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PLANTS AND ARCHITECTURE: THE ROLE OF BIOLOGY AND BIOMIMETICS IN MATERIALS DEVELOPMENT FOR BUILDINGS

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PLANTS AND ARCHITECTURE: THE ROLE OF BIOLOGY AND BIOMIMETICS IN MATERIALS DEVELOPMENT FOR BUILDINGS

ABSTRACT

This paper presents a review of the state-of-the-art in plant-inspired biomimicry for novel materials applied within architecture and buildings. Bioinspiration is considered in examples at a materials level, and examples are explored which move through increasing scale towards elements and components for application at the building level in new designs and approaches. The review of plant biology mechanisms indicates that a single plant attribute can give rise to many biomimetic concepts. It is common for these to overlap, and to be applied to similar technological or design challenges, via different routes. By focusing on six specific plant inspirations (self-cleaning, self-healing, cell wall structures, plant movements, cellular structures and branched structures) the paper highlights approaches which have been taken, and some emerging fields, within bioinspired materials.

The process of abstracting biomimetic concepts requires interdisciplinary research, and there is much scope for collaboration between biologists, materials scientists, designers, architects and structural engineers. The paper concludes by discussing several of the areas where additional research is needed to progress from the concept within materials and small assemblies up to the building element or full structure. One of these is service life, and may necessitate that self-cleaning and self-healing concepts are re-visited for new inspiration which is compatible with the new generation materials. Multi-functionality may therefore become increasingly important as the new materials are applied to delivery of biomimetic concepts at a building level. Scaling of concepts from laboratory and small prototypes to full elements for buildings also poses challenges in both the materials selection for stresses incurred, and the alteration of geometry to be accommodated into the structural form while retaining the biomimetic function. In addressing these challenges it may be necessary to deviate from the frequently proposed top-down and bottom up models of bioinspiration to a holistic approach which can accommodate multiple inspirations and adaptations to deliver the final functioning element or structure.

Keywords: Building Materials, Biomimicry, Plant biology, Multi-functionality

1. Introduction

Architects are constantly seeking new solutions and inspiration, both in building form and in the interaction between buildings and their environment. These approaches may provide radical changes in the design and form of structures. They may also place additional requirements on the materials selected to deliver the new designs. Inspiration is frequently sought based on forms found in nature, especially plants, which demonstrate highly efficient structures, optimised use of resources and adaptation to their environment (Pawlyn 2016). For example, various modern architectural projects have investigated the relationship between building form and solar gain to reduce heating costs, or the use of active shading and ventilation systems to reduce over-heating.

Concurrently, many opportunities can be identified by looking at the strategies used by nature to fabricate strong, tough or responsive materials; many of which are suited to construction, or to bioinspired concepts for buildings. Further, we can look to employ the materials efficiency demonstrated in nature within man-made structures. The insights gained from the underlying concepts of natural materials and structures often lead to designs which mimic nature. Each of these processes are referred to as biomimicry or bioinspired design, whether applied at the materials level, the component level or the building level (Pawlyn 2016, Wegst et al. 2015, Okumura 2005). When inspiration is drawn from the structure and functionality of plants, it may be referred to as phytomimetics.

Many scientists have studied concepts from plants and other areas of biology to inform materials development, create efficient structures and generate novel designs for a wide range of applications. Plant inspired response to stimuli and shape changing properties of materials are active areas of research, not only for applications in buildings but also in robotics and medicine (Jahan et al. 2018, Meng and Li 2013). There are many examples where concepts abstracted from plants help to generate new ideas through biomimetic solutions to design challenges. Frequently they can provide environmentally benign solutions. For example to utilise plant-based structures and motion or responses to achieve passive control of the internal climate of a building; to develop energy-efficient architecture; or to mimic water harvesting structures on plants and animals to create water-saving structures in the built environment (Portilla-Aguilar et al. 2015, Wegst et al. 2015, Liu and Jiang 2011, Malik et al. 2014). Often, this development of materials using bio-inspired concepts is driven by the aim of reducing our impact on the environment.

In many respects, plants and buildings share similarities in their interaction with the environment. Their largely static nature requires that plants self-regulate their temperature, access to light and other resources, and building design must also incorporate control of solar gain, ventilation, temperature control, and access to daylight for the occupants. Architects control these aspects by design and by selection of building materials for their functional properties in addition to their structural characteristics. As a result, multi-functional materials are increasingly investigated, and many opportunities for bio-inspired designs based on plant forms or plant adaptations arise.

The aim of this article is to review the current state-of-the-art research relating to plant-inspired biomimetic concepts at a materials level, and their potential for application within buildings, and innovative building designs. This distinction, including plant-derived biomimicry and excluding biomimicry from the animal kingdom, relates to the field of research of the researchers. The inter-relationship between the three aspects (plant biomimicry, materials and building design) provides innovation in materials which can support the development of biomimetic architectural concepts and new building designs. The understanding of fundamental principles, mechanisms and roles of plant structures, plant surfaces and plant forms can be developed into new products and applications. There are many opportunities for these principles to be applied in building materials, and subsequently in components of built structures. Therefore it is important to state that this paper seeks to the development from the plant to the plant-inspired material, up to their use in assemblies and components, and ultimately in delivering building design. The topics identified in this paper are reviewed to define future research challenges, which can be addressed in developing novel materials and building designs.

2. Common Frameworks in Biomimetic Design

Biomimetics utilises the mechanisms and functions of biological science to inspire innovation in diverse fields, including engineering, design, architecture, transportation, agriculture, medicine, and communications (Gruber and Imhof 2017, Portilla-Aguilar et al. 2015, Lepora et al. 2013, Elzay et al. 2003). The search for biomimetic applications has become a well-established discipline, and is likely to drive a significant shift in modern science (Badarnah and Kadri 2015, Lurie-Luke 2014). From the literature, it is evident that biomimetics has a significant impact in the architectural field leading to a wide range of innovative and sustainable building solutions, which have been well reviewed elsewhere (Pawlyn 2016, Nachtigall and Pohl 2013, Al-Obaidi et al. 2017).

Phytomimetics is a significant branch of biomimetics, and deals with plant inspired materials, structures and movements. In a review of biomimicry literature Lurie-Luke (2014) reported that approx. 16% of references relating to plant inspired biomimicry, mentioning the global distribution of plants and large number of species (approx. 300,000) as possible reasons for this significant sub-group of papers in the phytomimetics field. The same study indicated that approximately 50% of references related to biomimicry in the materials field. These could be grouped into smart materials inspired by response to stimuli; surface modifications and topographies with improved function; material architectures featuring novel shapes and structural arrangements; and technologies based on enhancing existing systems using specific parameters of an adaptation.

Practicing biomimetics means learning from nature (in this case - plants) for the development of new designs and technologies (for example – functional materials, or new building designs) in parallel with the environmental issues (Lopéz et al. 2017), as shown in Figure 1b. Some form of interpretation or abstraction is required to translate the concept from biology into technology (Speck and Speck 2008, Nachtigall and Pohl 2013). Direct interpretation is not a possible solution, instead implementation of a well-designed abstracted concept is needed to successfully provide inspiration of nature based concepts for architecture. This is especially the case when developing functional designs in an interdisciplinary context, as is required in modern buildings. Speck et al. (2013) specify that the approach of biomimetics for architecture and design requires certain steps, as shown in Figure 1c. Where concept generation/research is followed by abstraction and then followed by emulation/evaluation steps, this helps to generate new solutions using the biomimetic design process. By observing a cognitive biomimetic design process within the context of interdisciplinary research, identification and abstraction are the key steps.

FIGURE 1

It is frequently commented that the development of biomimetic architecture requires an interdisciplinary approach between biologists, engineers, materials scientists and architects (Xing et al. 2018). This is all the more the case where building services such as active or passive ventilation or shading are considered to address technically demanding challenges. The required properties and performance of new materials to fulfil biomimetic designs can pose exciting challenges to the materials scientist, who may also turn to natural materials for bioinspiration.

Various models have been proposed for describing this transfer of biological concepts to architecture. Theoretical biomimetic design frameworks are generally used, and two distinct approaches can be taken: a bottom-up (solution-based, or biology to design) approach and a top-down (problem-based) approach as shown in Figure 1a (Speck et al. 2006, Gruber and Imhof, 2017). Therefore, bioinspiration may be considered to be:

- Biology influencing design: identifying a particular characteristic in an organism or ecosystem and translating that into designs which meet societal needs
- Design looking to biology: identifying a human need or design problem and looking to the ways other organisms or ecosystems solve this

Badarnah and Kadri (2015) review biomimetic design strategies within these two groupings, and the active strategies employed by biomimicry researchers in abstracting concepts from nature (in the biology to design approach) or in identifying challenges and exploring bioinspired solutions to address this (in the problem based approach). Among the examples explored within their review, the opening and closing of stomata, and the crassulacean acid metabolism in CAM plants were two which related to phytomimetics, both offering moisture regulation strategies, and permitted comparison with non-plant derived moisture strategies in developing a design concept.

Pedersen Zari (2007) proposed different levels of biomimicry, describing a framework for understanding the application of biomimicry to architecture as a potential research tool for designers. It was proposed that biomimetic technologies can be demonstrated at three levels of mimicry: the organism, the organism’s behaviour and the ecosystem. The first level refers to a specific organism like a plant or animal and may involve mimicking part of or the whole organism. This is the level which can be most easily applied to plant-based biomimicry. The second level refers to mimicking behaviour, and may include translating an aspect of how an organism behaves, or relates to a larger context. As plant behaviour relates primarily to growth and tropic or nastic movements, many examples of response to stimulus have been considered here. The third level is the mimicry of the whole ecosystem, for example the forest or the grassland, and identifying common principles that allow the ecosystem to function successfully. This level has been occasionally considered relating to urban design, for example the placement and arrangement of buildings in close proximity to manipulate and enhance local climatic effects, services etc. While this is an essential topic for a future where two thirds of citizens live within urban areas by 2050 (Carreiro et al. 2008, Wooton-Beard et al. 2016), it falls outside the scope of this paper. Other researchers have applied plant or algal living structures to architecture, as a bio-inspired strategy for energy efficient or self-sufficient buildings (Wooton-Beard et al. 2016, Dutt et al. 2017, Wilkinson et al. 2017, Elrayies 2018), these also fall outside the materials-centric focus of this review. Table 1 presents examples of bioinspiration relating to the various levels of Pedersen Zari’s biomimicry framework, with specific reference to plant biomimicry and buildings.

TABLE 1

The above biomimetic frameworks typically follow linear approaches, and they can only depend majorly on technical abstraction of a single function (Knippers and Speck 2012). Building design may in fact rely on the interaction of many disciplines, and require an iterative process to balance the complexities of holistic design (Xing et al. 2018). In this review, the authors followed a bottom-up approach to examples from the literature. These will present the plant science, the materials derived and the transfer into buildings. Pull through to building design is illustrated in the case studies presented in the final portion of the paper.

3. Plants as an inspiration

Plants are frequently considered as models for inspiration in designing and developing new technologies. This is especially the case in development of the new materials required to deliver exciting design concepts, and generating new features in modern architectural designs (Gruber and Imhof 2017, Portilla-Aguilar et al. 2015, Lepora et al. 2013). The inspiration may be in the morphology (appearance, form and structure), or in the mechanical mode of delivery (response to stimulus, mode of action). A simple example would be the location of balconies around a central tower in a phylotaxic pattern to mimic leaves arranged around a stem; versus designing light tracking behaviour of solar panels on the exterior of a building to mimic the phototropic behaviour of a leaf following the sun. Both are bioinspired, one is mimicking form, the other is mimicking behaviour.

Table 2 lists various sub-topics within the field of plant biology that can provide bioinspiration. Several of them, such as the structure of the plant cell wall, may provide inspiration in multiple ways for materials development, due to the number of distinct strategies employed by plants in the cell shape, cell wall architecture and cell function of specific tissues within the plant, as discussed later. In addition, features such as stomatal opening and closing mechanisms (which facilitate gas exchange by opening and closing according to the plant's needs, Parlange and Waggoner 1970, Franks and Farquhar 2007) may provide inspiration at the mechanical function level (motion), or in the inspiration of responsive ventilation systems (air flow). Thus from one plant component a multitude of design inspirations may be taken.

TABLE 2

Similarly many bio-inspired designs have been generated from plant architecture (i.e. leaf and branch placement) and light harvesting mechanisms. These starting points provide models which can be applied at the materials level, the design level, and the architectural level. Each approach may take different aspects forward into designs and structures, often within the same field. Plant movements such as phototropism and nastic responses to stimuli are another area under investigation (Li and Wang 2016). The emerging understanding of these biological principles has been used to stimulate development of actuators and shape morphing materials. These developments often feed into the same type of design challenges as those addressed by plant architecture approaches. There is frequently overlap between different biomimetic routes, and different bioinspired designs.

This overlap is seen within this paper, with several plant motion concepts being explored individually, and designs arising from these identified, these finally converge in the form of designs for applications in building facades, allowing a discussion of some of the challenges which will arise at the implementation stage.

4. Biological Principles from Plants and their Translation into New Materials

Several key biological mechanisms identified from plants that lead to new technical innovations were presented in Table 2. Six of these concepts will be discussed in greater detail in this section of this review, first from the plant science perspective, then considering the materials developed by phytomimetics. The development of additional biomimetic concepts such as these from plant biology still presents a major opportunity for future inspiration in new building materials and in structural design research.

4.1.1 Self-cleaning in plants

The self-cleaning principle is based on the observation of plant leaves, which show high water repellence (Barthlott and Ehler 1977). Professor Wilhelm Barthlott introduced the concept of the “lotus effect” (Neinhuis and Barthlott 1997, Barthlott and Neinhuis 1997, Barthlott and Neinhuis 2001, Solga et al. 2007), which has since gained much attention among scientists and from a wide range of companies, resulting in various applications, surfaces or treatments utilising superhydophobicity (Solga et al. 2007, Karthik and Maheshwari 2008).

The micro and nano texture of the leaves of lotus (*Nelumbo* spp.) causes water to bead and roll easily off their surface (Figure 2). The same high water-repellence are often observed in plants such as *Tropaeolum* spp. (nasturtium), *Opuntia* spp. (prickly pear), *Alchemilla mollis*, and on the wings of certain insects (Barthlott and Neinhuis 2001). The opposite effect, superhydrophilicity, also exists in nature where the structures in plant surfaces show unrivalled attraction towards water, for example mosses and rose petals. Spanish moss accomplishes this by having both highly water-absorbing pores and multicellular absorptive hairs (Koch and Barthlott 2009). In the rose petal the effect is related to micro and nano surface texture, in a variation of the effect seen in the lotus leaf (Feng et al. 2008).

FIGURE 2

The superhydrophobic properties exhibited by the lotus leaf surface are now well understood (Brown and Bhushan 2015). Microscopy revealed the presence of hierarchical structures, with the relatively coarse (macro scale) papillae, which are super-imposed nanotubules, also formed from hydrophobic wax. The multi-scale texture of the surface is the key reason for the water repellence (Barthlott and Neinhuis 1997, Barthlott and Neinhuis 2001). Other plant surfaces have also provided textures, which generate super hydrophilicity, and adhesion effects (Brown and Bhusan 2015).

To characterize wetting phenomena of surfaces, several modes or regimes have been described, including the Wenzel and Cassie-Baxter regimes (Figure 3) (Wenzel 1936, Cassie and Baxter 1944). This is due to the hierarchical structure of surfaces having micro- and nanoscale roughness (Nosonovsky and Bhushan 2012, Gopalan and Kandlikar 2014, Mitra et al. 2017, Kubiak and Mathia 2014). According to the Wenzel and Cassie-Baxter models, a homogeneous and a non-homogeneous/composite regime can exist for a rough surface (Wenzel 1936, Cassie and Baxter 1944, Mitra et al. 2017, Kubiak and Mathia 2014). These regimes are defined as solid–water two-phase interface and solid–water–air three-phase interface. The air inhabits the fine texture of a Cassie-Baxter state interface as shown in Figure 3.

The petal regime, resulting in high adhesion and based on water interaction with the surface of a rose petal, has also been described (Bormashenko et al. 2009, Feng et al. 2008). Here the texture retains, rather than shedding, droplets of water, and has applications in adhesion. Bormashenko et al. (2009) reported a transition between wetting regimes dependent on contact angle and the volume of a droplet for a surface based on lycopodium spores, which possess a suitable nano-texture. In some plants it has been recognised that leaves may have areas which favour both droplet shedding, and droplet accumulating behaviour, to aid water harvesting, or water management.

FIGURE 3

4.1.2 Application in self-cleaning materials or surfaces

To achieve water repellent qualities on man-made materials, surfaces need to be designed by modifying features through adjusting the physical and chemical properties at the micro to nano scale levels in a manner that mimics the hierarchical nanotextures seen in plant leaves (Barthlott et al. 2017). Self-cleaning surfaces have been widely known and self-cleaning glass or self-cleaning paints have been in the market for several decades. The concept has found application in not only self-cleaning surfaces, but also corrosion resistance and reducing flammability (Cannavale et al. 2010, Min et al. 2008, Davis et al. 2015, Payra et al. 2015, Wu et al. 2011).

To characterize the wettability criterion of a smooth surface the equilibrium contact angle of a droplet on the surface can be related to the interfacial tensions between the solid–vapour, solid–liquid, and liquid–vapour states. Hydrophobic surfaces have contact angles (θ) greater than 90°, and hydrophilic surfaces have $\theta<90°$ (Bico et al. 2002). For achieving superhydrophobicity ($\theta>150°$), the higher surface roughness and wetting in the Cassie-Baxter state rather than in the Wenzel state, is generally a requirement (Zheng and Lu 2014). Where the contact angle between water and a solid surface is less than 90°C the resulting wetting phenomena lead to strong adhesion.

To achieve bioinspired effects, either in superhydophobic or superhydrophilic surfaces, researchers have attempted to modify the texture and surface energy of materials. Surfaces need to be designed by modifying features through physical-chemical properties at the micro to nano scale levels (Ramón-Torregrosa et al. 2008). Liu et al. (2015) presented a novel way to prepare raspberry-like superhydrophobic silica coatings. The silica particles are embedded in silica matrix through the sol-gel technique and deposited on glass plate, which exhibit a contact angle of 152° and sliding angle of 10°. Similarly, Xin et al. (2015) developed multi-layered nanocomposites films by deposition of imidazolium based ionic liquid and titanium dioxide nanoparticles via a layer-by-layer technique. The resulting nanocomposite film showed an efficient self-cleaning ability with superhydrophobicity as well as photocatalytic activity.

The concept has found application in not only self-cleaning surfaces (windows, paints and solar panels), but also corrosion resistance and reduction of flammability (Cannavale et al. 2010, Min et al. 2008, Davis et al. 2015, Payra et al. 2015, Wu et al. 2011). Many other researchers have studied surface wettability, and applied it to building products and other engineering fields (Brown and Bhushan 2015, Zhang et al. 2016, Wang et al. 2014, Soliveri et al. 2015, Pinho et al. 2015, Li et al. 2016, Kumar et al. 2015).

4.2.1 Self-healing in plants

The concept of self-healing is very familiar, as the healing of a small cut on human skin or healing of blood vessel injuries takes place naturally without any external intervention (Rittie 2016), and many organisms share this healing capacity. In plants it may be possible to abstract different concepts for application to materials and structures, due to the different mode of action in response to stress or injury. In mammals the healing of skin wounds is a four stage process, whereas in plants, the process occurs in two stages: self-sealing, and self-healing.

FIGURE 4

The plant *Delosperma cooperi* (Figure 4) demonstrates a very rapid self-repairing phenomenon, which takes place within 30-60 minutes (Konrad et al. 2013). The first step, the self-sealing process, mainly protects the plant from invasion by pathogenic organisms and also minimises water loss. The mechanism of sealing a wound happens through physio-chemical reactions i.e. by oxidative bursting of surviving cells and formation of a drought layer. The sealing phenomenon is a fast process occurring rapidly after damage occurs, whereas the healing process typically takes considerably longer. In *Delosperma*, the notable speed of self-sealing is a requirement of high risk of drought stress due to its environment, and sealing is completed by an adjustment of leaf angle to close the wound. In the self-healing process of plants in general, callus formation takes place over a prolonged period, determined by the rate of cell division, differentiation and wound closure. To restore full mechanical function of the plant stem or leaf, cell wall formation and other biological healing processes take place (Flues et al. 2009).

4.2.2 Application in Self-healing Materials

In materials design, self-healing based on biomimicry permits a dynamic response to damage of the material, mimicking the processes taken by natural living systems. Several materials have been designed and fabricated based on inspiration from self-healing phenomena in plants. Many different reagents are used, as reviewed by Hillewaere and Prez (2015). Some examples are polymers based on microencapsulated healing agents (Yang et al. 2015, Zhu et al. 2015), self-healing poly (N-isopropylacrylamide) hydrogels (Gulyuz and Okay 2015), and glass-encapsulated minerals for healing cement-based composites (Kanellopoulos et al. 2015). Self-healing processes can provide huge savings in terms of maintenance costs and protection for large structures by extending material lifetimes and avoiding failures initiated by the accumulated micro-cracks (Tang et al. 2015, Hillewaere and Prez 2015). Systems have been developed for cementitious materials, fibre composites and organic materials (Hayes et al. 2007, Wu et al. 2012, Huang et al. 2014, Yin et al. 2015).

Chemical reactions based on microcapsule technology (Zhu et al. 2015) are frequently used to create self-healing polymers and polymer composites. The self-healing process occurs when micro-cracks are formed in polymer/polymeric composites under loading, which expose the encapsulated healing agent and initiates a reaction. Microcapsules incorporated into polymeric materials for self-healing may be found in a number of forms such as a single capsule, a single capsule with a dispersed catalyst, a phase-separated droplet and single capsule, a double-capsule or an all-in-one microcapsule (Yang et al. 2015, Zhu et al. 2015, Heo and Sodano 2015). The capsules can contain monomers, so that when a micro-crack initiates and subsequently propagates near to a capsule the capsule will break releasing the monomer reagent. The monomers then react with pre-loaded neighbouring catalyst and polymerization occurs and results in closure of the micro-crack. Self-healing technologies are likely to become widely adopted industrial options for healing cracks in structural materials. Further developments in the field could include systems for sensing crack formation and initiation of the healing process. One example is the activation of shape memory polymer 'tendons' within concrete, which can be activated by an electrical resistance wire heating system, also embedded in the material (Teall et al. 2018). Most shape memory polymers are thermo-responsive, requiring the heat input to initiate the healing system. A PET tendon which had been pre-stressed was embedded in concrete and activated by heat from a nickel chromium wire in laboratory tests.

Self-healing concepts used in the cement and composites industries are known but have not become wide-spread in the market. Adoption is limited to applications where ensuring long term performance is considered a primary aim, rather than commodity items where replacement may be more cost-effective. However huge scope still exists for further developments of this healing capacity, especially be revisiting the plant self-healing mechanisms rather than the animal-based healing phenomena. For example, it may be possible to utilise the adaptability of the callus formation process, and re-alignment of fibrils within cells in the callus tissue (which alters strength and toughness) to develop appropriate sealants and covering materials for repair of structures.

Another interesting chemically driven self-healing process for materials can be achieved using biomineralisation, which is a property of various microorganisms (Addadi and Weiner 2014). The microorganisms, such as diatoms and bacteria, can be induced to generate minerals such as silicates and carbonates that lead to considerable strengthening of materials when deposited. This deposition process can be harnessed to achieve self-healing, especially in cementitious materials (Mann 2001). It has also been proposed as a method to counter act water-induced deterioration of concrete structures (Pacheco-Torgal and Labrincha 2013).

The formation silicates in algae and diatoms, carbonates in invertebrates, and calcium phosphates and carbonates in the hard tissues of vertebrates leads to strengthening mechanisms in the surrounding material (Arakaki et al. 2015, Iwatsubo et al. 2006). Microorganisms have been used to produce concrete that self-heals when cracks occur. Silva et al. 2015 used axenic ureolytic spores that had the drawback of being expensive, whilst Luo et al. 2015 used non-axenic ureolytic bacteria able to sporulate and to induce calcium carbonate precipitation in concrete structure. Similarly, Achal et al. 2011 used *Bacillus* spp. isolated from concrete in the environment, and studied the effect on compressive strength and performance in water absorption tests. In the construction industry, the bio-mineralization concept is also used for soil stabilization to strengthen unconsolidated sands and gravels (Achal et al. 2015, Navdeep et al. 2013). Bio-mineralization therefore provides several benefits such as the reduction in the use of stabilizing agents lowering pollution levels.

4.3.1 Cell Wall Microstructure

It is well-known that wood has a cell wall formed from microfibrils of stiff cellulose, within a matrix of two more compliant materials, hemicellulose and lignin. In fact, wood cell walls comprise several distinct cell wall layers, and each layer has the microfibrils aligned in a particular manner. These angles vary in each layer i.e. primary (P), secondary (S1, S2, S3), and tertiary (T) layers (Figure 5, Xing et al. 2018). In softwood tracheids the microfibril angles (MFA) at secondary layers are around 4° to 6°, whereas the outermost layers have 60°-80°. The dominant S2 layer has a very low MFA, which permits high stiffness in the loadbearing axis of the cell, and the whole tree. The significance of much higher MFA in the outermost layers may be to confer collapse resistance and other lateral properties (Mark 1967, Donaldson 2008).

FIGURE 5

Donaldson (2008) studied the effect of MFA in relation to properties like longitudinal modulus of elasticity and longitudinal shrinkage behaviours. The properties of wood largely depend on the MFA in the S2 layer, with smaller MFAs resulting in higher stiffness (Young's modulus) measured along the cell axis. The axial stiffness of hardwood fibres and softwood tracheids depends on the MFA in the S2 layer, therefore this layer plays prominent role in wood properties. Many other researchers have considered the effect of microfibril angle on the properties of the cell and the resulting timber (Sheng-Zuo et al. 2004, Lichtenegger et al. 1999, Hofstetter and Gamstedt 2009).

Other plant cells, for example in non-woody plants, may have a simpler cell wall structure, without a secondary wall. In the primary cell wall the cellulose microfibrils may be approximately randomly aligned to achieve isotropic behaviour within the plane of the cell wall, although some microscopic studies have inferred a level of anisotropy (McCann et al. 1990, Reis et al. 1994). The three main components of these cell walls are cellulose, xyloglucans and pectins, and two co-extensive networks are proposed, comprising the cellulose/hemicellulose, and the pectin. The two main roles for the primary wall are to provide high intrinsic strength (sufficient to contain turgor pressure) and the ability to accommodate cell expansion during active growth (Carpita and Gibeaut 1993, McQueen-Mason 1997). Studies of the properties of cellulosic and cellulose-xyloglucan tissues from plants, and from bacterially grown cellulose fibrils are revealing the role of the xyloglucan in reducing stiffness while offering a cross-linking mechanism which allows extensibility of the fibril mat (Whitney et al. 1999, Hayashi and Kaida 2011).

Specialised tissue within annual plants however may incorporate cells with specific shape and may use controlled cell wall microfibril alignment to resist pressure or facilitate movement responses. Motion of the scales in a pine cone relates to the microfibril angle within sclerenchyma and sclerid cells. These two tissues are located in separate layers within the hinge region of the pine cone scale, and show a differential response to moisture content which relates to the microfibril alignment, and the alignment of the long axis of the sclerenchyma cells (Dawson et al. 1997).

4.3.2 Application in bio-inspired tough composites

Fibre composites are widely used materials, often used for developing large lightweight components within structures. Fibre composites are used in a wide range of engineering applications due to their ability for properties to be tailored for specific uses. The strength of the stiff fibres, and their alignment within a more compliant matrix material are well recognised, and many opportunities to design strong lightweight materials exist. Researchers may also look to the plant cell wall to better understand the potential of this fibre alignment.

Fibre reinforced polymer composites can be developed using the ideas taken from wood microstructure i.e. mimicking the microfibrillar alignment within a cylindrical form.

Composite tubes or other sections may be formed and control of winding angle applies this concept within the polymer composite design. The central part of the wood cell is taken as reference for developing filament wound fibre-reinforced composites (Prabhakaran et al. 2016). Fibre reinforcements are wound on a cylindrical mandrel and different fibre orientations are incorporated as per the strength requirements. The wound profiles are then infused with a polymeric resin to obtain hollow lightweight tube components with high strength.

The cell wall also comprises distinct layers, with different microfibril angles in each layer. Layered structures are already common in fibre-reinforced composites, where the fibres and polymers are combined to build up an anisotropic or orthotropic structure by combining different fibre alignments. The fibre reinforcements can be synthetic or natural fibres, whereas the binding material can be a synthetic or a natural polymer. The fibre orientation can be altered by designing the materials as per the product design and by tailoring the properties. If the fibres are oriented parallel to each other then we can obtain unidirectional composites (used today as main laminate in wind turbine blade design mainly to handle wind loads, see Prabhakaran 2014). With advanced design and manufacturing techniques, any complex shaped product can be obtained by altering fibre orientation.

Other researchers have sought to bring bioinspiration based on a different aspect of cell wall structure, namely the combination of materials with different values of stiffness and viscoelasticity. A study by Flores and Friswell (2012) developed a multi-constituent material inspired by the magnitude of differences in stiffness of the three main constituents of wood. Wood contains three main components: fibrils of cellulose with both crystalline and amorphous regions, surrounded by hemicellulose and encased in a lignin matrix. Each of these components have different mechanical properties. An order of magnitude difference in stiffness is recognised (Gibson 2012), from the crystalline cellulose (stiffness of 134 GPa) to the amorphous cellulose (stiffness 10.42 GPa), the hemicellulose (0.04 GPa), and the lignin matrix (1.56 GPa). Therefore, within the wall, the stiffness decreases abruptly from the cellulose of the microfibril (134 GPa) to the hemicellulose regions and the lignin matrix. However, the combination of these stiff and compliant elements leads to benefits including toughness, crack deflection and damping behaviour, while also delivering a material which has excellent overall stiffness (Scots pine 10 GPa, Lavers 1969).

In the study by Flores and Friswell, a simplified model, using constituents with approximately equivalent stiffness values were considered as analogues for the constituent materials of wood. Thus a new 3-component material was designed using alumina (stiffness 414 GPa, proxy for cellulose), magnesium alloy (31.26 GPa, proxy for amorphous cellulose), and epoxy matrix (2.6 GPa, proxy for the hemicellulose and lignin). As the stiffness for hemicellulose and lignin phase is around 1.0 GPa, both constituents were considered together. Therefore, inspired by the wood microstructure, a new material was designed as a 3-phase composite, which increased the capacity to absorb a large amount of strain energy before failure (Flores and Friswell 2012).

A further option considered by Chanliaud et al. (2002) has been to re-assemble cellulose microfibrils with hemicellulose and pectin as a matrix, to develop sheet materials which mimic the primary cell wall of plants. Although this study uses randomly aligned cellulose microfibrils from bacterial sources, this has allowed the effect of hemicelluloses and pectin on the stiffness of sheet material to be observed. More recent studies by Mikkelson et al. (2015), Prakobna et al. (2015), and Bonilla et al. (2016) are revealing the influence of interactions between the amorphous polysaccharides and the cellulosic fibrils and increasing understanding of the plant wall. This is leading to increased capability to model and predict behaviour of these composite sheet materials, or of hydrogels containing cellulose fibril reinforcement.

In this area we have therefore identified several different materials approaches to bioinspiration, with the long fibre composites being quite widely known and adopted, and others being at a demonstration level or academic study. Here the field of fibre composites is so well established that it is only certain researchers presenting novel designs who may highlight the biomimetic nature of the material. For example novel braided composites formed by Milwich et al. (2006), where pultusion of the braided cylinder formed artificial plant stems. Many other composites may also feature bioinspiration, but this is now indirect, such as filament wound composites, and multi-layered lay ups, due to their widespread adoption within the industry. Future developments with cellulosic composites and nanocomposites, using biopolymers and polysaccharides as matrices (similar to plant cell walls), are set to continue developing during coming years, and may generate a new generation of bioinspired materials which reach widespread market acceptance within the decade.

4.4.1 Plant Movements

The movements of plants are a fascinating area of study, and a great number of bio-inspired technologies have already resulted from study of the basic principles. These movements can be classified into two forms: tropic (direction dependent) and nastic (direction independent). Tropic movements are mainly in response to sun light, gravity, water, chemical substances, and mechanical forces. These responses are exhibited as, for example, phototropic tracking of sunlight (Trewavas 2009), the growth of stems and leaves, the flowing movement of cytoplasm in a cell, the bending movement of leaf bud because of differences of growth velocity, plants bending due to gravitational forces and touch-sensitive growth (Scorza and Dornelas 2011). In contrast, nastic movements are a response to non-directional stimuli, such as touch. This is well demonstrated by the Venus flytrap (*Dionaea* spp.) closing its leaf trap as a response to an insect touching its sensitive hairs (Markin et al. 2008, Guo et al. 2015). This ability of plants to react rapidly to mechanical stimulus, despite not having muscles or nerves has fascinated plant biologists, and has led to many attempts to transfer the concepts observed into materials and structures (Guo et al. 2015).

Plants offer a large number of mechanisms which can provide inspiration for adaptive movements (Forterre 2013, Oliver et al. 2016). These may relate to cell internal pressure – as seen in opening and closing of stomata (Franks and Farquhar 2007), or in the action of pulvinus tissue at the base of a leaf (Volkov et al. 2010). Alternatively they may use anisotropic alignments of cells, or of the dominant cell wall microfibrils, to achieve differential swelling, flexure or torsion on hydration or dehydration (either in live tissue, e.g. flower opening mechanisms (Figure 6, Liang and Mahedevan 2011), or dead tissue, e.g. pine cone scales or seed pods (Studart and Erb 2014)). Further, some mechanisms may be activated once only, such as the catapult action of redstem filaree (*Erodium cicutarium*) seed pods which involves dehydration then fracture (Evangelista et al. 2011, Abraham et al. 2012, Aharoni et al. 2012); while others are reversible, such as the opening and closing of the scales in a pine cone. The motion may be amplified by fast release of potential energy as seen in the bistable structure of the Venus fly trap closure (Markin et al. 2008, Forterre 2013) or may occur on a much slower time scale if reliant only on diffusion processes and sorption or desorption of moisture from the tissue. Plants thus blur the boundary between structure, material, and mechanism to regulate their motion (Schleicher et al. 2015), this in-turn helps plants to transfer force, torque and motion to their structural elements.

FIGURE 6

4.4.2 Application in Shape Morphing Structures

As noted above, there are several different strategies employed by plants to achieve movement, and each may be used to generate bioinspired solutions in new materials or in new components for motion within structures.

The first form is characterised at a cellular level, for example by tissue which is designed to rapidly reduce internal cell pressure in response to stimulus. One example is the touch sensitive leaves of *Mimosa pudica* where the leaflets respond to stimulus by folding, due to sudden decrease of cell pressure. The leaf later slowly returns to its initial position, as cell pressure in the pulvinus tissue is returned to its original state (Volkov et al. 2010). Here analogies can be drawn to pneumatic or hydraulic controls of hinged structures or building elements, and potential to develop cellular materials in which the pressure may be controlled to achieve movement of the element. There is some overlap with concepts explored within section 4.5, relating to the cellular structure into which the hydraulic effect is introduced.

Secondly at the microstructural level the plant cell wall structure (cellulosic microfibrils within a pectin, hemicellulose, or other polysaccharide matrix) may be specifically designed to ensure that change in hydration of the cell wall material results in an anisotropic change of dimensions, resulting in motion (it can also be combined with changes of cell turgor pressure to amplify the intended movement, as in the pulvinus example above). The degree of alignment of the cellulosic microfibrils is correlated to the degree of anisotropic expansion of the cell under an increase of turgor pressure (Charpentier et al. 2017). Therefore, the use of aligned stiff elements within flexible hydrogels has been investigated to achieve actuators for motion within automated systems (Erb et al. 2013, Ionov 2013, Gladman et al. 2016). A range of motions and folding actions have been achieved, many of which have bio-inspired origins, relating to microfibril angle within plant walls. Twisting motions can be achieved which mimic the opening of orchid seed pods as described by Armon et al. (2011) and demonstrated in synthetic materials by Wu et al. (2013).

Between the cell pressure model and the hydration of the cell wall model, the second form is most commonly adopted in shape-changing materials. Bilayers of materials with differently oriented fibres or microfibrils in a responsive matrix can be used. Oliver et al. (2016) classified movements occurring in plant tissues resulting from these anisotropic changes in volume. In hydrogel materials based on bioinspiration the stimulus could be hygroscopicity, chemically induced, heat driven, light driven, or result from electric or magnetic effects. The hygroscopic mechanisms are diffusion driven, and often require stiffening agents, such as cellulose microfibrils or nanoparticles to be introduced to the hydrogel with controlled orientation in order to create the flexing response. This could be achieved by various methods such as ultrasound or magnetic fields to align particles or 3D printing combined with extrusion to achieve aligned fibrils. This 3D printing method was utilised by Gladman et al. (2016) to create complex curvature and twist within bilayers of cellulose fibril reinforced hydrogel.

Many hydrogel based responsive materials are currently being developed for medical fields, rather than for building materials (Aguilar and San Román 2019). One area is photo-responsive polymers, which have potential application in smart surfaces, where texture and patterning alter wettability, or creation of responsive porosity in thin films, or hydrogels containing guest molecules (Bertrand and Gohy 2017). Initial steps are being made towards development of photo-responsive materials that can adjust angles or orientation in response to their environment, which may one day contribute to delivery of this bio-inspired concept. Photo-responsive polymers are the synthetic approach to the natural flexing process, for example reverse photochromism is exhibited by modified poly-L-lysine polymer solubilised in hexafloro 2-propanol (HFP), and spiropyran-modified poly-L-lysine acts as a photo-responsive system (Fissi et al. 1995). Kuksenok and Balazs (2016) developed a material based on a combination of photosensitive fibres and thermo-responsive gels that has the ability to reconfigure into various shapes when exposed to heat and light. These concepts are likely to be used in adaptive facades and passive ventilation in future buildings.

A third form of plant motion which has provided bioinspired materials and elements is based on mechanical response amplified due to the element design. These plant motions are induced by a third party, either prey or pollinator, interacting with the plant structure. Inspired by this design for motion in plants, Lienhard et al. (2009) identified an elastic kinetic system in the flower of *Strelitzia reginae*. The motion is an adaption for bird pollination, where the *Strelizia*'s perch bends down under the weight of the bird, causing simultaneous sideways rotation of the lamina by 90° to open the flower structure. After pollination and the departure of the bird, the flower closes with a combined elastic and viscoelastic motion. The movement of these plants, which is usually based on (visco)elastic deformation serves as inspiration for an innovative, biomimetic approach for creating responsive surface structures in architecture. A new fibre reinforced polymer (FRP) composite material was designed to deliver the high tensile strength with low bending stiffness, allowing elements to be constructed which showed large elastic deformation in the designed direction. The concept has also been developed into architectural design for a window and facade shading system (Masselter et al. 2012).

The hydrogel based responsive materials have been widely investigated, but at a laboratory scale often within the petri dish or beaker, whereas systems based on mechanical action or response to a mechanical displacement have been developed at larger scale, working towards elements for building facades. One exception is hygroscopic bilayers based on wood veneers (Holstov et al. 2015, Menges and Reichert 2012), which have also been used to form panels or incorporated in demonstration projects. These will be considered further in Section 5 as responsive materials are frequently sought for adaptive facades in buildings. While relatively few bioinspired elements are currently in use, this area of research is likely to remain active, and continue to stimulate innovation at the materials level in coming years.

4.5.1 Plant Cells as Inspiration

The cell wall ultrastructure is only one tier in the hierarchical structure of the plant itself, which defines the performance of plant materials. For example it is claimed that wood shows five levels of hierarchy, moving from the aligned cellulose chains of the microfibril, through the cell wall layers as a composite, and combined to form the laminated structure of the cell wall, to the distribution of cell types within growth rings of alternating early- and late-wood tissue, to the cylindrical assembly of these growth rings into the log (Hofstetter et al. 2005, Spear 2018). At the macro scale then it is important to consider the cellular material which is the wood itself. In annual plants the cellular structure is also a defining property, although cell walls may be thinner, and the functioning of the cell relies on hydrostatic pressure. A great many cellular structures can be found in the stems, roots, leaves, flowers and fruits of plants, and each may provide bioinspiration (Monniaux and Hay 2016).

Gibson (2012) proposes that differences in mechanical properties between wood tracheids, parenchyma taken from potato or apple, and tissue taken from palm trees can be related to the cell shape, in addition to the microfibrillar alignment within the cell walls. Advances in the understanding and modelling of load transfer and failure modes in naturally occurring foams such as balsa wood will inform design of bio-inspired foam systems (Malek and Gibson 2017).

There is also significant progress in modelling the mechanical properties of plant cells acting together within living tissue, which could have application within pneumatic or pressurised structures (Brulé et al. 2016). Abstraction of this concept is in early stages, however the advances in 3D printing and other manufacturing systems has allowed bio-inspired two-component materials to be fabricated to respond to stress, heat or other stimulus (Al-Ketan et al. 2018, Li et al. 2018, Xu et al. 2018).

4.5.2 Cellular Structures in materials and buildings

Use of cellular solids to achieve lightweight but high stiffness materials is a biomimetic concept, which has already been used in sandwich composites and advanced materials. Foam cores in composite materials are widely known and the engineering principles of sandwich composites well understood. Here the foam is used to separate face layers of stronger material at a distance from the neutral axis. Thus the tensile and compressive faces of the product may be optimised to resist bending load, while achieving weight reduction. Open celled foams and closed cell foams may provide different levels of stiffness due to the entrapped air, and the buckling behaviour of the complete network, therefore manufacturers seek to nucleate the foam of suitable pore dimensions and desired structure for the intended application.

More recent examples of materials based on plant cell structures have been demonstrated. Zou et al. (2016) studied the structural biology of bamboo and used the microstructure as a design template for developing thin-walled structures with improved crashworthiness. The cellular structure of bamboo has a graded distribution of vascular bundles, between the nodes, resulting in a radial gradient in density. The distribution of vascular bundles can be categorised into three regions i.e. intensive (56%), sub-intensive (25%) and sparse areas (12%). The advantage of designing thin walled cylindrical structures distributing vascular bundles as bionic elements in a similar way aims to improve energy absorption in a similar manner to the structure of bamboo.

At a building level examples of foams or cellular structures may also be seen. By looking at the performance of the cells themselves, or considering the load transfer achieved from cell to cell within a plant tissue, new efficiencies can be achieved. For example, modern building designs in cross-laminated timber in blocks of flats may utilise the mechanical efficiency of the individual compartments acting in combination as a cellular solid, one example is the Stadthaus, Murray Grove (Karl 2012).

Architects have also looked to cell packing and the efficiency of hexahedral or polyhedral forms to create domed and free-form building envelopes. The plant may typically have palisade cells in the epidermis of its leaf, creating a strong cohesive unit through which stiffness and flexibility are balanced to retain leaf shape despite wind or mechanical forces. Architects, seeking to create free-form exterior surfaces of buildings of stiff yet efficient lightweight design, may mimic this in the use of cell based structures. Some attribute the bioinspiration to the honeycomb of bees, or to the mineralised skeleton of radiolaria (Pottmann et al. 2015), and the technique has been abstracted into computer optimised design processes, which may in future make it difficult to attribute a specific bioinspiration source. A high profile example is the Heydar Aliyev Cultural Centre in Baku (2007), by Zaha Hadid Architects with Werner Sobek (Zaha Hadid 2012). The complex abstract form can be modelled using a weighted centroidal Voronoi tessellation (Pottmann et al. 2015). The space frame allowed the building skin to be free form, while the substructure incorporated flexible connections between the rigid grid of the structure and the space frame and its sheathing (Winterstetter et al. 2015, Januszkiewicz 2016). The skeletal space frame is entirely enclosed by the building cladding, the finished structure therefore simply expresses the weightlessness, undulations and fluidity of the form.

4.6.1 Branched Structures

Branching in biology is a well-known phenomenon that relates to plants and especially trees, providing structurally optimised forms to support the canopy in a mechanically efficient way. As a basic biological need, tree leaves need fluids and water. The branching often also delivers spatial optimisation of leaves for light and air circulation, ensuring the canopy is sufficiently open. In annual plants branching of the stem guides leaf placement, flower formation and fruiting or seed head formation (Sussex and Kerk 2001).

Branching systems are classified as nihil, apical or lateral, and can be exogenous (in the case of stems), or endogenous (in the case of roots) (Hallé 1999). The angle and placement of branches in three-dimensional space relative to the primary stem can influence many biological functions, as well as altering the required mechanical stiffness. Considering the tree branches in particular, many are optimised for supporting compressive loads, acting as a downward force, and may therefore adopt only a small angle away from the vertical of the trunk. Others, at a greater angle from vertical become subject to bending loads, and may contain tension wood on the upper side (in hardwoods) or compression wood on the lower side (in softwoods), in order to maximise performance. For the non-woody plant strengthening in branched tissue may be achieved in the form of the cross section of the stem or leaf bract, to achieve efficiency through design. There are therefore many aspects of plant anatomy which may serve as stimulus for bio-inspired approaches to structural systems.

Leaves are considered as essential organs in trees, which generate food through photosynthesis, requiring exposure of a large surface area, and relying on gas transfer through the leaf surface by stomata. Placement of leaves is therefore an essential criterion, which also relies on branching. The majority of trees morph the outer shape of the crown so that leaves can be exposed to sunlight throughout all the hours of daytime, with the sun path from morning to evening (Rian and Sassone 2014). The strategy adopted for this varies from species to species, resulting in the characteristic form of the crown in spruce (conical) being very distinct from the dome-like habit of a maple, for example, with the habit of many other species falling between these extremes.

4.6.2 Tree inspired dendriforms and branched structures

A dendriform is an imitation of the form and shape of a tree or plant. It has long been recognised that the structural efficiency of branching seen in plants and trees can be transferred to development of efficient structures in architecture. Study of the principles underpinning tree branching patterns reveals the efficiency of energy and resource use. These principles also offer potential in developing bio-inspired structural forms based on branching or stem patterns.

Although there are many complicated and elegant methods available to design a branching architecture, several simple models also exist in the literature, which use simple rules, functions and random variables to produce branching patterns. These include a genetic algorithmic approach for minimal paths; the area and volume filling fractal trees using Tokunaga taxonomy (Newman et al. 1997); a computer simulation employing the concept of cellular automata; a 3D tree generation with a data-driven modelling approach; and the application of L-systems to the generation of botanical trees.

In the computer models, bending of branches can be simulated, branching angles can be manipulated, and geometric parameters such as the length and diameter of the internodes can be altered. Figure 7a demonstrates the computer simulation branching patterns following four different iterative steps (Rian and Sassone 2014). The models obtained from the above approaches are further considered to develop and test prototype for the functionality aimed at for building applications.

FIGURE 7

Interesting architectural approaches such as tree-like internal components to support the roofs of large, open buildings are an efficient way of stabilising large roof structures (Rian and Saasone 2014) while minimising the amount of usable floor space that is taken up. The architectural articulation of tree patterns observed in many buildings aims to provide lightweight structures. For example, Bangalore international airport (built 2010-2015, Figure 7b), and Orient Station in Lisbon, Portugal (built 1993-1998, Figure 7c). Steel tree-columns are also the main structural element in the interior of Stuttgart Airport Terminal (built in 1992, Rian and Sassone 2014). Pinned connections and bundled base were used design of the branching columns of the Stuttgart, Germany airport terminal, designed by Frei Otto at the Institute for Lightweight Structures at the University of Stuttgart (Figure 7d).

Development of branched structures can be inspired by branched biological concept generators, such as the *Schefflera arboricola* tree studied by Born et al. (2016). Here the prominent vascular bundle arrangement at leaf insertion zones provided inspiration to consider fibre composite sheathing for concrete structures, to retain or enhance performance at branching points. Fundamental principles were abstracted from the ramifications at the branching points within the plant for application to fibre reinforced plastic tubes (Bunk et al. 2017).

Current material systems used for branching structures include steel, solid wood and glue-laminated wood. To reduce the weight of the structures further, Masselter et al. (2016) proposed fibre-reinforced composites that can replace steel or wood with an optimization of form and design of fibre-arrangement to create bioinspired technical branched fibre composites. The morphology of the stem-branch attachments was based on systems found in arborescent monocotyledons, and columnar cacti, and were used to develop Y-shaped, and T-shaped branchings that are present in technical structures. Masselter et al. (2016) proposed braiding techniques, and manufactured a prototype braided Y-shaped preform. Carbon-fibre reinforced polymer (CFRP) specimens was carried out on a single and multi-layer (diamond) braided composites to evaluate the mechanical properties. These braided profiles pillar connections must allow high deformation in case of a crash and therefore could be produced with a less stiff conventional diamond braid pattern with stationary threads that allow for high-energy absorption.

In both the cellular structures and the branched structures, the majority of examples provided above have centred more on the structural element, superstructure or complete building, rather than examples from the materials perspective. They may draw upon existing or emerging materials to deliver this, and may highlight other aspects of computation or engineering where advances may help deliver the bio-inspired concept. In terms of materials innovation, fewer directly plant-inspired examples were found, either due to widespread prior acceptance of the materials or the bio-inspired source not being stated by the researcher. It is likely that further developments in cellular structures will occur, relating to the ease of access to 3D printing for example.

5. Transfer of bioinspired materials into building designs

Examples of plant forms influencing the design of building structures are often presented (Yuan et al. 2017, Spear 2018), however these aspects are of lesser importance to this review of bioinspired materials and elements within buildings. Several of the material developments discussed in previous section can be applied to buildings or building elements. For example, the reduction of required maintenance to building structures by using products based on the ‘Lotus effect' and 'self-cleaning' principles. Lotusan façade paint can be applied to building masonry or rendered surfaces to extend the life of bright façades as rain naturally picks up dirt and washes it away (Benedix et al. 2000, Daoud 2013). Self-cleaning glazing has become widely used for high-rise structures, where window-cleaning services would be difficult, and can be applied to maintain optimum light transparency in the faces of solar panels.

Other proposed concepts for buildings require sensing, reaction, locomotion, adaptation and differentiation, processing of information and energy operation, which can also be influenced by nature and bioinspiration (Mead 2008, López et al. 2017). For example the move to passive control of ventilation or shading, self-regulated by the building would require sensing and control systems (Biggins et al. 2003). Thus the first intention, to mimic regulation of water use and sunlight capture in plants, achieved by leaf angle changes, must be assisted by technologies for sensing and response. Additionally, when applied to buildings, these new concepts and designs may require new construction materials, or new composite building elements, also based on advanced technologies, in order to perform the intended nature-based mechanisms. As a result, new materials and new building design concepts are combined, for example to derive advanced adaptive facades (Fiorito et al 2016, López et al 2017).

Six biological mechanisms inspired from plants and applied to materials within buildings were explored in Section 4. The two examples which follow have been selected to develop from the materials concept level up towards the building element level. They show the state-of-the-art related to concepts transferred from plants to buildings. By considering these, it is possible to highlight and discuss advantages and limitations as seen in the approaches taken and progress demonstrated to date. The implications of this will then be discussed and reviewed.

5.1 Plant Leaf Movements applied to Shape Morphing Structures

A multitude of plant motions have been investigated for building facades and shading systems. Plant leaves exhibit photo-tracking as they adjust to follow the sun daily, or grow to maximise solar radiation capture on their surface. Adjustment may also be made to reduce drought stress by decreasing the area presented to the sun during periods of excess heat. A prime example of this is the sunflower (*Helianthus annuus)* that demonstrates considerable and well-studied phototropic solar tracking behaviour (Kutschera and Briggs 2016). Sunflower leaves show complex control adaptations in order to adjust the angle of their leaves to either selectively capture maximum light or reduce it when the intensity is too great. Shade avoidance responses are used to maximise light-driven CO_2 assimilation (Kutschera and Briggs 2016, Masselter and Speck 2009). This has inspired research into optimising angles in the receivers for heliostat fields in concentrated solar power systems, with the proposal of programming a response to the movements of the sun (Renzi et al. 2014). While heliostats are typically installed in arid or high solar gain landscapes, the concept has also been modelled for the urban landscape in vertical heliostat fields (Gonzalez-Pardo et al. 2013, Gonzalez-Pardo et al. 2014).

The same principles can be applied to shading or ventilation for buildings (Badarnah and Knaack 2008). Energy efficient buildings require building envelopes which are interactive and responsive to natural inputs like solar radiation, daylight, and seasonal wind, in a similar manner to a plant's responses (El Ghazi et al. 2017). Therefore, building facades can be designed as living skins using bioinspired systems, learned from plant biology. It was previously noted that plants possess several different strategies for motion (Forterre 2013, Oliver 2016). These are achieved by different mechanisms both in the live plant, such as leaf angle – under active control, and in dead tissue, such as pinecones – programmed to deliver a movement independent of any biological control, at a future point in time. Both active (stimulus induced) and passive (functioning based on environmental conditions) systems have been investigated for building skins.

The elastic and dynamic movements of plants have been mimicked to develop kinetic structures that can react to internal and external stimuli through specially design spatial systems. The flexible motion principles in plant movements are transferred into new design and developments of bio-inspired mechanical devices that can control heat, light, humidity and ventilation.

Several research groups have considered designs for building exteriors that utilise plant inspired structures, and in particular plant-inspired motion concepts, to create a building envelope which functions as a "living" skin (Gruber and Gosztonyi 2010, Schleichter et al. 2015, Yowell 2011). This skin could provide smart ventilation, adjustable shading, deployable solar collectors or other elements rather than the simple facade systems of inert materials more commonly used, which supply only structure and protection (Gruber and Gosztonyi 2010).

An advanced skin system that acts similarly to the plant's epidermis, cuticle or bark, regulating the flux of gases and water vapour into and out of the plant by adaptive elastic and dynamic movements provides opportunities for controlling the indoor and outdoor environment of the building enabling better internal ventilation. Ventilation within wall elements, based on the motion of pine cone scales were proposed by Holstov et al. (2015) and bilayer elements harnessing this principle have been demonstrated (Reyssat and Mahadevan 2009, Cordero and Smith 2013, Reichert et al. 2014, Holstov et al. 2015), and deployed in structures such as the Hygroskin meteorosensitive pavilion created by ICD, University of Stuttgart (Menges and Reichert 2012).

The system also has the potential for controlling quality of light within the structure (López et al. 2017, Badarnah 2017, Gruber and Gosztonyi 2010). The building envelope/skins acts as an interface between the exterior environment and the occupied interior spaces. Envelope elements can be a roof frame, external wall, windows, external doors, floor, and ceiling and their finishes. Fiorito et al. (2016) reviewed shape morphing solar skins using the interface of shape memory materials and alloys as intelligent shading components. The materials used in the building envelopes work as actuators designed to move components that control shading, to increase threshold comfort levels automatically.

The skin forms an active negotiator between the organism and its environment (Gruber and Gosztonyi 2010). Adaptive building skin systems generally consist of an outer membrane (that is watertight, but ventilated to allow air through); an insulation layer (which is sound proof, provides thermal insulation) but permits light accessibility through eye-shaped openings (operational dimension of the opening, and light accessibility), and contains structural elements (which may be visible as well as providing their structural capability); and finally an inner membrane (which is visible to occupants and must permit ventilation).

To design adaptive skin systems for buildings, researchers frequently use information technology based design techniques (Loonen et al. 2017). These advanced skin systems have capability to respond in real time to data, in the same manner as plants respond to environmental stimuli. Therefore communication and data-regulation protocols are essential in these building systems for sensing and processing contextual information such as air flow rate, temperature, humidity or moisture, sunlight and user proximity. Biloria and Sumini (2009) designed a strategy for inter-relating environmental parameters and topological transformation of a building skin system by introducing building information modelling protocols. Biloria (2009) developed real-time simulation tools to demonstrate the intrinsic inter-dependencies between data, structure, and material logistics resulting in smart building skin systems.

5.2 Plant adaptive dynamic movements leading to Smart Building Ventilation

One example of the scale up of a concept derived from plant motion into the flexing of building elements is the Flectofin concept (Lienhard et al. 2011). This is based on the elastic kinetic system seen in the flower of the bird of paradise plant, *Strelitzia reginae*. The deflection of the perch under the weight of a bird landing on the flower causes a sideways rotation by 90° to open the flower structure, as reported by Lienhard et al. (2009). Based on this concept the research team developed a hingeless louvre system that is capable of displacing its fin by up to 90° and could have application in adaptive shading or responsive facades. The concept was then scaled up into elements of 2m to 14m length manufactured using fibre reinforced composite to evaluate the potential for building applications (Lienhard and Knippers 2013).

The scale up study revealed that the scaling of elastic systems is highly dependent on the influence of dead load and stability (Lienhard and Knippers 2013). The stabilising effect of tensile curvature and destabilising effect of residual compression stresses may be encountered, with potential for self-stiffening effects if the component is under tension in its deflected state, as was observed for Flectofin. It was also observed that component thickness was not scaled by the same factor as length. An upper limit is imposed on the potential for scaling, based on the dead load.

The use of FEM modelling was important in the process, allowing the project team to test the bioinspired system under different geometrical and structural considerations. It also allows permutations of the design to be considered which depart from the precise form of the biological role model, yet function according to the principles abstracted from it. Further, materials combinations to deliver the necessary stiffness and motion can be evaluated (Schleicher et al. 2015).

On the basis of the Flectofin case study, and two others developed from a lily opening mechanism and the closure of an *Aldrovanda* carnivorous plant trap, Schleicher et al. (2015) hypothesize that plant motions can be transferred into large-scale compliant mechanisms in architecture. The application of multiple Flectofin elements on a double-curved surface of a high rise structure was one case study considered. Tessellation of multiple elements is required, and various options for arranging the elements together onto the building surface can be considered, which may require adaptation of element form. The *Aldovandra* inspired elements and the lily inspired elements were modelled on an elliptical domed surface, giving rise to discussion of the effect of shading achieved on different points of the building surface, and the suitability for elements to overlap without interfering with the performance of neighbouring elements. It is clear that design challenges at the building level will occur, possibly influencing the design of individual elements to ensure delivery of the building facade. Control methods are also required, for the *Aldovandra* example it was suggested that one actuator would drive the opening or closing of four elements. The arrangement of the elements on a quadratic grid, with four wings meeting at the centre of a square aperture may be the inspiration for this.

6. Discussion

For each of the six examples of plant concepts identified within this paper (self-cleaning, self-healing, cell wall microstructure, plant movements, plant cells and branching) several bio-inspired material examples were presented which have been researched and demonstrated at the lab scale. Several of these have been developed further into building elements, while others may rely on advances in technology before they may be fully deployed. This indicates that the route from concept to building element has only partially been mapped, and challenges may be encountered in scale up or development of prototypes at the next working scale. It is therefore interesting to consider the research challenges which will present the greatest barriers to development, yet offer great rewards if successfully overcome. A great many other concepts, currently under exploration in biomimicry, have not been reported or reviewed in this paper, however may also encounter similar technical or practical issues.

In the case of plant motion for example, reviews of the topic indicate that research is ongoing to further develop the various classes of plant motions (Forterre 2013), identifying specific mechanisms and details from different plant species. This will yield further variations of bio-inspired responsive materials or bio-inspired designs. Similarly, while simple examples of cellular material were discussed here, the use of advances in computer modelling to predict mechanical behaviour of complex cellular forms is likely to yield many further designs, and allow exploration of plant-inspired cellular forms as structural systems. Botany provides a well-stocked library of design concepts, structural forms and efficient use of materials, which may be harnessed by the materials scientist and the architect. The intention of this section is to use the examples presented previously to abstract various of the key challenges and research questions which are emerging in the area of scaling up biomimetic concepts to the element level.

At the materials level, one of the barriers is the precision in manufacturing, for example the challenge of precision in assembling, aligning and manipulating the components for plant-inspired responsive materials, such as multi-phase hydrogels or nanofiber reinforced composites. The progress to date has been achieved due to dramatic improvements in precision manufacturing, 3D printing, 4D printing, alignment of fibrillar reinforcement in polymer melts or fluids, laser and plasma etching, nano-deposition and many other techniques. These advances are likely to continue, allowing materials scientists to seek new designs in composites or new combinations of hydrogel-based responsive matrix material from which shape morphing designs can be developed. However the cost of such techniques, and such materials may be high, and prohibit wide adoption of the technology, especially in architectural applications. Current hydrogel research and development is at small scale, and targets biomedical applications. In the long-term transfer of these techniques to larger scale lower cost applications may be expected.

Another challenge is longevity, or durability in service. Many of the shape morphing materials are currently developed with short term applications in mind. By contrast, construction applications require long term performance, and even well accepted materials such as Perspex, paints, timber and concrete are known to alter their properties over time, depending on their location and exposure to ultraviolet light, oxygen, carbon dioxide or water. If shape morphing materials from hydrogels require a hydrated state, their suitability for long term applications is likely to be low, with loss of functionality once moisture is lost. The most iconic application for plant-inspired use of shape morphing materials are in adaptive facades, yet here a long service life (circa 25 years) would be desired as a minimum. Exposure to harsh conditions (UV light, heat, fluctuating relative humidity, rainfall) would also lead to earlier failure of sensitive shape morphing elements. Therefore systems which utilise the same concepts, but without the risk of short service life materials could be investigated to provide an alternative for this application.

Durability is a key criterion for many materials in the context of the built environment, which has given rise to interest in self-healing as a strategy to extend service life of some composite materials and mineral based materials. The future potential for self-healing in new materials is therefore highly relevant, and further consideration of opportunities in this area may be beneficial. Service-life prediction will also remain a very necessary field of study as new materials or combinations are explored. Advances in understanding the effect of UV light or rainfall on performance of paints and coatings may therefore be transferred into new responsive materials, for example incorporating UV stabilisers or free radical scavengers to enhance product longevity for the built environment applications.

Scale factors were well explored by Schleicher et al. (2015) in reviewing three architectural elastic systems, which included the Flectofin system reported earlier, and more recent developments such as the Flectofold system (Körner et al. 2018).

The first point is that while buildings may already use mobile elements, e.g. flaps, vents, louvres, blinds, shutters, these are frequently simple hinged structures, whereas natural analogues of these tend to act as a whole element rather than a simple hinged joint (Schleicher et al. 2015). Taking the pinecone scale example previously introduced, the motion is achieved by curvature of the scale, not a rotation about a single point. This may present a challenge to building design, where conventionally the services engineer may seek a vent which is fully open, or fully closed, with simple gradations in between these states, not curving into the closed position, and curving into the open position, with the curvature of the biomimetic flap material generating a non-linear alteration in air flow rate for the intermediate states.

Even hinge-less systems may require consideration of a hinge region, and complex combinations of forces. The Flectofold system, based on the underwater plant *Aldrovanda vesiculosa*, sought to use a hinge-less motion, in order to reduce failure due to repetitive motion, which often occurs at hinges (Körner et al. 2018). However, when comparing different actuation systems, materials combinations and manufacturing options, while seeking to increase in scale, the increased thickness of hinge zones led to potential for material failure from shear and tensile forces. A number of iterations were considered prior to selection of acceptable geometry and materials combinations for the larger prototype system. A pneumatic actuator, and an element with midrib length 850mm, were used to demonstrate potential scalability of size, and successfully tested to 1000 cycles.

The hygromorphic pine cone example also hints at a second challenge to the building design team in using bioinspired materials and systems, as nature uses compliant materials in preference to rigid elements. Compliance (the inverse of stiffness) is a property which is rarely utilised in engineering, or used only for specific applications, such as design of flexible seals or accommodating different levels of motion in joints between adjacent segments of a structure. Viscoelasticity, creep and time dependent behaviour may therefore play a greater role in future bioinspired materials and designs, requiring a transfer of specialist knowledge into common use. Such concepts are commonly considered in the mechanical properties of wood and other biological materials (tendon, muscle etc.) yet are simplified into factors for load duration within engineering design calculations. Timing is also a key element in designs which use such bioinspired shape morphing materials. Oliver et al. (2016) noted that while the swelling induced actuation could take place over a wide range of time scales (milliseconds to hours), the rate could be accelerated by various means, such as volume change plus fracture (irreversible), volume change plus pressure drop due within the cells causing cavitation and spore release, and the use of bistable structures such as the Venus fly trap. These changes happen through the transport of ions, movement of fluids, and permeability changes resulting in key volume changes such as swelling, buckling, and cavitation.

New design challenges will emerge, relating to application of bioinspired elements into larger assemblies required for a building, whether this a facade, an interior element or a less prominent component within the building services. If the bioinspired element relies upon shape or form in order to function, this shape must be suited to tessellation with adjacent elements, to be successfully incorporated into the building form. Some research has addressed suitable tessellation options, to make up a larger surface which functions as intended (Menges and Reichert 2012, Holstov et al. 2015). Partial or truncated elements, on the edge of the wall or facade, may present a challenge, as their incomplete shape may inhibit motion, for example. The element shape and size may require adaptation for edge regions, or may necessitate different combinations of materials to alter stiffness, regulate motion and retain a deflection which is similar in magnitude to neighbouring full sized elements. If such structures are used as flaps or valves within ducting, any change in diameter of the ducting may require redesign of the element, or may alter flow rates. Conversely the use of a standard sized bio-inspired flap assembly might lead to over-sized ducting and incorrect airflow for the design requirements. Each of these issues is solvable, given time and thought, but the pressure on architects and building technicians is to deliver the new concept on time, on budget and using fully worked concepts. Where concepts are one-off inventions specific to the project, these time constraints may lead to pressure points in these areas, where bio-inspired elements are being installed into the building.

In addressing these challenges it may be necessary to deviate from the commonly accepted models of bioinspiration (top-down and bottom up) to a holistic approach which can accommodate multiple inspirations and adaptations to deliver the final functioning element or structure. The resulting combination of bioinspired material (e.g. a responsive bilayer wing) which then requires a secondary bio-inspired trait (e.g. self-healing) to accommodate stresses in situ will lead to multi-functionality of the material. Here two biomimetic concepts act in parallel. Inspirations may also be applied iteratively, as demonstrated in the evolution of different lay-ups of materials to deliver the Flectofold system. Concepts may also be applied sequentially, i.e. a responsive bilayer is produced (material level), which is applied in a flexing element within a wall facade (element level) for ventilation, and adapted to adjust the aperture, the orientation of the flaps, and the surface colour or coating to promote or inhibit direct and reflected light from entering the building (additional or secondary benefit).

Many of the newly developed phytomimetic materials discussed here may improve delivery of biomimetic concepts on the whole building scale, resulting in greater potential for bioinspired building designs. If the living skin concept can be combined with shape morphing materials, to deliver passively controlled systems there may be benefits in terms of energy efficiency, solar shading (avoiding overheating), passive ventilation, each contributing to greater efficiency of the building in service and occupant comfort. Similarly, if building integrated photovoltaic systems can be combined in multi-functional elements such as photochromic glazing, the additional benefit can be delivered without increasing the thickness of the building envelope allowing design flexibility. Simplicity in delivery of these additional benefits is required to avoid unnecessary consumption of materials.

Performance simulation will be required, to ensure that the building performance is in line with national requirements (in terms of energy efficiency, ventilation and other parameters), and is delivering a beneficial level of performance compared with conventional designs (Loonen et al. 2017). In this area it is particularly important to consider the simplicity for building occupants to understand the systems, and any provided over-ride functions, to ensure the environmental benefits of passive ventilation, shading, humidity control, water management or lighting are delivered in practice. Reports from post occupancy assessments of simpler structures highlight the need for training and simple guidance to occupants or building managers to best understand and utilise the smart technologies within the structure. Over-complex designs and systems may inhibit occupant understanding, and present future challenges for service engineers and maintenance activities.

7. Conclusion

Plants play a key role for the inspiration of new technologies inspired by biological principles due to their similarity to buildings in their static nature. Both plants and buildings need to manage their interaction with the environment to control internal conditions. This results in many useful strategies which may be abstracted from the plant and applied to building elements, such as adjustment of leaf angle and opening and closing of structures with daylight or other stimulus.

The review of current and emerging technologies presented here, demonstrates the potential of biomimicry and bio-inspiration drawn from plant biology in new materials, building elements and architectural design. It is evident that new bioinspired concepts in architectural design are becoming popular. It is expected that ultimately this will spill over into mainstream construction industry. Modern houses with new features inspired by nature will contribute to sustainability targets through the use of responsive elements, or altered design.

In the future, developments in bio-inspired materials, and manufacturing techniques required to fabricate these materials, are likely to lead to further significant improvements. For example, new materials may provide the multi-functionality required to permit development of biomimetic designs at a structural or whole building level. Access to newly developed responsive materials may also improve delivery of biomimetic concepts on the whole building scale, resulting in astonishing buildings. The concepts such as living skins, building integrated photovoltaic systems, and shape morphing structures are some of the emerging concepts being developed and demonstrated in architectural designs. Benefits include increased energy efficiency, reduced cost, reduced CO_2 emissions, and occupant comfort, health and well-being.

However, if these new materials, functionalised surfaces and self-healing capabilities become more frequently used in new buildings, they require further development to ensure service lives which match the expected performance of construction materials and building elements. There are benefits, such as self-healing and self-cleaning, which may be required to deliver this longevity. Another essential element is likely to be the sensing or response to stimulus needed for passive operation in the building. This could be achieved using bioinspired responsive materials or advanced sensor systems within buildings, to deliver the intended regulation of internal conditions to promote occupant comfort and energy efficiency. If correctly designed, installed and implemented, they will have a strong influence on building whole life performance.

Interdisciplinary collaborations between biologists, materials scientists, architects and engineers are highly desirable to continue the evolution of biomimetic concepts in the context of the built environment and construction. Scientists and engineers should continue to work jointly to formulate new strategies and innovative research ideas for implementation at all levels, from materials design, structures and forms, through to delivery of integrated whole buildings. There is a great future for bioinspired architectures within modern building designs.

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Figure 1a) Biomimetic Framework - Biological Push and Technological Pull Model (Gruber and Imhof 2017)

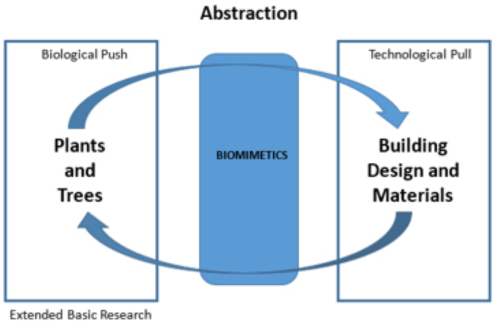

Figure 1b) Design Concept Generation (López et al. 2017)

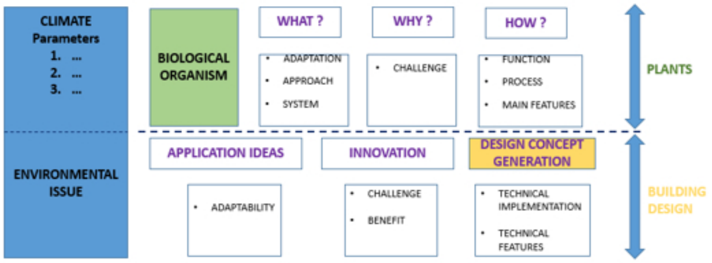

Figure 1c) Transition of a Biomimetic Design Process (Heil and Salgueiredo 2016)

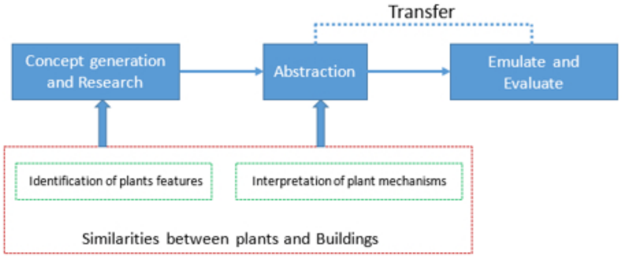

Figure 1. Role of biomimetics in bringing new concepts from plants to buildings

165x232mm (96 x 96 DPI)

Figure 2. Water repelling surfaces: Example - Lotus (Nelumbo spp.) leaves (Karthik and Maheswari 2008)

225x91mm (96 x 96 DPI)

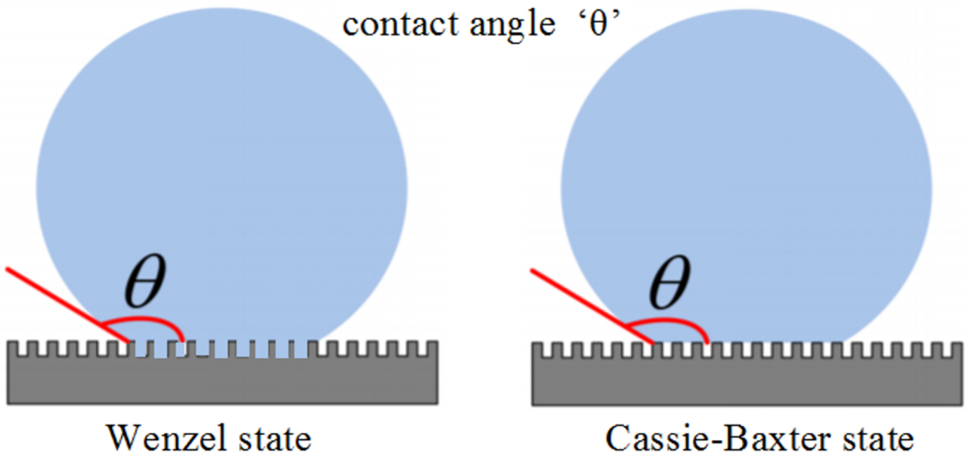

Figure 3. Regimes of wetting of a rough surface

292x134mm (96 x 96 DPI)

Figure 4. Self-repairing plants (Delosperma cooperi) (Konrad et al. 2013)

147x92mm (96 x 96 DPI)

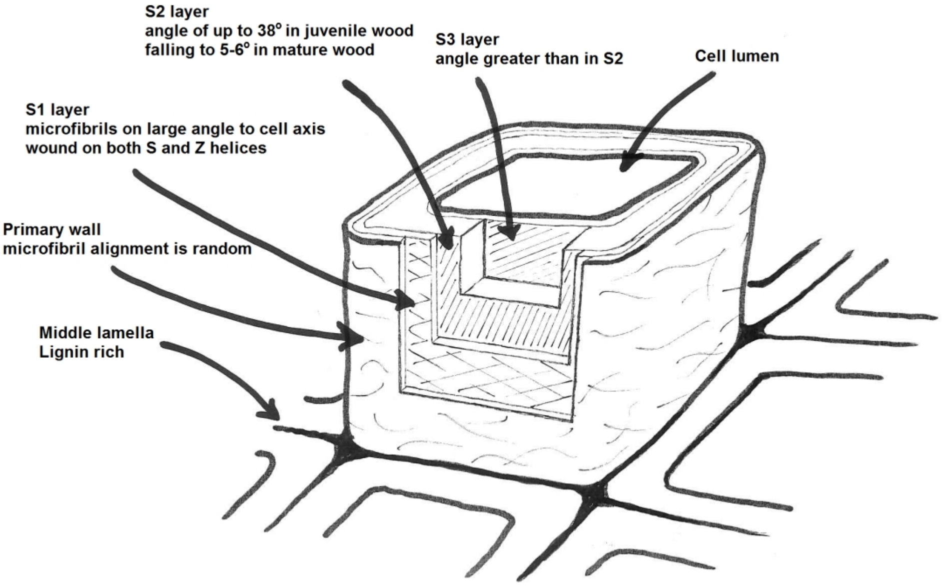

Figure 5. Schematic of a tracheid in softwood xylem, showing a cross section and cut away layer-by-layer to indicate the microfibril angle. The Secondary wall comprises S1, S2 and S3 layers. Source: Xing et al. 2018.

512x395mm (96 x 96 DPI)

Figure 6. Opening movement of lily bud and reversible moisture driven opening and closing of spruce cones (Al-Obaidi et al. 2017; Schleicher et al. 2015)

303x114mm (96 x 96 DPI)

a) Computer simulation for branching patterns

b) Bangalore, India International Airport

c) Oriente Station, Lisbon

d) Structural 'trees' in Stuttgart Airport

Figure 7. Tree inspired and Fractal-like branched structures and examples (Rian and Sassone 2014)

179x124mm (96 x 96 DPI)

Table 1: A Framework for the application of biomimicry to building design (adapted from Pederson Zari 2007)

Level of Biomimicry		**Example – A Building that mimics Plant/Tree**
Organism level (Mimicry of a specific organism)	Form	The building looks like a plant or tree. Example: it has a columnar form
	Material	The building is made from the same materials as a plant. Example: it is made of timber or cellulose
	Construction	The building is made in the same way as a tree. Example: it is made of cells, or it has growth rings
	Process	The building works in the same way as an individual plant/tree. Example: by selection of proper orientation for solar gain, shape and form to adapt building to local climate, incident light, shading
	Function	The building functions like a tree in some context; Example: it collects sunlight and utilises to this energy for metabolism (analogy – to heat the building, whereas plant leaves harvest sunlight for photosynthesis)
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	Form	The building looks like it has a plant form. Example: it replicates the structural patterns of leaves or branches
	Material	The building is made from the same materials that a plant/tree grows with. Example: Sequential deposition of tissue, as seen in plant bark, or tree trunks – tree bark for protection, insulation etc. Example 2: Elements which are designed for removal and regeneration, as seen in plant leaves – design for disassembly
	Construction	The building is made in the same way that a plant would grow in. Example: plant roots grow under the soil, whereas building foundation goes under the soil
	Process	The building works in the same way as a plant. Example: Growth and tropic responses in plants optimise light capture or air flow around leaves, fruit etc, analogy – the responsive elements regulate building conditions
	Function	The building functions in the similar way that a plant behaves in the environment: Example: internal conditions are regulated to be optimal and thermally stable by opening and closing stomata (in plants – respiration, transpiration, temperature) – analogy with passive or dynamic ventilation strategies in buildings, using adaptive facades
Ecosystem level (Mimicry of an ecosystem)	Form	The buildings look like an ecosystem a plant would live in. Example: multiple high-rise structures acting together to create a local environment – influencing shade, sun, deflecting prevailing wind at street level vs roof terrace level
	Material	The building is made from the same materials that a plant ecosystem is made of. Example: the use of green infrastructure to introduce sustainable drainage, passive temperature regulation, reduce urban heat islands, improve air quality.
	Construction	The building is assembled in the similar way to a plant ecosystem. Example: plants are combined together in the ecosystem to generate a canopy structure, principles of succession and altering complexity over time, as buildings are added or replaced in urban areas
	Process	The building works in the same way as plant ecosystem. Example: it forms a microclimate at each level in the canopy, and influences humidity and air quality between buildings for example. Leaves scatter light or slowing rainfall run-off, altering conditions at the forest floor, analogy – building facades reflect and scatter light and alter temperature.
	Function	The building functions in the same way that a plant would in its ecosystem, forming part of a complex system, formulating relationships among various processes. Example: multi-functional approach to building design in the urban context can deliver holistic benefits for occupant comfort in adjacent structures, or for pedestrian comfort.

Table 2. Plant characteristics, mechanisms, and their inspiration to new technical innovations

Plants – Basic Mechanisms	Basic Principle Observed	Technical Innovations	References
Cell Wall Structures	Crystalline polymer cellulose is assembled into long microfibrils that have higher stiffness than surrounding hemicellulose and lignin matrix.	New composites with varying fibre orientation and alignment	Bashline et al. 2014
Surface textures give functional surfaces	Surface wettability induced or reduced by micro and nano-texture. Water channelling, harvesting and management on plant leaf	Self-cleaning materials and corrosion resistance	Barthlott et al. 2017
Photosynthesis	Synthesis of oxygen and energy storing compounds from carbon dioxide and water, using sunlight energy through the green pigment chlorophyll.	Chemical mechanisms found in plants resulting in a new approach that uses sunlight to split water into hydrogen and oxygen Light-harvesting photonic materials	Janik et al. 2017 Brimblecombe et al. 2008
Nastic motions	Response to stimulus, such as touch, by mechanical reaction based on structure.	Shape morphing structures and adaptive facades	Li and Wang 2016, López et al. 2017
Tropic responses	Response to stimulus such as growth towards sunlight, control of leaf angle	Heliostat fields with adjustable angles	Renzi et al. 2014, Gonzalez-Pardo et al. 2013, 2014.
Stomata Mechanisms	Opening and closing of stomatal pores to control transpiration and respiration. Concentration of solutes in the pairs of guard cells controls opening/closing.	Responsive facades in architecture Microfluidic devices such as Thermo-responsive stomata-inspired membrane (SIM) and mesophyll-inspired agarose cryogel (MAC)	Gruber and Gosztonyi 2010, Hõrak et al. 2017 Kim et al. 2016,
Self-healing	Wound-sealing processes generate a protective drought layer, or formation of callus tissue	Use of microencapsulated healing agents in concretes or fibre composites.	Hillewaere and Prez 2015
Plant Architectures	Diversity in the growth patterns of apical and axillary meristems, e.g. branching, leaf placement and stem angles, for optimal light capture, shade or air circulation	Innovative design solutions for placement of windows, balconies, shading structures Modern structures inspired from plant architectures, e.g. dendriform structures	López et al. 2017, Sussex and Kerk 2001, Born et al. 2016, Rian and Sassone 2014
Light Harvesting Mechanisms	Regulating excess light by a non-photochemical quenching process	Light harvesting mechanisms through energy transfer and photoprotection processes leading to photovoltaic solar panels	Pan et al. 2013
Cellular structure	Optimisation of structural or mechanical properties based on cellular forms, from high	Architected cellular materials	Schaedler and Carter (2016)

	compressive stiffness in wood, to plate stiffness in leaf design		
Stiffening effects	Use of ribs, thickenings and different tissues to create stiffness	Braid-pultruded artificial plant stems based on horsetail stems, and giant reeds for	Milwich et al. 2006
Design for unfolding and re-folding	Structures designed to grow from within the bud, by expansion, unfolding and increasing turgor pressure. Leaf design to minimise wind resistance by folding (broadleaves) or by needle-shapes (conifers)	Structures for rapid assembly, or collapsible structures, e.g. inflatable, ribbed, or modular units for disaster relief Origami approaches to kinetic skins	Pesenti et al. 2015, Li and Wang 2015
Decellularization	Plant tissues such as xylem may be programmed to decellularize, removing cell contents, leaving behind a cellular scaffold as a structural form	Plant cell scaffolds for bioartificial heart	Gershlak et al. 2017