construction of pairwise comparison matrix, calculation of the consistency ratio, measuring alternatives' performance and finally ranking and selection of best alternative (final decision), figure (4).

a. Developing the decision hierarchy model

The decision goal defined for the criteria in AHP is represented as a hierarchy in problem modelling, figure (4). In this phase, the decision hierarchy is divided into four levels as follows:

Level 1: The decision problem goal (at the top).

Level 2: The criteria needed to achieve the goal which is to select the optimum design alternative at the early stage.

Level 3: Sub-criteria.

Level 4: Set of alternatives.

b. Construction of pairwise comparison matrix

After choosing some of the main evaluation criteria and sub criteria, the evaluation begins with ranking them based on their importance level. This is done through pair-wise comparison of the criteria to determine the preferences between them.

A set of pair-wise comparison matrices for levels 2 and 3 of the analytic hierarchical model are created. Judgments must be done through a conversation with the decision-making team. Pair-wise comparisons are then performed between each of the matrix's two criteria. The relative importance is measured according to pair-wise comparison scales that were suggested by Saaty [8]. Construction of a judgment matrix is in the following equation, Eq. (1).

$$A = \begin{pmatrix} I_{11} & I_{12} & \dots & \dots & I_{1n} \\ I_{21} & I_{22} & \dots & \dots & I_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ I_{n1} & I_{n2} & \dots & \dots & I_{nn} \end{pmatrix} \quad \text{where} \begin{cases} x_{ii} = 1 \\ x_{ji} = \frac{1}{I_{ij}} \end{cases} \tag{1}$$

Elements I_{11} represent the relative importance of each criterion. Relative scales reflect the level of relative importance as equal, moderate, strong, very strong, and extreme by 1, 3, 5, 7, and 9, respectively. These nine points are used to show each expert's judgments for each comparison. Experts should critically set these relative scales based on their experience and knowledge.

c. Construction of the Normalized DM

After constructing the pair-wise comparison matrix, the next step is the normalization to form the matrix elements on a common scale. Every element of matrix A is normalized by dividing each element in a column by the sum of the elements in the same column to create a normalized pairwise comparison matrix $A_{\text{norm}}.where\ A_{\text{norm}}$ is the normalized matrix of $A(1)$, where $A(I_{ij})$and $A_{\text{norm}}\ (a)$ is given in Eq. (2) and (3).

$$a_{ij} = \frac{I_{ij}}{\sum_{i=1}^{n} I_{ij}}, \quad (2)$$

$$A_{\text{norm}} = \begin{pmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & \cdots & a_{nn} \end{pmatrix} \quad (3)$$

d. Calculation of All Priority Values (Eigenvector)

AHP pair-wise comparison employs mathematical procedures to transform expert's judgments into weights for each criterion. Eq. (4), can calculate the weights of decision factor i.

$$w_i = \frac{\sum_{j=1}^{n} a_{ij}}{n} \quad (4)$$

n is the number of the compared elements. The AHP measurement steps should produce weights based on the evaluator's preferences.

e. Calculation of the Consistency Ratio (CR)

The degree of inconsistency is measured by the consistency ratio [31]. If the CR of the judgment matrix A is less than 0.10, the weight results are consistent and valid and A is considered to have acceptable consistency. Otherwise, if the CR value is larger than 0.10, the matrix results are inconsistent and the elements in A should therefore be reconsidered, reviewed and improved. The consistency ratio is calculated by applying Eq. (5).

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \quad (5)$$

CI is the consistency index and is calculated by using Eq. (6), where n represents the number of criteria.

$$\text{CI} = \frac{\lambda max - n}{n-1} \quad (6)$$

RI is the related measure of a pairwise comparison matrix's degree of inconsistency and is computed by Eq. (7).

$$\text{RI} = \frac{1.98(n-1)}{n} \cdot \text{CI} \quad (7)$$

f. Final scores for the alternatives (Overall Score of each alternative)

In this step, the weight for each criterion is used to get scores for each alternative, Eq. (8).

$$\text{Final scores for the alternatives (Q)} = \sum w_i \,.\, A_V \quad (8)$$

g. Ranking of alternatives (final decision)

The set of alternatives can now be sorted by sorting the value Q in ascending order. Each alternative is given the highest priority depending on their highest.

5. Implementation of AHP Model in the Design of a Self-sustained House

5.1. Implementation procedure:

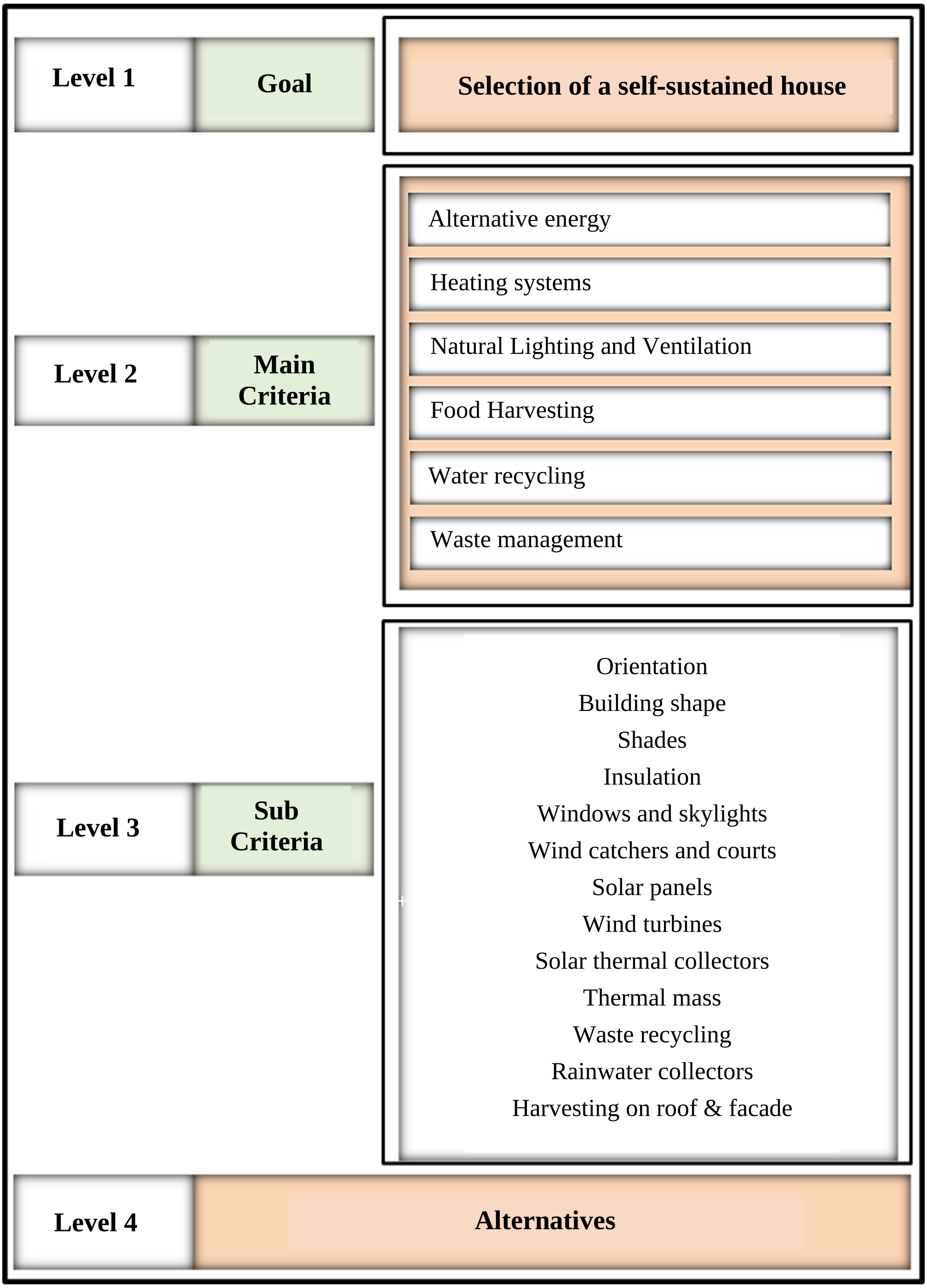


Fig. (5): Decission hierarchy of AHP for a self-sustained house

Our proposed analytical work was implemented using Jupyter Notebook version 6.0.0[32], along with Python version 3.4.0[33]. The software runs on a PC with an Intel Core i5 processor [34], and 4 GB of RAM, as well as Windows 10 Professional 64 bit as the operating system [35].

The proposed AHP model has been tested on three tentative self-sustained houses design alternatives (A, B and C) with different intentionally imposed features. They have been put forward to simplify and test the selection process. The designs were generated by the authors after several consulting meetings with expert architects and are so shaped to give different rankings for the selected criteria. Each design has a unique combination of 13 design features.

In the first stage of the AHP method, a 4-level analytic hierarchical model was constructed as shown in figure (5).

The first level is the goal of this study, which is to select the optimal design alternative for a self-sustained house. The second level represents the six main criteria namely: alternative energy, heating systems, natural lighting, natural ventilation, food harvesting, and water recycling and waste management. The third level then shows the detailed composition of the six major criteria being sub divided into 13 sub-criteria namely: orientation, building shape, shades, insulation, windows and skylights, wind catchers and courts, solar panels, wind turbines, solar thermal collectors, thermal mass, waste recycling, rainwater collectors and food harvesting on roofs. Afterwards, the last level of the decision hierarchy comprises the three proposed design alternatives for an environmentally self-sustained house. They are then ranked to determine the optimal design based on the selected criteria.

After constructing the decision hierarchy, a pair-wise comparison matrix was performed between each of the matrix's two criteria as discussed before.

The next step following the pair-wise comparison matrix is the normalization to form the matrix elements on a common scale. Then the computation of criteria weights or vector of priorities in the matrix is accomplished by applying terms of matrix algebra. After calculating the weights of each criterion, the results were rearranged in descending order of priority. Table (1), shows the weights of judgment matrix and all priority values (eigenvector) for all main criteria and sub-criteria.

Table 1: Weight computation of each sub-criterion

Criteria and Sub-criteria	**Orientation**	**Building shape**	**Shades**	**Insulation**	**Windows and skylights**	**Wind catchers and courts**	**Solar panels**	**Wind turbines**	**Solar thermal collectors**	**Thermal mass**	**Waste recycling**	**Rainwater collectors**	**Food harvesting on roofs and facades**	**Eigenvalue (Eg)**	**Weight**
Orientation	1	3	3	3	1	1	1	1	1	3	1	5	1	1.587	0.114
Building shape	0	1	1	1	2	2	2	2	2	1	2	3	2	1.452	0.105
Shades	0	1	1	1	2	2	2	2	2	1	2	3	2	1.452	0.105

Insulation	0	1	1	1	2	2	2	2	2	1	2	3	2	1.452	0.105
Windows and skylights	1	1	1	1	1	1	1	1	1	3	1	5	1	1.050	0.076
Wind catchers and courts	1	1	1	1	1	1	1	1	1	3	1	5	1	1.050	0.076
Solar panels	1	1	1	1	1	1	1	1	1	3	1	5	1	1.050	0.076
Wind turbines	1	1	1	1	1	1	1	1	1	3	1	5	1	1.050	0.076
Solar thermal heaters	1	1	1	1	1	1	1	1	1	3	1	5	1	1.050	0.076
Thermal mass	0	1	1	1	0	0	0	0	0	1	2	3	2	0.729	0.052
Waste recycling	1	1	1	1	1	1	1	1	1	1	1	5	1	0.914	0.066
Rainwater collectors	0	0	0	0	0	0	0	0	0	0	0	1	4	0.334	0.024
Food harvesting on roofs and facades	1	1	1	1	1	1	1	1	1	1	1	0	1	0.726	0.052

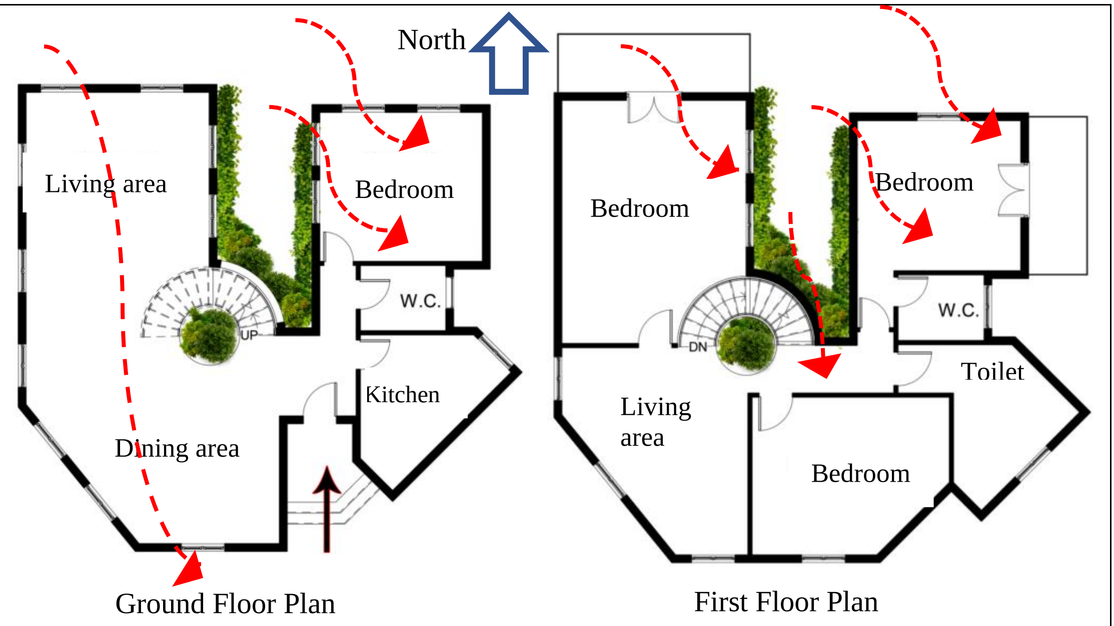
5.2. Case study

By way of example, three alternatives were designed to fit hot dry climates. The first is a traditional design, the second incorporates smart eco-technologies and the third is an underground house.

In the first two designs, the plans are composed of two floors: a ground floor consisting of living and dining areas, bedroom, toilet and kitchen. The second floor consists of a master bedroom with a private toilet and two bedrooms, living area and a bathroom. Concerning the underground house, it is composed of an underground floor with the same previous spaces. The three different alternatives are presented in table 2

Table2: Proposed design alternatives

First Alternative
Plans
The plans are traditional solutions of a house regarding natural ventilation and lighting. Main spaces face the North for natural lighting and ventilation. There are many projections in the plan in the south to cast shades. There is an outdoor court to trap the air from the North to ventilate the spaces found in the southern part of the house. Windows are well oriented to permit cross ventilation.

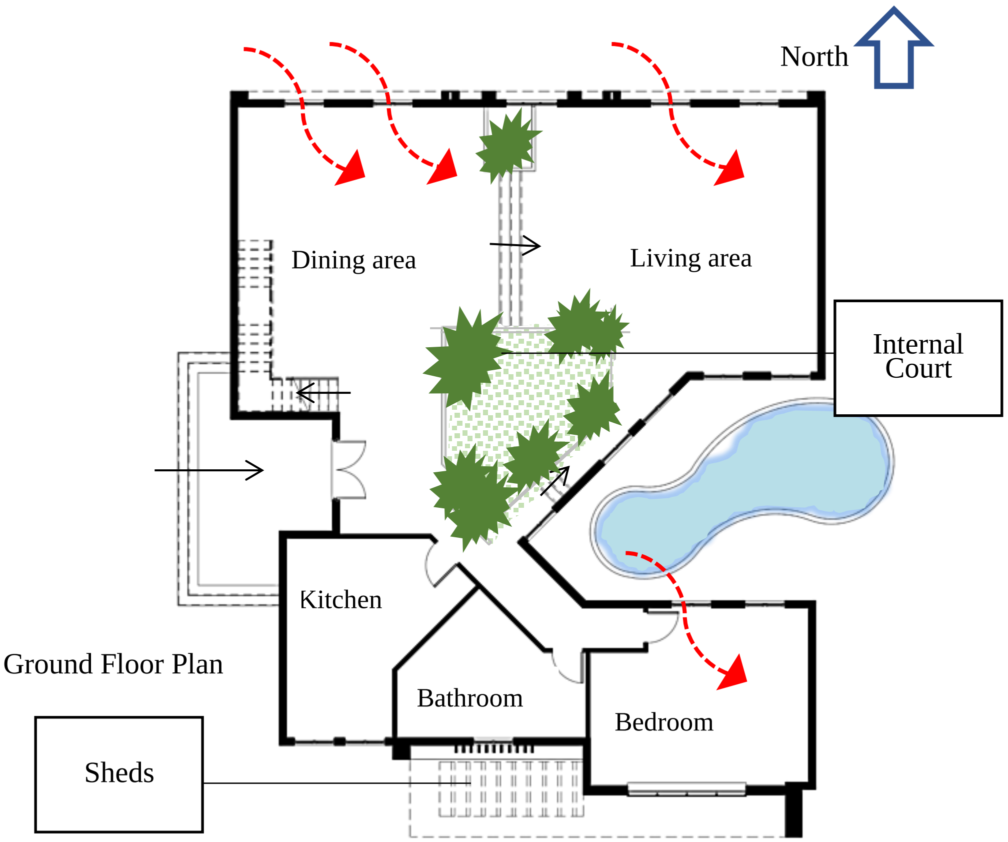


Elevations

The back elevation facing the north has openings to permit natural ventilation and lighting for the main spaces of the house. On the other hand, the main southern elevation has projections

The stair with a tilt towards the north acts as a malquaf for natural ventilation.

Second Alternative
Plans



First Floor Plan

The plans are more elaborated considering wind direction and sun path diagrams by using both, passive and active techniques.

Passive techniques include good orientation of building where living rooms and bedrooms are well ventilated and naturally lighted. Sheds on windows on the southern façade are placed. There is an internal court for cooling and ventilation and can be used for food harvesting.

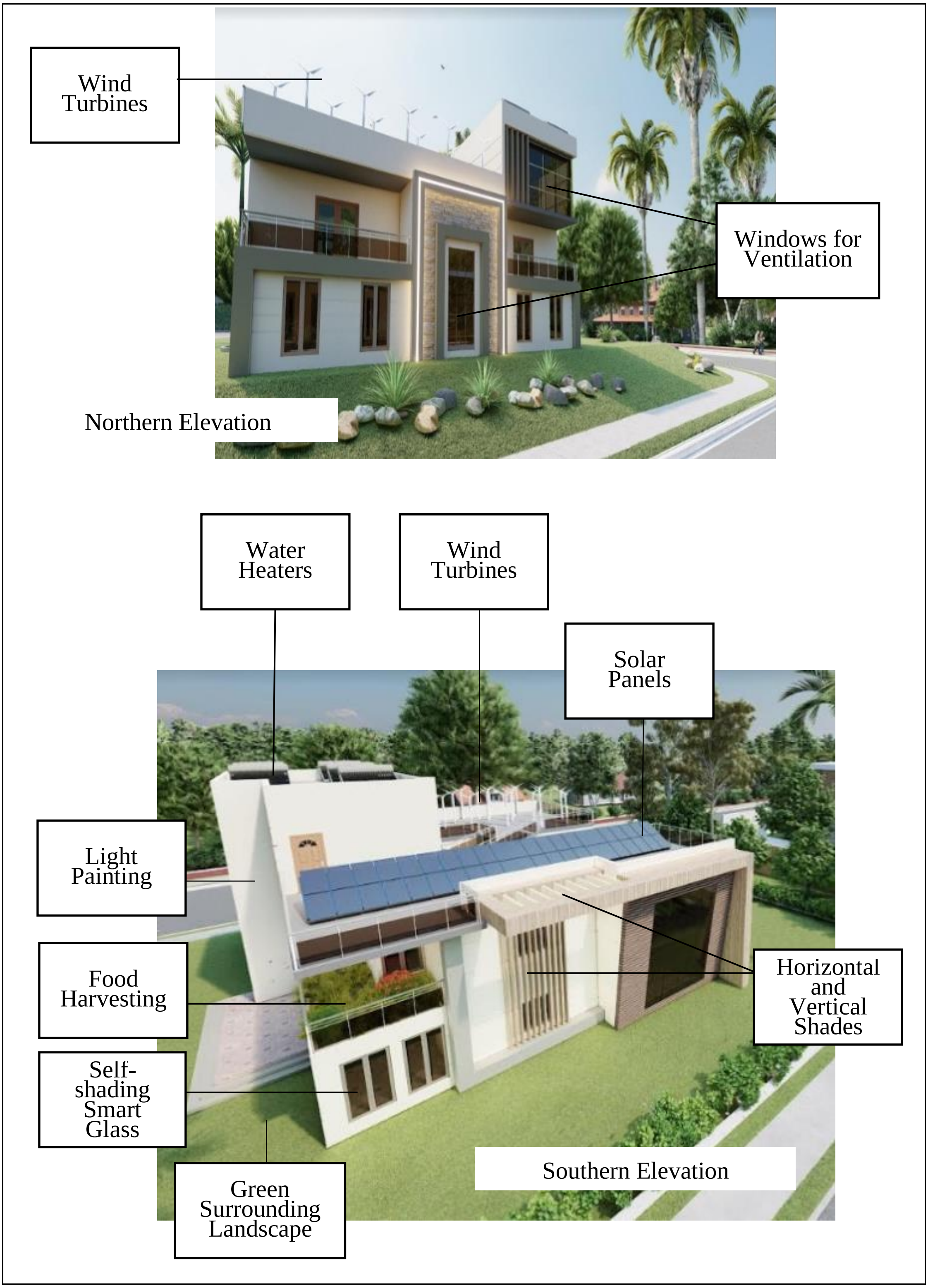
Windows are well oriented to permit cross ventilation.

Elevations

The use of light paints on the façade. Active techniques are used including the presence of solar panels on the roof and are tilted towards the south, wind turbines are also placed on the roof.

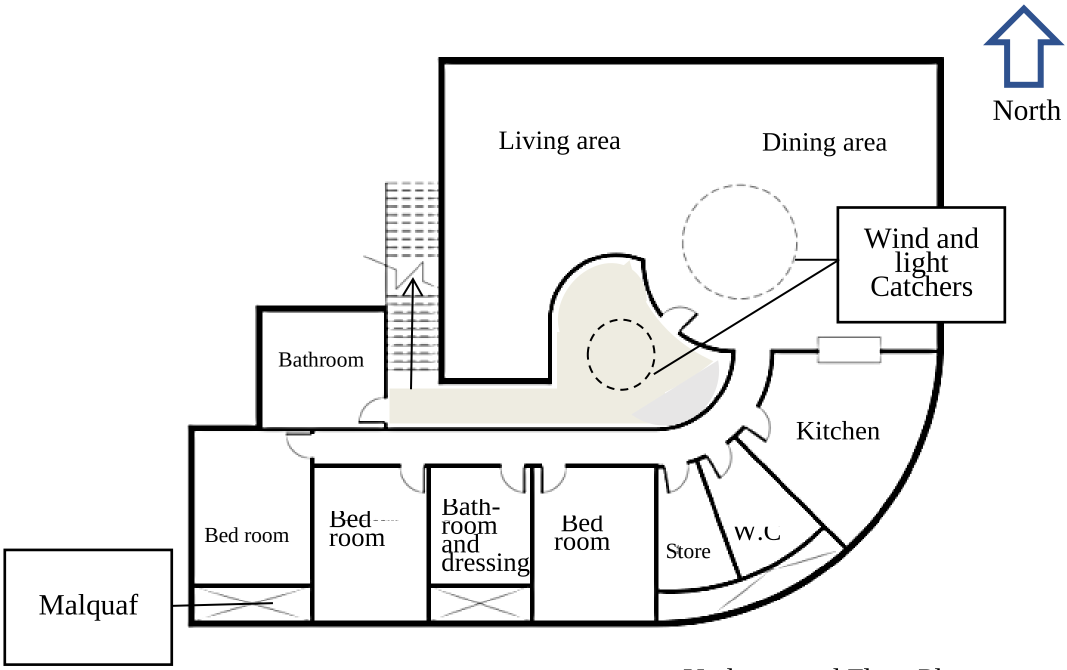
The glass used in the windows of the southern façade is self-shading smart glass.

Food harvesting is present on roof and there are solar heaters. There are water and waste treatment systems.


Wind Turbines
Windows for Ventilation
Northern Elevation
Water Heaters
Wind Turbines
Solar Panels
Light Painting
Food Harvesting
Self-shading Smart Glass
Green Surrounding Landscape
Horizontal and Vertical Shades
Southern Elevation

Third Alternative

Plan



Underground Floor Plan

The underground alternative offers natural insulation for the house through the earth. It possesses wind catchers for ventilation and light tubes provided with internal mirrors for reflecting the light to the interior.

5.3. Results

As illustrated in table3, the proposed AHP model ranked alternative (2)as the first design (optimal design alternative) with the highest overall score 2.093 , alternative (3) as the second in order with an overall score of 1.63 and alternative (1) as the third with a lowest overall score of 0.96.

Table3. Overall Score of each alternative

	Overall Score of Alternative	AHP rank
Alternative (1)	0.96	Third
Alternative (2)	2.093	First
Alternative (3)	1.63	Second

6. Conclusion

The architectural design process of self-sustained buildings is an iterative process to evaluate and select an optimum solution among different alternatives. The process has to deal with numerous criteria some of which are contradicting and of qualitative nature. The most critical phase in design is the initial phases where decisions are taken that have a significant role in ensuring the quality of the final project.

AHP method has proven to be fully compatible with dealing with architectural problems encountering many criteria and constraints. It is applicable for practical application e.g. in evaluation of self-sustained buildings' design to ultimately find an optimal design out of different alternatives.

7. Recommendations

Analytical hierarchy process is one of the essential decision support tools (DSS) that are needed to be incorporated in the architectural design process. Other tools as Building Simulation and Building Information Modeling (BIM) are currently being linked with the DSS to further improve it and make more useful improvements to the conventional design process, such as evaluating energy usage, air circulation, sound, lighting, and other factors. The created DSS tool can be improved by utilizing from all the previous tools in subsequent work together with including the viewpoint of design experts from various disciplines and/or adding new design criteria that boost performance concerning a particular discipline(s), resulting in better-coordinated design.

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