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Sustainable Building Design: A Brief Review

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ABSTRACT

Buildings are liable for the highest global energy consumption and CO_2 emission. Wider adoption of sustainable design in buildings can significantly reduce such energy consumption and CO_2 emission, along with contributing to a healthier environment, cost savings from reduced energy use, and enhanced occupant comfort. Also, the combination of active and passive design strategies is more effective in reducing energy consumption and CO_2 emissions. In this regard, and as the beginning of a recently launched wider study on adopting passive design strategies in buildings, this paper presents a brief and summarized outcomes of the initial literature review. The target is to allow a better understanding of sustainable design practices and extract various active and passive design strategies/features. A total of 59 design strategies have been identified: eight active strategies, 18 passive strategies for lighting and 33 passive strategies for heating, cooling and ventilation purposes. Such strategies/features include: solar panels, shading devices, roof garden and wind towers. These do not use any externally supplied energy, but improve building energy profile. The strategies will be further refined/adjusted for a questionnaire survey to identify their degree of actual practice in building design, which will be feeding into the wider study of adopting passive design strategies. The findings provide a reference for construction professionals and practitioners, pave the route for further academic research, and allow policy makers further insights.

1. Introduction

Construction sector is the largest energy-consumer, as buildings consume about 40% of global energy, and emit over 30% CO_2, e.g., for heating, air conditioning and lighting [1]. Increasing rate of infrastructure development in general, and building construction in particular, has led to higher energy consumption. Moreover, the rate of new building construction is greater than demolishing rate, which causes increased CO_2 emissions that further affect climate change [2]. The adoption of sustainable development principles in building design (i.e., sustainable design, or SD) can considerably help this situation, with much reduced energy consumption and CO_2 emissions [3]. SD is an architectural design strategy that uses environment-friendly techniques and buildings components, as well as energy conservation futures [4]. Focusing on such strategies, building design

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can target enhancing energy efficiency during operation of buildings [5]. SD has a number of advantages, including being cost-effective, improving indoor air quality, and reducing environmental impact by lowering energy consumption and CO_2 emission [6]. The use of SD concepts through passive and active design strategies can help in reducing energy usage and CO_2 emissions [7].

Passive design strategies/techniques minimize the use of carbon-based fuel energy throughout the lifespan of a structure. This is achieved by reducing the amount of fuel needed to generate electrical energy [8]. On the contrary, active strategies employ electrical-mechanical equipment to meet human needs for a comfortable environment [9]. External wall insulation and the use of high-performance glass, solar hot water heating, and low-energy fluorescent (LED) lighting are just a few examples. Also, more efficient and effective tactics in building design approach that takes advantage of the local climate to meet some, or all, of the heating, lighting, ventilation and cooling, and needs of the occupants can reduce energy use and CO_2 emissions [10, 11]. As a result, SD must be practiced to meet and improve the occupant needs.

Several studies have reported their outcomes on adopting technologies that help to reduce energy consumption and relevant CO_2 emissions through the use of SD design practices [12, 13]. However, there is a scarcity of research that identifies common SD technologies and/or strategies for specific climate zone [14], e.g., in hot and humid countries like Indonesia, Thailand, Malaysia, Philippines and Brunei. Identifying such SD strategies/technologies is important, because it allows decision-makers to focus on and practice common technology/strategies, to increase the chances of successful adoption of SD. Moreover, these technologies and strategies can serve as benchmarks for determining whether the necessary knowledge and resources are available to meet the requirements for SD. Such practice will gradually increase the wider practice of SD strategies/technologies, and help to move toward a more climate responsive and effective construction industry through reduced energy consumption and CO_2 emissions.

A study was launched in Brunei Darussalam to meet this knowledge gap using multiple methods of literature review and questionnaire surveys, to identify: (1) available SD strategies/technologies focusing on passive design strategies/technologies; (2) sets of their challenges and motivators, along with relevant strategy for wider use; and (3) developing a framework for adopting SD strategies in buildings. However, this paper summarizes the initial outcomes of the first batch of literature review, focusing on an understanding of SD strategies/techniques, and extracting various active and passive design strategies. These outcomes will serve as the basis for further analysis and refinement for a questionnaire survey targeting to examine the degree of use of the identified strategies/techniques in actual practice. The outcomes are also expected to updating existing literature, increasing awareness among construction industry practitioners and policymakers, and provide relevant materials for further study. The remainder of the paper presents the methodology deployed, summary of findings, and concluding observations.

2. Methodology

A structured literature review (SLR) was conducted in academic listings of Science Direct, Taylor & Francis, and Emerald Insight, published within the last two decades, i.e. from 2001 to 2020. The SLR assisted in extracting the bias-free knowledge of sustainable building design in hot, dry and humid countries through a systematic process [15], and consolidating the knowledge from extant literature only on sustainable design features [16]. The keywords "residential building," "energy efficiency," "low carbon building," "passive design," and "optimization” were used in searching the databases. These keywords were chosen to represent the research focus area (i.e. ‘residential building’) and attributes/targets of sustainable design, to sufficiently cover the scope of the search.

To increase the overall search quality, additional individual searches were also conducted in each database. After the database search was done, the results were recorded on coding sheets to keep track of which records were chosen and which were rejected, as well as to classify the articles that were chosen. A total of 261 publications were initially identified, with duplicates (of keywords and titles) removed during the first stage of screening. In the second stage, publications that were unrelated to the topic were excluded, resulting to 195 publications.

Further screening focused on ensuring that the individual papers deal with sustainable design in hot, dry and humid countries, which narrowed down the selection to 156 publications. Therefore, the criteria used for selecting these 156 papers are: they are on residential buildings, and deal with sustainable design in hot, dry and humid countries, like Nigeria, Malaysia, Singapore, Indonesia, and India. These 156 papers were then processed for content analysis. Each paper was systematically read and individual sustainable design features/strategies were extracted, listed and tallied. Such systematic thematic content analysis led to eight active strategies (Table 1), 18 passive lighting strategies (Table 2) and 33 passive heating strategies (Table 3). While these 156 papers formed the core of this study, only a few key references are used in this paper due to space limitations.

3. Literature Review

3.1 Sustainable Design (SD): Background

SD targets minimum negative impacts of buildings/structures on the environment [18]. It improves building performance by increasing the health of the building occupants, while also lowering environmental impacts [19].It uses reduced non-renewable resources, eliminates waste, and generates productive environments [20]. Sustainable buildings are designed to influence positively, on their occupants and the environment, throughout their lifetimes. The benefits of SD are summarized as follows:

1. Environmental protection

SD approaches maintain biodiversity and ecosystems, and reduce CO_2 emissions. They also alleviate the harmful consequences on the environment originating from development [18,19]. These are achieved by protecting existing habitats, planting trees around a new site, and choosing sustainable materials to lower carbon footprint.

2. Reduced waste and energy consumption

Reduced energy consumption and waste generation are achieved, for example, through adopting solar energy, arranging centralized water and heating distribution systems, and using renewable materials [23].

3. Improvement of occupant health and well-being

Healthy buildings boost healthy lifestyles of their occupants, as environment responsive buildings allow for increased air and water quality [21, 22].

3.2 Elements of Sustainable Design (SD)

Architectural and interior design elements, as well as electrical, mechanical and structural engineering components, are all incorporated into sustainable design [26]. The five key characteristics of sustainable design are:

1. SD requires thorough planning and design, since early decisions have the biggest influence on energy efficiency, passive solar design, daylighting, and natural cooling [27].
2. SD is more of a building concept than a prescriptive construction style [28].
3. SD not necessarily to be sophisticated or expensive than traditional construction [29].

4. Successful SD requires integrated design, where each component is considered as a part of a larger whole [24, 27].
5. SD focuses on human health, energy conservation, ecological system elements, building envelope design, and preservation of occupant health and well-being; and these are achieved through interior design[31].

3.3 Principles of Sustainable Design (SD)

Sustainably designed buildings aim reduced environmental impact by maximizing energy and resource efficiency [11]. Application of SD principles vary in different countries or climate zones. Therefore, it is important to first grasp the guiding principles of SD:

1. Understanding the location: SD starts with a deep grasp and identification of the characteristics of the location [32]. Understanding the location helps in the selection of design principles. It is critical to adapt to the location and use locally available materials, e.g., the solar orientation of a building, environmental protection, public transport accessibility, and the use of finishes and furnishings [33].
2. 'Identifying the relationship between the building and the natural environment', such as the urban/rural location and the connection between inside and outside, aids in the creation of effective design [34].
3. Recognize natural processes: In nature, there is no waste, and one organism's by-product produces food for another. The built environment can be brought to life by recreating natural cycles and processes and making them apparent [35].
4. Understanding environmental impact: Mitigating the negative impact of buildings requires a comprehension of the environmental impact by accessing to the location, the embodied energy and toxicity of materials, and the energy efficiency of design, materials, and construction practices [36].
5. Recognizing co-creativity: Creating synergy in building design requires collaboration between architects and/or consultants, engineers, and other professionals, as well as listening to the views of local populations [12].
6. People understanding: SD must consider a diverse variety of cultures, races, faiths, and habits of the people who will use and inhabit the built environment [19]. This requires awareness and empathy for the needs of the people and their community.

3.4 Sustainable Design Strategies

Sustainable design strategies are of two types: active strategies and passive strategies. Active design strategies use externally supplied and purchased energy, e.g. natural gas or electricity, to generate and distribute energy for occupant comfort [20]. These strategies rely on mechanical system components, such as air conditioning, heat pumps, radiant heating, heat recovery ventilators, and electric lighting [37]. Active lighting systems are used to illuminate the rooms, while active cooling and heating systems regulate temperature [38]. The performance of such strategies depends on lighting type, location of light, and duration of use. Careful consideration of electro-mechanical equipment, building's attributes, and occupants' comfort requirements is necessary for optimal performance [39]. The active strategies are convenient for achieving desired comfort conditions, but consume a significant amount of energy, which incur higher financial costs and pollution generation [38]. The SLR identified eight such active design strategies/techniques, as shown in Table 1. Two of these strategies are used for lighting and the other six are used for heating, cooling and ventilation purposes.

Table 1
Active Design

Strategies
1. Electric lightning/LED
2. Solar tubes devices
3. Heat pumps (Ground and air source)
4. Air conditioning (HVAC system)
5. Solar panel device
6. Wind turbines
7. Operable louvers or blinds
8. Cool or green roof

Some active techniques do not consume active energy, e.g. cool/green roofs, louvers/blinds and wind turbines. They are built to improve the building's energy profile, e.g. cool/green roof, or utilize wind and/or solar energy, e.g. wind turbines are run by wind energy and the energy generated by the movement of the wheels are deployed to do other works, like lifting loads or water to a height. A school in Singapore installed solar tubes with light diffusers to maximize natural daylighting, reduce the need for artificial lighting and minimize heat gain, creating a more comfortable and energy-efficient learning environment [39]. Other techniques, like heat pumps that utilize cooler underground temperatures for air conditioning in Thailand, significantly reduce energy consumption compared to traditional systems, providing both economic and environmental benefits [40].

Passive design strategies are principles that take advantage of the building envelope's design and features to reduce energy demand by maximizing or minimizing heat losses and gains [20]. Passive techniques make use of what nature provides for free in order to maintain occupants' comfort in buildings without relying on purchased energy [37]. Passive strategies are built into a building's design to work with the site's natural features (such as sun and wind patterns) to offer natural (i) lighting, and (ii) heating and cooling of areas throughout the year [41]. The goal of both passive and active measures is to improve lighting and heat movement into and out of occupied spaces, with the ultimate goal of thermal comfort in mind [42]. Table 2 shows such 18 sustainable passive design strategies that are used for lighting, while Table 3 shows 33 strategies used for heating, cooling and ventilation purposes.

Table 2
Passive Design for Lighting

Strategies:
1. Light wall colours/paints
2. Skylight strategies
3. Translucent walls and roofs
4. Skylights
5. Window glazing materials
6. Building orientation, e.g. East or West
7. Atrium glass roofing system
8. Glass window
9. Light shelves
10. Overhangs
11. Clerestories with reflective roof paint
12. Window placement orientation, e.g., N/E, S/W
13. Building shape, such as U-shape/L-shape
14. Window glazing materials, e.g., low-e/double/triple glazing
15. Window to wall ratio, e.g., low (N/E) or high (S/W)
16. Shading devices, e.g., external or internal for solar control
17. Use of natural light, e.g., reflective blinds, light shelves
18. Building shape, such as U-shape/L-shape

Table 3
Passive Design for Heating, Cooling and Ventilation

Strategies:
1. Trombe wall systems
2. Sunspaces
3. Building corridors design pattern e.g., shallow floor plan
4. Courtyard or Green spaces
5. Air vents for ventilation
6. Overhangs
7. Exterior wall insulation
8. Verandas
9. Interior shading devices
10. Evaporative cooling system
11. Solar chimney
12. Wind catcher or wind tower
13. Night flushing for window control (window)
14. Insulation material for wall, roof, and ceiling
15. Thermal mass, e.g., PCM, aerated concrete
16. Utilize surrounding landscape design
17. Use of site conditions
18. Double skin façade system
19. Light colour exterior paint
20. Buffer spaces, e.g., double-skin, the atrium, glazed balconies
21. Building shape and orientation
22. Roof design type, such as pitched, flat, or plant roofs
23. Natural ventilation through the window
24. Green wall
25. External insulation material
26. Heat reflects insulation sheet
27. Natural ventilation for wind controls, e.g., stack, or cross
28. Reflective roof design type
29. Double-layer high-gable roof type
30. White-painted roof type
31. Window shutter
32. Solar reflective walls
33. Operable window device

Although all of these strategies are commonly referred to as passive, some may involve a combination of active and passive energy. They are either designed to enhance the thermal performance of the building, such as green walls that utilize small shrubs like mosses, or powered by mechanical means such as overhangs and double façade system to reduce heat gain, and save energy consumption. For instance, in Malaysia, the use of green wall not only provided insulation and reduced the urban heat island effect, but also created an aesthetically pleasing façade and reduced energy consumption by approximately 18.3% [20].

Passive techniques are commonly used to improve the thermal and visual comfort of a building by enhancing the design of its envelope [43]. To create a comfortable thermal environment, heat avoidance and building cooling are key components of a passive strategy. Heat transfer can be minimized by employing techniques such as building orientation, self-shading, vegetation-based shadowing, and building-based shadowing in densely populated areas [44]. Another option is to optimize the material's heat capacity, heat transfer, and surface features, such as texture and colour [45]. For example, the use of reflective paint can reduce indoor temperatures, and improve illuminance levels when it is applied to walls with the appropriate orientation [40]. Convective cooling is another method utilized to cool a building, which involves the use of space vents, roof vents, and wall vents, among other things. In Malaysia, for instance, the use of roof vents can improve air temperature by about 3°C to 6°C with 50% opening and 2°C to 10°C with 100% opening roof angles [43]. Since the passive technique attempts to optimize environmental conditions, the benefit is that it cuts the amount of energy necessary to condition the room while also lowering CO_2 emissions [46]. However, the effectiveness of these techniques may vary depending on the surrounding conditions of the building which can impact the comfort settings of the room and potentially lead to suboptimal or excessive conditions [47].

4. Concluding Observations

Progressive increases in energy consumption and CO_2 emission are argued to have an increasingly significant impact on the global threat of climate change. However, this impact can be significantly reduced by adopting sustainable design practices in buildings. As such, under a wider study on adopting sustainable design strategies in buildings, this paper summarizes the preliminary outcomes of a review of relevant segment of literature, and extracted various active and passive design strategies. The emphasis is on the 59 passive design strategies, that can effectively enhance the surrounding environmental conditions, ensuring efficient energy consumption, and reduced CO_2 emissions, while also meeting the comfort requirements of buildings. The list of identified features will be further refined and adjusted by consulting a group of expert building designers and will be processed for a questionnaire survey to determine their degree of practice. This will be followed by another questionnaire survey identifying the challenges, motivators and strategies for wider adoption of passive design, and eventually develop a framework for wider adoption of passive design strategies. The study aims to provide practitioners with recommendations such as promoting ongoing training on passive design and encouraging early collaboration and integrated design. Policymakers can also benefit from recommendations and insights, such as providing financial incentives for passive design, raising public awareness, and investing in research and development.

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