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Amphibious Architecture: A Biomimetic Design Approach to Flood Resilience

Hope Ameh *, Lidia Badarnah and Jessica Lamond

School of Architecture and Environment, College of Arts Technology and Environment, University of the West of England, Bristol BS16 1QY, UK; lidia.badarnah@uwe.ac.uk (L.B.); jessica.lamond@uwe.ac.uk (J.L.)
* Correspondence: hope.ameh@uwe.ac.uk

Abstract: Amphibious buildings use the buoyancy principle in the design of their foundation systems to mitigate flood impact. In some cases, amphibious buildings are fitted with mechanical systems that further aid the buoyancy element to temporarily raise the building and guide its descent to natural ground level. These mechanical systems require external operation, preventing the amphibious building from passively responding during flood events as is one of the requirements of a robust flood mitigation measure. Additionally, buildings in flood environments are often left with stains on the exterior facade from floodwater contamination from sewage and chemicals, among others. This paper distinguishes three main components of an amphibious foundation: the buoyancy element, vertical guidance post, and structural sub-frame, and discusses their functionality. The natural world provides solutions to tackling environmental issues such as flooding. When systematically studied and transferred, nature can inspire innovative ideas for functional and sustainable designs for the built environments. Although there are many existing designs and a small number of constructed amphibious buildings, there are very few studies that discuss how the designs are derived, and even fewer on a framework emulating natural systems for transfer into amphibious building design. In that context, this research uses the biomimetic transfer process to abstract relevant biological systems, illustrating their potential for transfer into amphibious foundation design. The aim is to understand how these biological systems passively and continuously respond and adapt to their environment. Organisms such as the Venus flower basket, giant kelp, and red mangrove, among others, are discussed, to understand how they perform the identified functions. The steps of the biomimetic transfer process are used to integrate functions of amphibious buildings and processes of the studied biological systems. The final output of this paper is a discussion of the ways in which these derived relationships can be adopted in amphibious building design.

Keywords: architecture; amphibious buildings; biomimetics; flood resilience

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1. Introduction

Flooding is a frequent and widespread phenomenon that has a significant impact on humans and our settlements, and mitigating its impact is a cost-effective investment in lessening future losses [1–3]. Consequently, careful consideration is needed when building in areas prone to flooding to minimise potential impacts. In recognition of this, spatial design, mitigation, and planning strategies such as “Room for the River” [4], “Making Space for Water” [5], and “aquatecture” [6] have been promoted to help communities be more resilient to flooding.

Terminologies for describing on-site property-level flood mitigation strategies vary but are typically categorised into three approaches: avoidance through building elevation; water exclusion or resistance (controlling/limiting amount of water entering a building); and water entry or recoverability (allow water entry but in a way that limits damage to building interior through careful choice of materials and design) [7]. The effectiveness of each strategy in preventing loss and damage varies depending on factors such as flood depth, frequency, and duration, as well as building design and construction techniques [8]. Amphibious architecture is a flexible avoidance through elevation strategy that provides a passive response in a flood, adapts to changing conditions in its environment over time, and is flexible enough to deal with high depths of inundation not usually experienced in an area, as well as lower and more frequent flooding. Amphibious architecture works using Archimedes' principle, which states that the buoyant force on a submerged or partially submerged object is equal to the volume of the fluid displaced by the object [2].

Biomimetics can be defined as the implementation of design principles from biology [9]. Strategies for the application of biomimetics include the examination and application of nature's materials, structural or symbolic transfer of the studied natural forms, or the interrelation of building structure with the environment [10]. Biologically inspired design (BID), also known as biomimetic design, refers to the use of biological systems as a source of inspiration to develop or improve new systems [11]. There are four identified similarity types between the source (biological systems) and the result (design) in the BID process: analogy, literal implementation, biological transfer, and anomaly [12]. Analogy is the process of looking for similarities, that is, correlations in terms of form or function, and abducting their functionality into novel designs [12,13]. Analogy is the framework for biomimetic transfer adopted in research as it considers the form, functions, and processes of the biological systems for emulation.

Architects, engineers, and designers have often looked to nature for inspiration in their designs [13]. Nature serves as a good source of inspiration because form, function, and structure in biological systems are well-integrated, owing to constant evolution over billions of years [12,14]. Many strategies exist for the application of biomimetics in building and load-bearing structure design in general. Such strategies include the examination and application of nature's materials, structural or symbolic transfer of the studied natural forms, the interrelation of building structure with the environment, and so on [10]. For example, ventilation performance of building ducts can be enhanced by mimicking the shape of joints between plant trunk and branch; furthermore, the structures of coral reefs and plants have been mimicked in architecture to reduce material use, making buildings stronger, lighter, and easier to construct [15,16]. Some bio-inspired designs include Norman Foster's Gherkin Tower (2004, London, UK), the Eastgate Centre (1966, Harare, Zimbabwe), and the Qatar Cacti Building [17]. These inspirations were necessary to solve complex building problems and create more efficient building functions. However, there is yet to be a biomimetic design transfer from nature to amphibious building design. We propose that biological systems can also be emulated in the design of amphibious buildings, based on an understanding of the characteristics of relevant biological systems, through the biomimetic transfer process.

The main components of an amphibious foundation (buoyancy system, vertical guidance posts, and structural sub-frame) serve as the (design) challenges addressed in this paper. Another challenge addressed is durability, in the context of stain and damage avoidance. Buildings in flood environments are often left with stains on the exterior facade due to the probable presence of sewage effluent, chemical or biological contaminants, or silts, sands, and soils in the floodwater. Therefore, amphibious buildings are designed with durable materials that minimise damage caused by contact with floodwater.

The literature was reviewed to provide a theoretical background for this paper, exploring previous work on amphibious architectures and the potential for biomimetic design transfer from nature to architecture. The knowledge we gained from that review provided us with a key understanding of the main features of amphibious buildings, highlighting possible areas for improvement. Limited work has been carried out on the intersectionality between amphibious architecture and nature, especially the potential for knowledge transfer from the emulation of biological systems through biomimetics. This paper addresses that knowledge gap by proposing a method for designing concepts of sustainable amphibious foundation components by studying and emulating the characteristics of relevant biological systems.

There have been many designs for amphibious buildings, as well as several bio-inspired buildings [17]. Details on the development of most bio-inspired building designs are available in the literature, including the process of abstraction of relevant characteristics from nature and transfer into design [14,18]. On the other hand, the details of the design development of amphibious buildings are not readily available. This poses difficulties in highlighting their features and design challenges. Seeking to overcome those difficulties, in this research, we employed a comparative analysis of the amphibious buildings discussed, to highlight their features and recurring components. These components were then carried forward and their functions cross-referenced across biological systems with characteristics that can be emulated in the components' designs. To date, the emulation of nature in amphibious building designs is almost non-existent, despite the many opportunities and potential for its transfer into design. This paper proposes that the biomimetic design transfer approach can inform the development of amphibious building components that are sustainable, in that they continually perform their functions without interference (passive) or interruption.

2. Flooding and Amphibious Architecture

Flooding generally occurs via a combination of events such as heavy rain, coastal storms, blocked drainage systems, and excess run-off, among others [19]. Flooding is categorised differently across countries and regions based on the prevalence, characteristics, and sources of flooding. Based on the source, flooding can be broadly categorised into river (fluvial), coastal, surface (overland flow), and groundwater flooding [20,21]. River flooding results from rivers or waterways and is usually caused by heavy rain that exceeds river capacity and causes them to burst their banks. Coastal flooding results from the sea, either through high tides, storm surges, overflowing waves crashing onto the sea front, or a combination of these factors. Surface (pluvial) flooding usually occurs after periods of heavy rainfall on saturated ground where excess water cannot drain away. Groundwater flooding results from the natural water level below ground rising well above what can be accommodated on the surface [19,21,22].

The flood characteristics that influence the extent of flood damage caused to buildings are flood depth, flow of velocity, duration, and contaminant content [23]. Flood damage has been found to significantly increase as flood level rises above the ground floor, and the longer flood water remains in contact with buildings, the more extensive the damage caused [19]. The greater the distance from the flood source, the lower the velocity upon contact with the structure and vice versa. Generally, the greater the floodwater velocity, the greater the probability of structural damage [24]. Floodwater can also be contaminated, and the contaminants can influence the water absorption characteristics of building materials used and the drying time of the materials, as well as pose health risks and affect repair costs [25]. Amphibious architecture is designed to mitigate the flood damage characteristics highlighted above, with components designed to manipulate the building's exposure to flood depth by rising and falling with water levels and thus withstand flood velocity and contaminant content.

2.1. Amphibious Architecture

Factor and Boiten [26] define an amphibious building as one that will 'adapt' to a flood situation and float as water levels rise. English et al. [27] (p. 2) define amphibious architecture as a flood mitigation strategy that allows an "otherwise-ordinary structure" to float on the surface of rising floodwater levels. Moon [28] defines an amphibious house as one that lies on the ground or on a structure above water but floats during a flood as water levels rise. Prosun [29] defines an amphibious house as a structure with a buoyant foundation, constructed on solid ground with capabilities of floating up with rising water levels. Barker and Coutts [6] define an amphibious house as a building that rests on the ground when conditions are dry but rises in its dock and floats during a flood.

2.1.1. Amphibious Foundation: Design Principles

The foundation is extremely important for the stability and lifespan of a building [30]. The foundation system is designed to support and transmit gravity and lateral loads to the ground, stabilising the structure and preventing lateral movement without exceeding the maximum stresses to the building's members [31–33]. However, the function of the foundation is not only to transfer load from the structure to the ground but also to do so safely [32]. There is a consensus in the literature that an adaptative approach to foundation engineering and design should aim to reduce flood and erosion impact while reducing the amount of material used in construction to support various loading conditions [34].

As in a typical building, the amphibious building is in two parts: the foundation and the superstructure. The foundation of an amphibious building encounters water (regularly) while the super structure (above the ground level) is typically designed to either avoid contact with water or withstand this contact through the incorporation of durable, flood-resilient materials. All structures constructed in flood zones should be constructed with such materials [35]. Contrary to typically elevated buildings that are restricted to a fixed flood level, the flexibility in the amphibious building's height means it can accommodate rising water depths and adapt to rising sea levels and land subsidence as needed [27]. The amphibious building system was originally designed to act passively, without the need for any further preparations during a flood, except in cases where evacuation is recommended [27]. However, newer methods of constructing amphibious buildings involve the incorporation of mechanical systems in design, which eliminates the passive characteristic of the original system design [36].

Several limitations to the current methods of designing foundations have been discussed in the literature. Firstly, deep foundations are restricted to either vertical- or near-vertical-axis (i.e., 0°) cylindrical piles as current drilling techniques are unable to change direction [37]. However, it has been demonstrated that increasing the angle of piles (15° and 30°) can increase their load-bearing capacity due to a larger bearing area [36]. Secondly, foundations are typically designed to anchor a structure and bear its load, while depending on other systems for other functions [34]. Thirdly, most building foundations are not dynamic and thus cannot adapt to changing environmental conditions (varying loads, soil movement, water inundation) in terms of their capacity to resist lateral movement and bear loads [34]. Foundation designs are also limited in terms of their materials. Foundation piles are typically made of wood, concrete, and steel [38]. Although steel piles support high stresses and loads, they can be subject to corrosion and damaged during soil penetration. Pre-cast concrete piles are difficult to properly cut and manoeuvre, and timber piles are limited in load-bearing capacity [38].

2.1.2. Materials

Residential buildings are constructed with different building materials, which need to be durable to survive the natural wear and tear buildings undergo as they age [39]. In the case of amphibious buildings, durable, flood-resilient materials not only ensure survival against wear and tear but also minimise staining and damage to the building fabric or prevent that staining/damage from being permanent.

The materials mostly used in the design of the three essential foundation components (buoyancy element vertical guidance posts (VGPs) and structural sub-frame) are concrete and steel. The buoyant foundation prototype is constructed with a structural sub-frame holding or containing expanded polystyrene (EPS) buoyancy blocks (buoyancy element), which attach to the base of the building [27]. The excavated 'wet dock' in the UK's first amphibious house serves as the buoyancy element in the building. The wet dock is a hollow concrete foundation made of steel sheet piling with a mesh base [40,41]. Each amphibious building of the 'De Gouden Kust' project (Maasbommel) consists of a watertight concrete hull (buoyancy element) that rests on six concrete foundation piles (vertical guidance) [26]. The buildings are attached to a steel framework for structural stability when rising [26]. An amphibious house in Thailand is designed with steel Styrofoam-filled pontoons set within the pit foundation (buoyancy element), rising vertically along steel pilings during a flood [42,43]. The FLOAT house (USA) sits on a raft foundation made of polystyrene foam coated in glass-fibre-reinforced concrete (buoyancy element), which raises the building along two steel guidance posts (vertical movement and structural stability) [43,44]. Each building in the amphibious boulevard consists of steel watertight pontoon (buoyancy element) and a steel frame, which sits on a concrete foundation slab. The pontoon and steel frames are guided by four steel vertical posts as the buildings rise (vertical movement, structural stability) [45].

Research into nature-inspired and lightweight yet sturdy and efficient materials and methods is emerging in the literature [46–49]. Materials found in living organisms, like chitin in crab and shrimp shells, casein found in milk, and biopolymers (plastics made up mostly of biodegradable materials such as cellulose, starch, and sugar), have been discovered to produce highly energy efficient and structurally sound building materials. For instance, casein, when biologically extracted and fabricated, can create a building material that is very light and biodegradable but also as hard as concrete [46]. Materials from living organisms can be engineered through advanced technology and innovative research to provide alternative solutions to those currently adopted.

2.2. Theory and Technical Aspects in Amphibious Construction

Different solutions for amphibious foundations are employed around the world, from low-cost solutions to more complicated designs by specialists that incorporate a floating foundation and vertical guidance system into the structure's design. The International Conference on Amphibious Architecture, Design and Engineering (ICCADE) [50] provided an overview of constructed amphibious buildings, some of which include the Amphibious House on the River Thames (Buckinghamshire, England), the Lift House (Dhaka, Bangladesh), the FLOAT House (New Orleans, LA, USA), and the Amphibious House Prototype (Bangkok, Thailand). These buildings are selected as case studies based on two criteria, newly constructed buildings designed on land and designed to rise in a flood, and they are discussed based on their building characteristics, construction methods, materials, and utility design.

2.2.1. Amphibious House on the River Thames, UK

This building (Figure 1) is a lightweight timber-framed structure that sits inside an excavated concrete 'wet dock' cased with steel sheet piling. The base of the dock allows water to enter and escape naturally, keeping the house afloat during a flood [40,41]. To keep the structure level and avoid horizontal movement, it is fitted with four flexible vertical guidance posts known as 'dolphins' that can stretch up to 4 m as the building rises in its dock (Figure 2). The amphibious building comprises of a boosting mechanism that supports its buoyancy system. This necessitates regular testing and maintenance of the building, irrespective of a flood occurrence.

Figure 1. Amphibious House on the River Thames Reprinted with permission from [40]. 2015, BACA Architects.

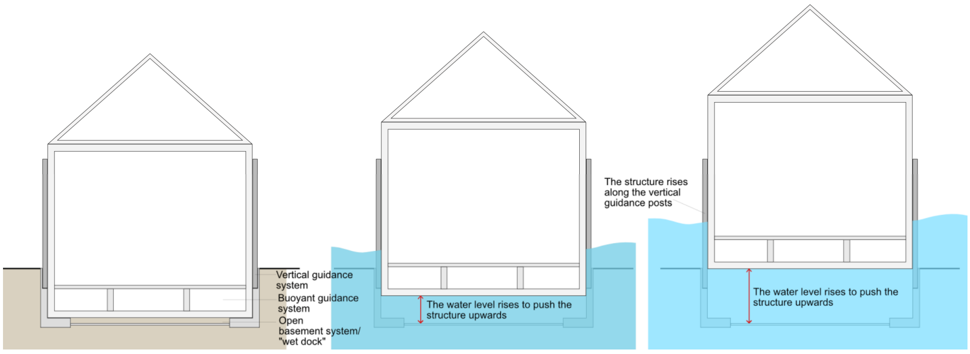


Figure 2. Diagram of the UK amphibious House showing the mechanism of adaptation.

2.2.2. Amphibious House Prototype, Thailand

This 100-square-meter prototype is made from prefabricated panels with steel frames to allow for a lightweight and sturdy structure. The building is also fitted with a prefabricated steel floatation system to lift the building up to 3 m off the ground [42]. The building sits in a 'trench' (a basement for the filling of water), with steel Styrofoam-filled pontons set within the foundation (Figure 3).

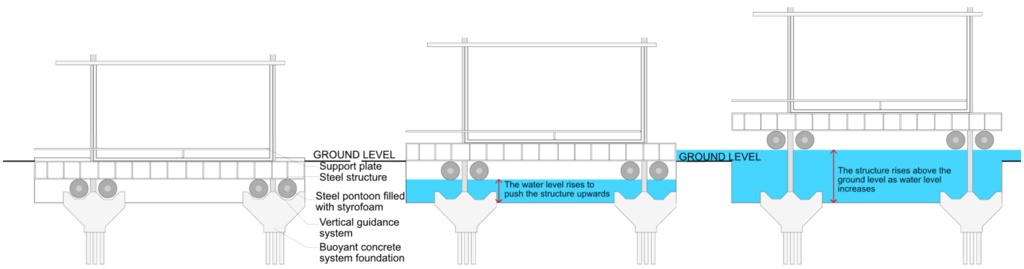


Figure 3. Diagram of the amphibious House in Thailand showing the mechanism of adaptation.

2.2.3. LIFT House, Bangladesh

Buoyancy is achieved from two different systems: one of the units consists of a hollow ferrocement structure and the other consists of a bamboo-framed foundation filled with up to eight thousand air-filled bottles, which displace enough water to lift the building (Figure 4) [29]. Both units are attached to the steel vertical guidance system, a static structure built out of brick and concrete that provides vertical guidance and stability to the two dwellings while the units float on water (Figure 5) [29].

Figure 4. Perspective view of the LIFT house. Reprinted with permission from [29]. 2011, Prosun Architects.

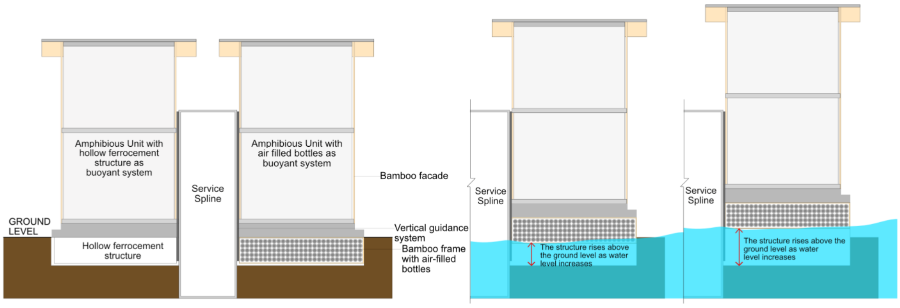


Figure 5. Diagram of the LIFT House showing the mechanism of adaptation.

From the definitions discussed above, an amphibious building must float (rise and fall in accordance with water levels), withstand strong water currents, preserve its structural integrity, and resist lateral movement. To maintain its structural integrity, an (amphibious) building must be made with durable materials and techniques to ensure its building envelope is not damaged when in contact with water. Such a building must be durable and long-lasting for it to continually survive in a flood. The amphibious foundations analysed consist of three essential components:

- Buoyancy system: The buoyancy elements that displace water to cause the building to float above the water's surface.
- Vertical guidance posts (VGPs): To restrain lateral movement so that the building can only move straight up and down.
- Structural sub-frame: A structural sub-frame installed beneath the floor framing system to support and stabilise the building while connecting the superstructure to the buoyancy elements and vertical guidance posts [51].

3. Methods

This research adopts a problem-based biomimetic approach to design in order to identify passive and sustainable approaches found in biological systems that are relevant to the research. The identified biological systems, whose characteristics can be emulated to design amphibious foundation components that float, are structurally stable and durable. Relevant biological systems were abstracted, illustrating their potential for transfer into amphibious foundation design. The aim is to understand how these biological systems passively and continuously respond and adapt to their environment and how their characteristics can be emulated in design.

The goal of experts in the field of biomimetics is to study, abstract, and transfer biological principles from nature into engineering, architecture, or art, resulting in the creation of products and processes that are sustainable [52]. Badarnah and Kadri [53] enumerate two main approaches to biomimetic design: the problem-based approach, which seeks a solution from nature to solve a problem; and the solution-based approach, inspired through the observation of nature to produce a technological design. The design process of the problem-based approach involves three domains: problem, nature, and solution. This research follows a problem-based approach to biomimetic design in the emulation and transfer of the functions of the selected living organisms into amphibious architecture. The biomimetic design process is broadly divided into the following steps: identify a problem; explore natural systems; extract features from the systems relevant to the problem; analyse strategies and principles, and abstract strategies; translate strategies into a design concept; evaluate and validate the solution; and apply the solution to solve the problem (Figure 6) [54]. The design process of the problem-based approach comprises 5 steps: challenge, functions, processes, morphology, and design. This approach forms the theoretical framework, and the steps will be discussed in more detail.

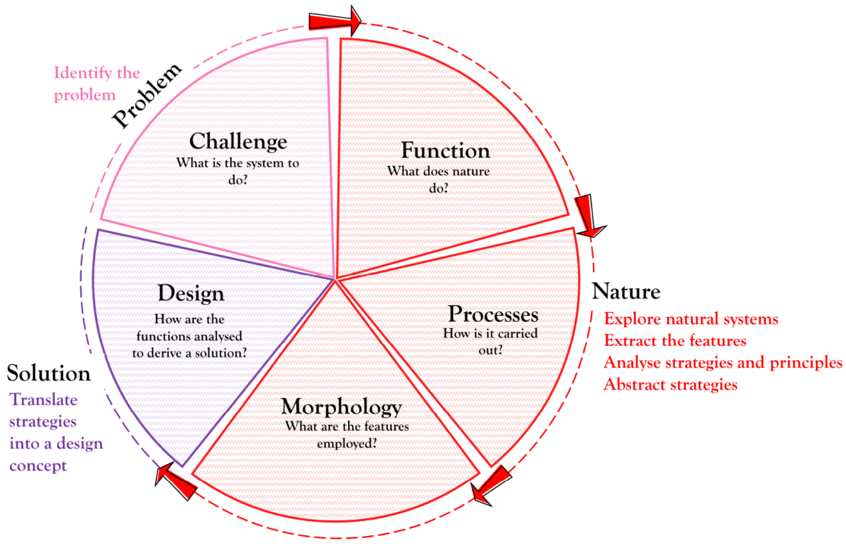


Figure 6. Diagram of the steps to the problem-based approach's design process.

The first step of the problem-based approach's design process is to identify the problem, which is achieved through a review of relevant literature and comparative analysis of selected amphibious buildings. Accordingly, a literature search was conducted using asknature, Google Scholar, architecture review websites, and official webpages (Dezeen, architecture daily, and BACA Architects). Identifying the overarching methods for designing amphibious buildings and extracting the main components of their foundations enabled us to identify the challenges that are addressed in this paper, as highlighted in Section 2. Several amphibious buildings were highlighted during the search, and three were chosen based on the following criteria: new buildings with details of the construction process available in the literature. The main components of the foundation (buoyancy system, vertical guidance posts, and structural sub-frame), affording the building buoyancy, structural strength, and stability, respectively, were utilized for a comparative analysis. Durability was another property highlighted as essential for a building's components through the review conducted. These four aspects served as our basis for identifying relevant natural systems.

The next step is to explore relevant natural systems to extract and analyse their features. In our case, those features were extracted and analysed using the next three steps of the design process (Figure 6): function (what does nature do?), processes (how is that carried out?), and morphology (what features are employed?). Relevant natural systems (with buoyancy, strength, stability, and durability) were chosen based on three criteria: passive (perform the function without interference from or reliance on another part of the organism or other organisms), static (without movement), or continuous (without interruption or cessation). Based on these criteria, the giant kelp, floating water fern, Venus flower basket, red mangrove, lotus leaf, wings of the cicada, and pitcher plant were selected as models for emulation. The next step was to translate the abstracted features into design. The proposed concepts we produced are a combination of the relevant characteristics abstracted from the emulated biological models. Based on those, this paper proposes that the biomimetic design transfer approach can inform the development of amphibious building components that are sustainable, in that they continually perform their functions without interference (passive) or interruption.

4. Models from Nature for Potential Applications

Organisms adapt to changes in their environment by applying strategies that are essential for efficiency and survival, not only in the organisms themselves but also in their structures [54,55]. Changing environmental conditions necessitate nature's development of different adaptation strategies, which occur across three main categories: physiological, morphological, and behavioural. Physiological adaptation is an organism's response to external stimuli to maintain homeostasis (balance between internal and external environments); morphological adaptation refers to a structural or geometrical feature (size, form, and pattern) that improves an organism's adjustment to a particular environment for better functionality; and behavioural adaptation refers to the action an organism takes for survival, to cope with the new conditions posed by the environment [54].

The models discussed in the following section are based on three functions of an amphibious foundation highlighted in the literature review (buoyancy, stability, and durability). The selected models embody features useful to perform these three functions while in a static position, without relying on other features in the system, and continuously without interference.

4.1. Buoyancy

Most buoyant living organisms exhibit this characteristic in motion. However, this paper focuses on organisms that exhibit buoyancy in a static position because amphibious buildings move only in a vertical direction (upwards and downwards according to water levels) and not in a horizontal direction. Bodies in water are constantly subjected to tensile stresses and drag. If a body is easily bent and stretched, then the drag on the body may be reduced and greater force of water will be required to break it [56]. Seaweeds can withstand flowing water in the following ways: Some large seaweeds have thick, strong cylindrical stipes (up to a meter long) that stiffly hold their fronds in fast flowing water [57]. Kelp, meanwhile, is a good example of a brown algae seaweed that not only manages to stay afloat on the water surface but also withstands flowing water by being flexible and extensible.

4.1.1. The Giant Kelp Model

Giant kelp (*Macrocystis pyrifera*) begins its lifecycle on the ocean floor, where root-like structures called holdfasts attach to large rocks, anchoring the kelp in place [58] (Figure 7c,e). The holdfasts give way to the strong but flexible stipe, providing support for the leaf-like blades. The upper portion of the stipe is hollow and extremely elastic, as it can stretch more than 38% of its length when exposed to wave forces (Figure 7a) [59]. The kelp also possesses hollow, gas-filled, spherical bulbs (pneumatocysts) at the end of a long, slim stem (Figure 7b). The gas content of the pneumatocysts can vary but usually contains a mixture of oxygen, nitrogen, and carbon dioxide [57]. The buoyancy of the gas-filled bulbs enables the fronds grow upright and float to the water surface to form a canopy (Figure 7c) [58,59].

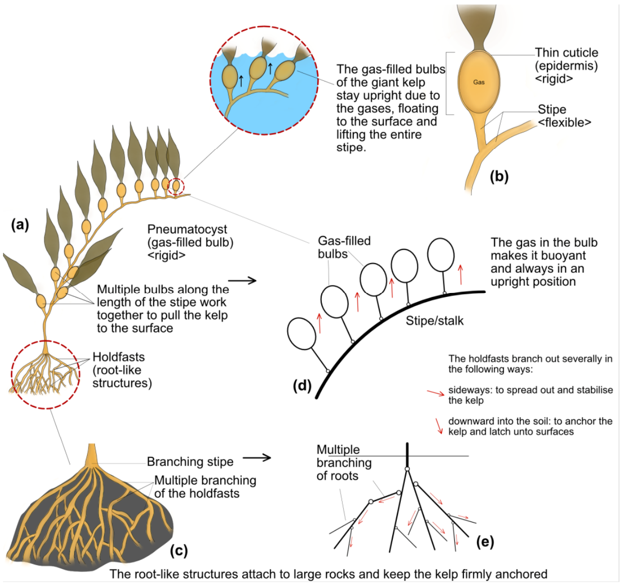


Figure 7. (**a**) Drawing of the giant kelp. (**b**) A single gas-filled bulb. (**c**) The root-like structures of the kelp. Node diagrams of the (**d**) floating bulbs and (**e**) anchoring holdfasts.

4.1.2. The Floating Water Fern Model

The floating water fern (*Salvinia molesta*) is a free-floating plant that retains pockets of air when fully submerged in water as its leaves are covered with tiny multicellular hairs [60,61]. Four hairs are connected at their terminal ends to form an 'eggbeater-shaped' structure (Figure 8a–c) [61]. This arrangement on its leaf surface not only equips it for buoyancy but also provides a water-repelling effect. Each trichome is coated with hydrophobic (water-repelling) nanoscale wax crystals, which prevent water from penetrating between the hairs [7]. The tip of each hair does not have these wax crystals, which means it attracts water molecules (hydrophilic) [60,62]. The combination of hydrophilic tips on the hydrophobic surface is known as the "Salvinia paradox" [7,60].

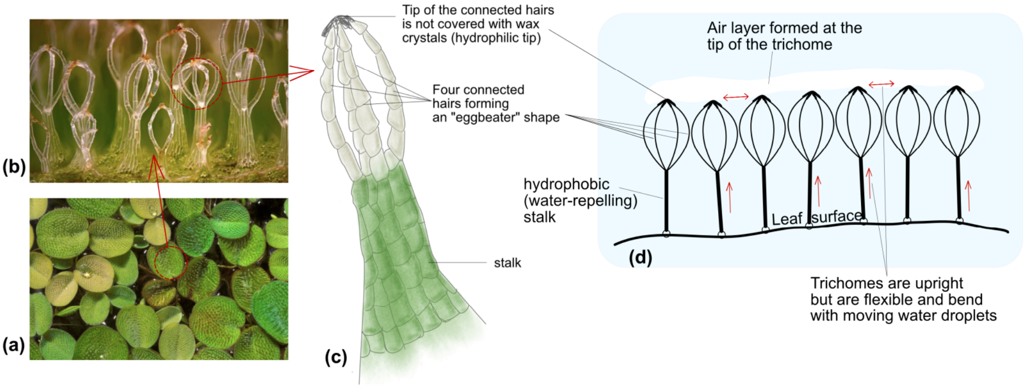


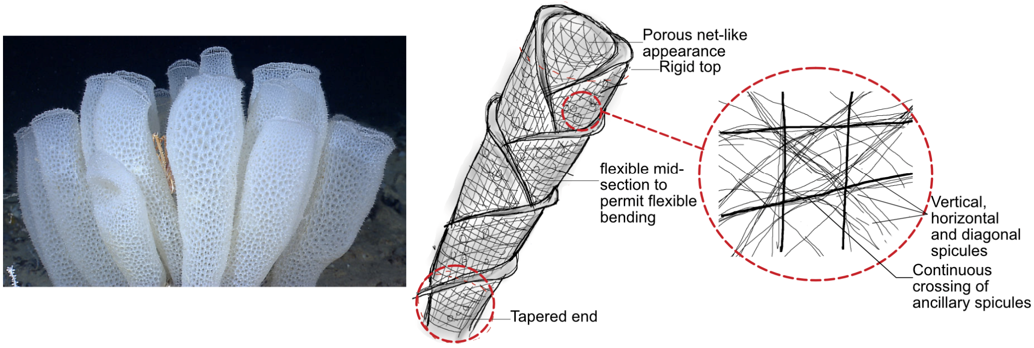
Figure 8. (**a**) A cluster of Salvinia water fern leaves. (**b**) Multicellular hairs on the leaf surface: light microscope, magnification ×12 related to 35 mm (alamy.com Stock photos). (**c**) A single water fern trichome. (**d**) Air layer retention characteristic of a row of trichomes.

The hydrophilic tips retain air pockets when the plant is submerged by trapping a thin layer of air between the leaf surface and the water molecules they attract (Figure 8d). The interface between air and water is shown to be because of the hydrophilic tip, with the enclosed air acting as 'pneumatic spring' when subjected to pressure fluctuations [7].

4.2. Structural Strength and Stability

4.2.1. The Venus Flower Basket Model

The Venus flower basket (*Euplectella aspergillum*) anchors itself to the deep ocean floor with numerous hair-like glass skeletal elements called spicules, a tubule structure made of concentric layers of amorphous hydrated silica separated by thin organic layers (Figure 9a) [63]. The four main regions of the Venus flower basket are the anchoring bulb, the curved section connecting the bulb to the main body, the main body, and the terminal sieve plate at the apex, called the osculum (Figure 9b) [64].



(**a**) (**b**)

Figure 9. (**a**) The Venus flower basket [47]. (**b**) Illustration of a Venus flower basket beam.

The skeleton of the Venus flower basket comprises at least seven structural levels, all of which contribute to its mechanical performance and help manage tension, compression, shear, and buckling forces, as well as prevent fracture and rupture [65]. At the macroscale, the surface of the silica beam consists of a rectangular square lattice comprising a series of vertical and horizontal 'struts' (each consisting of bundled spicules aligned parallel to one another). When exposed to currents, the elevated rigid beam attached to the ocean floor will experience bending stress concentrated at the anchor point. The rigid beam withstands these forces through its flexible anchor, loosely incorporating the spicules into the vertical struts of the rigid cage. The advantage of this strategy is that there is no limiting stress from the currents, and the beams swing freely in the ocean due to the inherent flexibility of the individual spicules forming the beams.

4.2.2. The Red Mangrove Model

The red mangrove (*Rhizophora apiculata*) has buttress roots, which are long, thin extensions of the tree trunk that begin to branch out from the trunk before reaching into the ground (Figure 10a,b) [66]. This tree grows in regions prone to storms and high winds and is commonly subjected to water currents and tidal forces [67,68]. Due to the shallow and waterlogged nature of the soil in which it is often situated, the red mangrove anchors itself to the soil using stilt roots (Figure 10c).

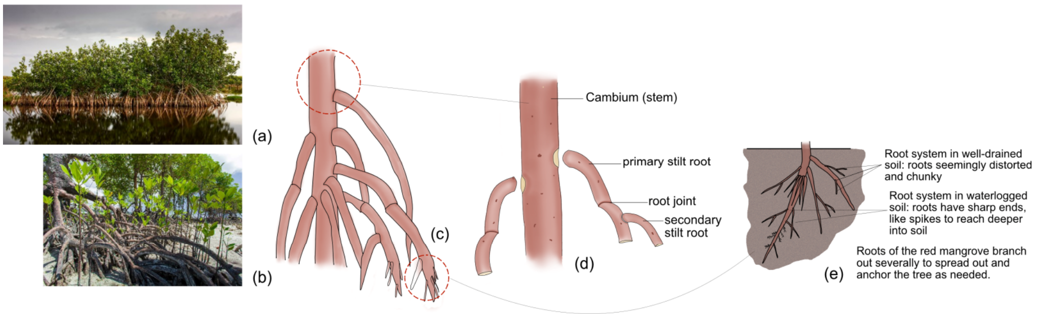


Figure 10. (**a**) Red mangrove trees (adobestock.com). (**b**) Close-up view of the root system (adobestock.com) (**c**) and its parts. (**d**) Diagram of the red mangrove tree (**e**) root system.

The stilt roots of the red mangrove (appropriately known as rhizophores) typically grow out perpendicular (as branches) or parallel (as columns) to the branches (Figure 10c,d) [69]. The established mangrove roots consist of rigid roots attached to the trunk and fixed to the soil, whereas newer and more flexible stems or roots hang from the upper branches and move back and forth with tidal currents (Figure 10b) [70]. The tip of the stilt roots develops a continuously branching underground root system once it reaches the ground, anchoring the entire tree to the soil. Rhizophores are highly effective in maintaining stability as their Rhizophora can branch as many as six times before entering the (swampy) soil. This is achieved by making the footplate of the tree much larger, whilst keeping the total amount of tissue required for stability.

4.3. Durability-Managing Stains and Damage to Surfaces

4.3.1. The Lotus Leaf Model

The lotus leaf (*Nelumbo nucifera*), typically found in a muddy aquatic environment, stays clean because of its cuticle (Figure 11a). The cuticle is made up of soluble lipids embedded in a polyester matrix-wax, which makes it extremely water repellent [60,71]. This water repellence is a result of the extensive folding and "epicuticular" wax crystals jutting out from its surface, giving it a roughened microscale surface (Figure 11b).

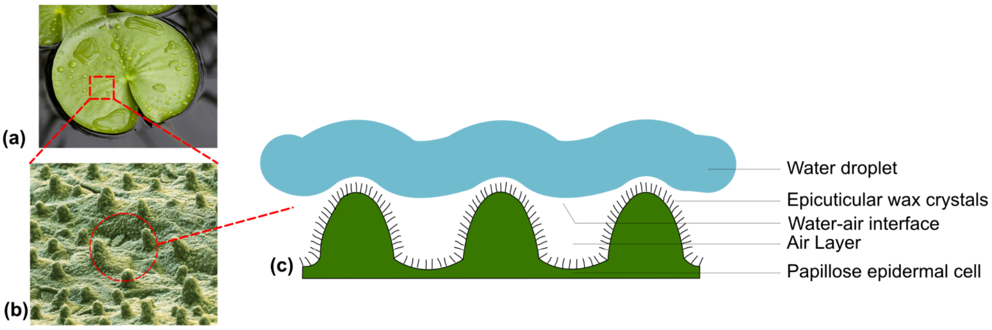


Figure 11. (**a**) Water droplets on a lotus leaf surface (Pixabay.com stock photo). (**b**) Coloured scanning electron micrograph (SEM) showing the microstructures on the surface (sciencephoto.com). (**c**) Interaction of the lotus leaf structure with a water droplet.

The surface of the lotus leaf has different topologies, with the topology of the upper epidermis being different from that of the lower epidermis. As a result, water rolls off the surface and collects particles along the way (Figure 11c) [72]. The mechanism behind this particle removal is based on the relationship between interfacial tensions of water, air, and the surface. In the case of the lotus surface, the epicuticular wax crystalloids form a composite surface, enlarging the water/air interface while the solid/surface interface is minimised [71]. When this occurs, the water forms a spherical droplet and dirt particles on the plant's surface then stick to these water droplets. The slightest angle in the surface of the leaf (caused by passing breeze) causes the water droplets to roll off due to gravity. In doing so, they take the attached dirt particles with them and clean the leaf [71].

4.3.2. The Wings of the Cicada Model

The wings of the cicada prevent it from becoming weighed down by rain droplets, sullied by dirt, or sighted by predators (Figure 12a). A wing is an ultrathin membrane comprising of an array of tubular veins, trachea, blood vessels, and fibre [73]. The tiny nanopillars on the wing's surface are arranged in rows, each measuring about 4000 times less than the thickness of a strand of human hair (Figure 12b) [73]. The nanopillars are spherically capped and hexagonally arranged, with a spacing and height of ∼200 nm and a radius of curvature at the apex in the range of 25–45 nm [74]. This contrasts with a water molecule, which is much larger and so does not stick to the wing's surface due to its bumpy nature. The cicada's wings are also coated with a water-repellent (hydrophobic) waxy substance, which causes water to slide off when the wings tilt. As the water droplets roll off the wings, they simultaneously flush away dirt particles.

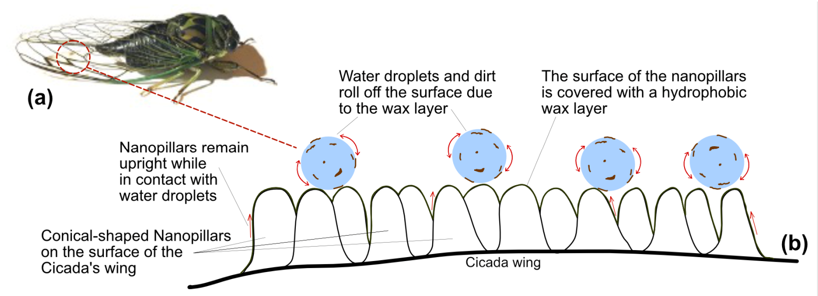


Figure 12. (**a**) Image of a cicada [75]. (**b**) Diagram of the nanopillars on the cicada wing surface and their water repellence system.

4.3.3. The Pitcher Plant Model

The peristome (pitcher mouth) of the pitcher plant is coated with waxy platelet-shaped aldehyde crystals, which protrude perpendicularly from the surface (Figure 13a) [76]. The peristome is a broad and smooth collar-shaped structure, which is made up of sloping macroscopic ridges (in turn, made up of microscopic ridges in themselves) (Figure 13b) [76,77]. Each epidermal cell of the peristome wall overlaps the cell adjacent to the pitcher inside, giving the surface the appearance of a series of 'steps' towards the inside of the pitcher (Figure 13c).

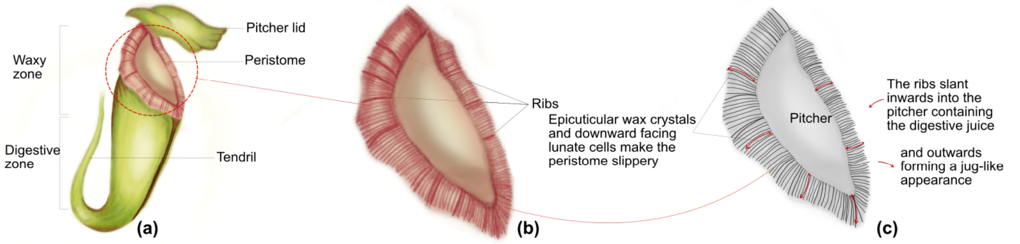


Figure 13. (**a**) Drawing of the pitcher plant. (**b**) Diagram of the peristome surface. (**c**) Direction of the radial ridges.

4.4. Abstracted Models' Characteristics

4.4.1. Stability and Anchoring

The models selected for discussion concerning structural support and stability are the Venus flower basket and the red mangrove.

The multiple branching system of the red mangrove provides structural stability and anchorage to the organism. The branching root system of trees like the red mangrove can provide inspiration for foundation design requirements such as multifunctionality, environmental adaptation, structurally stable branching configurations, anchorage, and soil penetration [34]. The red mangrove uses a 'soil-penetration' method like that of the pile foundation to stay anchored in muddy environments. One difference between the foundation piles and the root of the red mangrove is that while the foundation piles are often individual and standalone, the roots of the red mangrove branch out from the main stem and as many as six times. While it might be plausible to design pile foundations that all branch out from a central rigid and massive pillar, multiple pillars/piles can also be designed, from which smaller struts will branch out in emulation of the red mangrove's root buttress system. Research on the flow velocity of the roots of the red mangrove tree found that the most important factors affecting the flow velocity of the roots are tree diameter and velocity [70,78]. These studies have also reported that mangrove roots are very similar to circular cylinders of uniform diameter. In engineering, the (flexural) stiffness of the cylinder is achieved by placing rigid material on the outer limits of the cylinder [56]. The central part of the rigid material in the long, narrow area of the inner cortex then serves to provide flexibility rather than rigidity (provided by the outer cortex).

The Venus flower basket is both rigid and flexible due to its complex rectangular lattice structure and its composite nature of both organic and mineral material. The rigid upper part of the bulb enables the main body to swing freely in the ocean current while the bottom part is firmly anchored to the ocean floor to keep the organism in place. The advantage of this is that there is no limiting stress from the ocean current because the organism is flexible, due to very large numbers of relatively weak attachments that when combined form a strong bond. This organism provides great potential for the design of structures that incorporate numerous individual 'weaker' structures to form a strong and stable singularity.

An envisaged limitation to the emulation of these two systems is the extent to which they support the entire organism and the amount of load they can withstand in comparison with the load on a building. After assessing the steps involved in transfer processes from nature into architecture and engineering, the challenge then lies in how to apply the transferred knowledge from nature without resulting in merely copying or directly translating shapes or form [10].

4.4.2. Buoyancy

The emulated models for buoyancy discussed herein are the giant kelp and the floating water fern. The giant kelp uses its gas float while the water fern floats by using the multicellular hairs on its surface to achieve the same effect.

The giant kelp stays afloat in water because the gas-filled bulbs pull the entire algae stalk to the surface. Multiple bulbs on the kelp work together to lift the algae to the surface, as each bulb lifts the section of the algae strip to which it is attached. Similarly, the water fern floats by trapping a thin layer of air between the leaf surface and the molecules it attracts. There are some considerations that must be noted in the possible emulation of the giant kelp's system in architectural design. Firstly, the load on the giant kelp is not applied on top of it (like the structure on the amphibious foundation) but is transferred along the stripe, with many gas floats sharing the load to float the plant.

Due to the large surface area of hydrophilic hairs on the fern's surface, water forms a boundary that helps to reduce drag as the fern moves in water, creating less of an interaction between the water and the plant hairs [7]. It has been suggested that the entrapped air volume in this boundary formed could serve as a buoyancy aide, assisting immersed plants to swiftly return to the water surface [79]. Gandyra et al. [7] explain that the air layer stability on a submerged water fern leaf is maintained through the adhesion force (pinning force) between the tip of the eggbeater-shaped hairs and the liquid, and that iut is the elastic properties of the crown of hairs that allow elongation under pressure and deformation of the meniscus under pressure. The elasticity of the hairs is very important to retaining the air layer under changing pressure situations, resulting in variations in the air layer thickness, to which the hairs can adjust either by bending or through compression and expansion [7].

4.4.3. Durability

The cuticles of the lotus leaf, the tiny nanopillars on the cicada's wing, and the slippery surface of the pitcher plant are all equipped for durability. The cuticles on the lotus leaf surface are covered with wax crystals, which make the surface hydrophobic (water repellent). The wings of the cicada avoid stains and damage caused by water as droplets and dirt roll of the epicuticular wax-crystal-covered surface. Similarly, the peristome of the pitcher plant is not only covered with wax crystals, making it slippery in order to wash off dirt, but it also has a ribbed appearance made up of sloping macroscopic ridges (grooves). Each epidermal cell overlaps the cell adjacent to the pitcher inside, giving the surface the appearance of a series of 'steps' towards the inside of the pitcher.

In summary, the kelp possesses a gas-filled bulb, which enables the long, slim stem of the plant to float on the water's surface [59]. The leaves of the floating water fern consist of tiny multicellular hairs, with hydrophilic (water-attracting) tips [60,62]. These hydrophilic tips trap a thin layer of air between the leaf surface and the water molecules they attract. The rigid silica beams of the Venus flower basket, made up of relatively weak attachments combined to form a strong bond, provide structural support to the organism. The red mangrove, through its rhizophores (stilt roots), remains stable in swampy soil due to the branched network of its roots [76]. The lotus leaf stays clean due to its cuticle, made up of soluble lipids embedded in a polyester matrix-wax, which makes it extremely water repellent [60,80]. The wing of the cicada contains tiny nanopillars arranged in rows and coated with a water-repellent waxy substance, which causes water droplets to slide off [73].

Figure 14 shows a diagrammatic representation of the interrelationship between the amphibious building functions discussed and how they are achieved across the domains of nature and architecture.

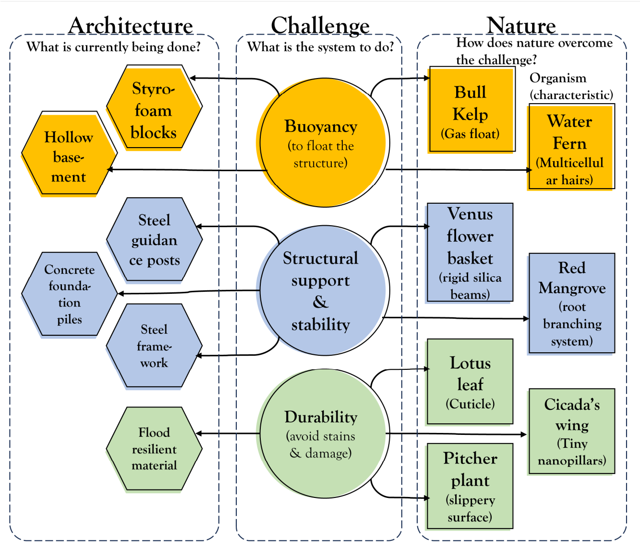


Figure 14. Amphibious building functions and corresponding characteristics found in living organisms.

5. Comparative Analysis and Synthesis

This section discusses the synthesis of model characteristics and their combination to create potential concepts that can support buoyancy, structural strength, and stability (corresponding to the main components of the foundation-buoyancy system, vertical guidance posts, and structural sub-frame, respectively). The features of the selected models were extracted and analysed in three steps of the design process: function (what does nature do?), processes (how is it carried out?), and morphology (what features are employed?). The following characteristics of the models were explored: gas-filled bulbs of giant kelp, air-pocket-retaining trichomes of floating water fern, rigid silica beam of the Venus flower basket, multiple branching stems of red mangrove, honeycomb structure of a beehive, cuticles on the lotus leaf surface, quick-drying material composition of a paper wasp nest, tiny nanopillars on cicadas' wings, and ribbed surface of the pitcher plant. The following sub-sections elaborate on specific aspects from the synthesis of models.

Table 1 shows a breakdown of the selected models, into their functions and processes, using the three steps discussed above in responding to challenges: function, morphology, and processes.

5.1. Stability + Anchoring

The stability and anchoring systems of the red mangrove and giant kelp can be emulated in the stability and anchoring components of the amphibious foundation. As soon as stilt roots of the red mangrove reach the ground, their tips develop an underground root system. The roots then develop one or more further stilt roots, which grow arcuately into the air to again run into the ground, repeating this process several times [70]. Similarly, root-like structures of the giant kelp called holdfasts attach to large rocks, anchoring the kelp in place [58]. This method of anchoring can be applied in the design of an amphibious foundation, such that the part of the system in contact with the soil branches out several ways into the soil to stabilise the foundation. Figure 15 provides an illustration of the branching method of the roots of the red mangrove and giant kelp.

5.2. Buoyancy + Durability

The buoyant bulb of the giant kelp and the dirt-repelling ribbed surface of the peristome can be emulated to design buoyancy and durability components in a foundation, respectively. The ribbed outer surface of the pitcher plant's peristome repels dirt, and the toughness of the surface improves water impermeability, while the slender and flexible midsection of the bulb enables the system to be attached to the branching piles emulated from the red mangrove. Figure 16 shows an illustration of a possible result of this combination.

Table 1. Breakdown of the selected models for emulation.

Challenge/Function	**Models**	**Morphology**	**Processes**
What Does It Need to Do/What Does Nature Do?	What?	What Features Are Employed?	How Does It Do What It Does?
Float	Kelp	Gas-filled bulb	The gas-filled bulb pulls the entire plant to the water surface
	Water fern	Tiny multicellular hairs on its leaf surface	The hydrophilic tips trap a thin layer of air between the leaf surface and the water molecules they attract
Provide structural support and stability	Venus flower basket	Rigid silica beams	A rectangular lattice arrangement of the struts, which is strong but flexible
	Red mangrove	Multiple branching of its root system	Multiple branching of its roots provides a stable anchor to weak soil
Durability—avoid stains and damage to surfaces	Lotus leaf	Cuticle made of soluble lipids; wax crystals on the leaf surface	Cuticle made of soluble lipids; wax crystals roll off water
	Cicada's wing	Tiny nanopillars	Tiny nanopillars on its wings, coated with waxy, water-repellent substance
	Pitcher plant	Inner pitcher surface; epicuticular wax crystals	Slippery surface and downward-pointing cells of its inner pitcher

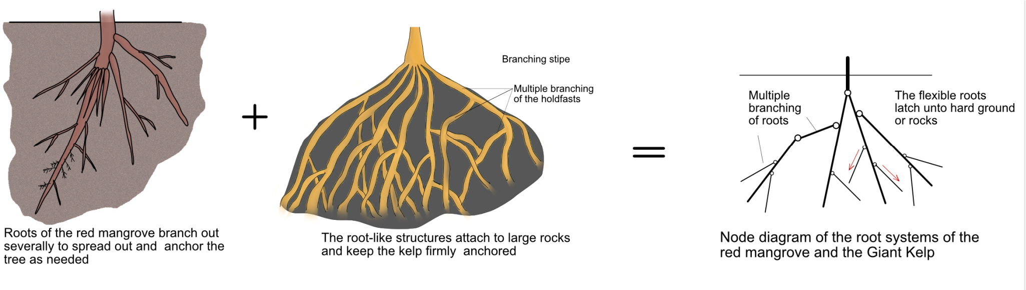


Figure 15. Illustration of the anchoring method of the red mangrove and the giant kelp.

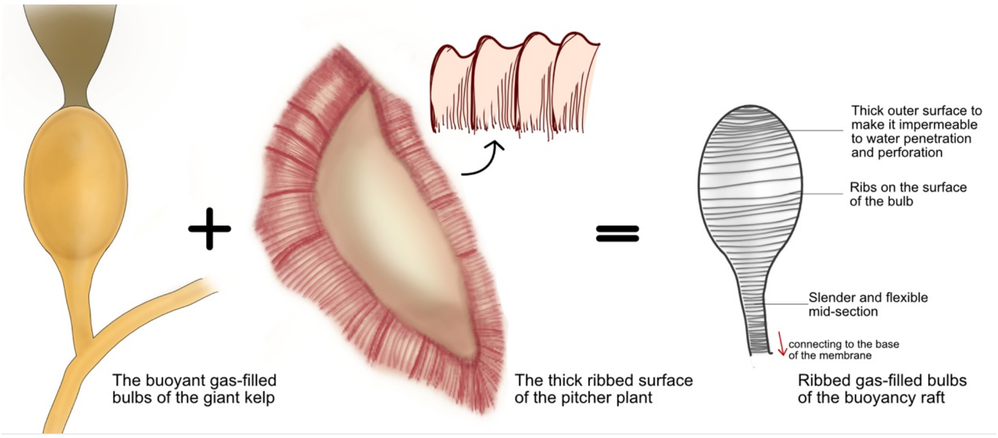


Figure 16. Illustration of the buoyancy bulb of the giant kelp and the ribbed surface of the pitcher plant.

5.3. Buoyancy + Stability + Anchoring

The multiple branching stilt system of the red mangrove and the buoyant bulbs of the giant kelp can be combined to provide stability and buoyancy to the foundation, respectively. While the conventional method of designing piles has been used in amphibious construction, multiple (large) piles can be designed, from which smaller piles branch out in emulation of the red mangrove's root buttress system. The assembly of bulbs may also be replicated and linked to the multiple branching 'piles', which may work together and pull one another to lift the entire structure. Additionally, the anchoring method of the red mangrove and kelp (holdfasts) may be emulated in the concept, to anchor the branching piles to the ground. Figure 17 shows an illustration of a possible result of this combination.

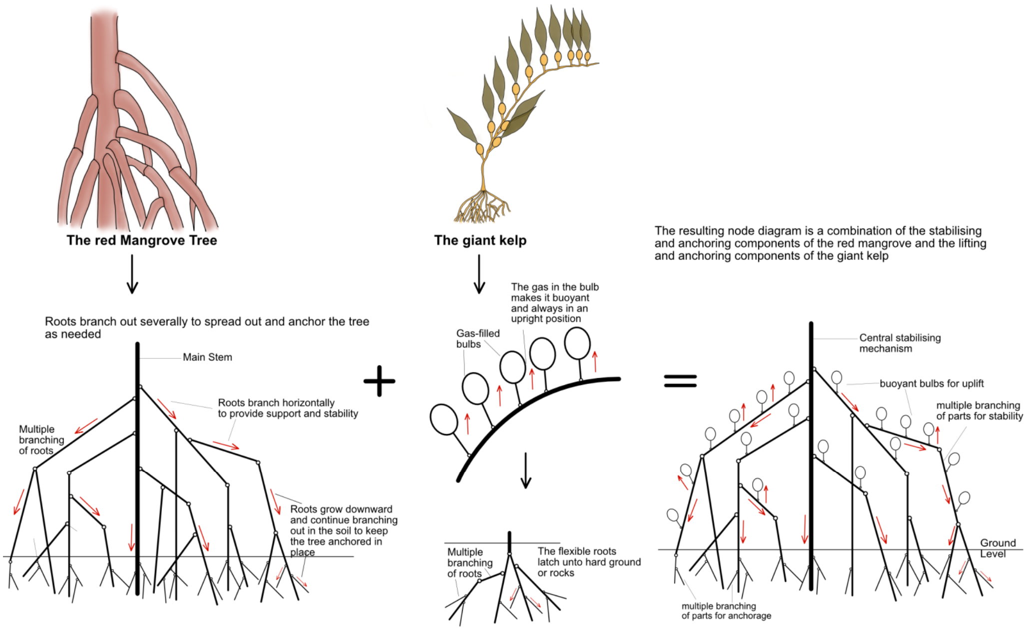


Figure 17. The resulting concept from the combination of the stability mechanism of the red mangrove and anchoring mechanism of the giant kelp.

6. Discussion and Potential Applications: Design Guidelines for an Amphibious Foundation

This section discusses some guidelines for potential applications from the synthesis conducted in Section 5. The design aspects from Section 5, such as "stability + anchoring" and "buoyancy + durability", may be applied to facilitate buildings to withstand various flood situations encountered in different areas. Although it is worth noting that buoyancy and stability will always be requirements in every flood situation, other functions might be understood in terms of priority. For instance, depending on the factors of flooding discussed in the introduction (flood depth, intensity, etc.), an area with poor soil and relatively low water flow and high flood depth might require buoyancy, anchoring, and durability but may not require ample stability as a priority. Meanwhile, a flood area subject to flash floods, high-intensity flow, and shallow flood depth might require buoyancy, stability, and anchoring, with durability possibly considered less of a priority (but still important). This is the reasoning behind the combination and synthesis of the characteristics. This research recognises that these statements require further research for real applications. However, the synthesis in this paper is presented as an overview of the manifold ways in which these combinations can be harnessed.

For example, the anchoring systems of the red mangrove and giant kelp models emulated can be applied in the design of the anchoring and stabilising components of an amphibious foundation, such as the parts of the system in contact with the soil, which may branch out several ways into the soil to stabilise the foundation (Figure 17). In the case of buoyancy, kelp is a good example of a plant that not only manages to stay afloat on the water surface but also withstands flowing water, not by being rigid and strong but by being flexible and extensible. Components of the giant kelp (buoyant gas-filled bulb, connecting stalk joining the full length of the kelp to the bulb) can be emulated to create a buoyancy system that raises a structure when components work together to push or pull the structure to the surface (Figure 16). The ridges on the pitcher plant's peristome may also be added to this system, along with its characteristic of repelling dirt, thereby improving the durability of the resulting components (as described in Section 5.2, Figure 16). The air pocket on the hydrophilic tip of a water fern (which has been referred to as the interface between water and air) is also an interesting characteristic that shows great potential for emulation in amphibious foundation design. As suggested in the literature, this entrapped air pocket could serve as a buoyancy aide, assisting immersed buildings to swiftly return to the water surface.

7. Conclusions

While amphibious foundations designed to date are limited to conventional construction methods and techniques, manifold opportunities for variety, creativity, and better responses to environmental adaptation lie in the study and emulation of nature's characteristics. Emulating nature's ways of solving design problems faced in architecture can inspire novel approaches to flood impact mitigation.

Through our review of living systems, highlighting their characteristics, morphologies, and correlations with the functions of amphibious foundation components, this paper contributes to the existing literature by providing a breakdown of relevant living system characteristics based on an understanding of the biomimetic design process. The buoyancy element, vertical guidance post, and structural sub-frame are the three foundation components discussed in this paper. Living organisms such as the Venus flower basket, giant kelp, red mangrove, and floating water fern, among others, are discussed, to describe how they perform the same functions of these components. For instance, the root system of the red mangrove and the rigid silica beam structure of the Venus flower basket provide insights into the anchoring of whole structures through multifunctional characteristics.

This paper offers one of many new ways of thinking about building design challenges and contributes to forging an improved understanding of the steps involved in the transfer from nature to architecture through the biomimetic design process, where a synthesis of the characteristics extracted from selected models is required. This process should be encouraged and included in the wide array of solutions in the design of amphibious buildings. The potential combinations of plant characteristics based on the three main functions of an amphibious foundation (buoyancy, stability, and durability) can be understood in terms of various flood situations encountered in different areas. It is important to note that though this paper presents concepts for potential applications in flood situations, a recommendation for further studies is that more in-depth research should be conducted into the opportunities for synthesis and the transfer of characteristics and processes from nature into prototypes for amphibious building components.

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