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Review

Biomimetics and Composite Materials toward Efficient Mobility: A Review

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Abstract: The development of new materials has always been strictly related to the rise of new technologies and progressively efficient systems. However, cutting-edge materials might not be enough to ensure the effectiveness of a given product if the design guidelines used do not favor the specific advantages of this material. Polymeric composites are known for their excellent mechanical properties, but current manufacturing techniques and the relatively narrow expertise in the field amongst engineers impose the challenge to provide the most suitable designs to certain applications. Bio-inspired designs, supported by thousands of years of evolution of nature, have shown to be extremely profitable tools for the design of optimized yet structurally complex shapes in which the tailoring aspect of polymeric composites perfectly fit. Bearing in mind the current but old-fashioned designs of auto-parts and vehicles built with metals with little or no topological optimization, the present work addresses how biomimicry is being applied in the mobility industry nowadays to provide lightweight structures and efficient designs. A general overview of biomimicry is made regarding vehicles, approaching how the use of composite materials has already contributed to successful cases.

Keywords: biomimicry; bio-inspired design; polymers; FRP; mobility; sustainability

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1. Introduction

1.1. Biomimicry

Biomimicry can be defined as the branch of science for developing technology by mimicking nature, where forms and structures of creatures are the basic sources of inspiration to come up with optimized design solutions [1]. Wildlife species need efficiency in their processes: a simple mistake in the hunt of a prey or defending against a predator can draw the line between life and death. The mechanisms that enable organisms to thrive in their ecosystems can be imitated or adapted for different purposes [2]. These efficient processes occur at different levels, including molecular ones. Biomolecules have the potential to interact with each other and to self-organize in a functional way. In this sense, several products explore this self-organization process at the molecular level, creating new solutions [3].

The application of such concepts to industrial projects may begin from one of two starting points [4]: (a) solution-to-problem, where a known biological solution is applied to suitable problems; or (b) problem-to-solution, where a particular problem is tackled by searching for biological solutions to analogous natural challenges.

In 1960, Steele [5] defined the word "bionic" as the science of systems that have some functions copied from nature. The use of this method draws attention to what one can learn from nature instead of what can be extracted from it [6]. The basic concept is that engineers and designers should pay attention mainly to the details and designs of natural systems, using them as a source of inspiration for effective, self-sustainable, renewable and definitive solutions to the problems that compete with environmental sustainability [7]. According to Zhang [8], biomimicry can be achieved at different levels, including, (1) imitating the form or function of nature, (2) imitating natural processes and (3) imitating natural systems; where the first is seen as the most common approach.

When we carefully analyze nature's projects and systems, we understand why these are considered the best example of eco-friendly design and why they deserve great attention from those who seek to solve problems related to sustainable technologies in energy, medical engineering, materials and technological innovation. Among its specifications, there is the operation with sunlight, restricted use of the necessary energy, recycling, containment of excesses and adjustment of form to function [7]. Bionics is a systematic research tool that relates to biological mechanisms, which are systems and subsystems that allow the interaction of the design parameters with the natural characteristics of the analyzed elements [9]. The main objective of biomimetics is to provide a better understanding of the solutions and strategies used by nature in 3.8 billion years of evolution and their possible implementation in current technological practices [9,10].

Nature provides resources and conditions for all organisms to grow and reproduce. Those that take better advantage of these factors, in a process that may take thousands or millions of years to happen, can be considered as more adapted. For an organism to adapt, it is necessary that its morphology, physiology and ecology are modified creating new structures that allow this living being to succeed in its habitats and niche [2]. For example, it is common knowledge that marine mammals such as whales and pinnipeds, which have their ancestors common in terrestrial mammals, had their forelimbs modified for swimming, thus adapting to the new needs that the aquatic environment demanded [11,12].

The adaptations developed often have functions that are not obvious to the observer; for instance, even though cactus spines are efficient tools for defense, there are more functions for these structures [2,13]. Since the thorn is a modified leaf, it took this form to reduce water loss once cacti had their habitat mostly in arid regions. In addition, the proximity of the spines makes the cactus shaded, and with this, its internal water distribution becomes more efficient [14].

Another process that we can mention is the convergent evolution, where organisms that are not phylogenetically related develop similar characteristics and for the same purpose [2]. As an example, we can observe the wings of birds and the wings of bats. While the two groups had different terrestrial ancestors, they evolved independently into animals with flying ability. The bat's wing is an extension of the interdigital epithelial membrane connected between its fingers, which are more elongated than those of other mammals, while the wings of birds are a feather-covered structure attached to its arm that has been fused to its forearm [11,12].

Thus, it is extremely important in biomimicry projects to understand the actual origin of structures, that is, how organisms have adapted to the most different challenges and environments, and the most varied functions of the same structure, including the least obvious ones [15]. This wide comprehension allows designers to create more efficient products, guaranteeing that their success is not accidental [16].

Nowadays, it is possible to find biomimetics applied in several areas, mainly in materials with different functions, ranging from anti-repellant surfaces, adhesive stamps, anti-abrasive coating, glue and rubber to medical applications, ceramics, color changing materials, light-weight strong materials, thermo isolation materials, and so on [17].

1.2. Composite Materials

Going back in time in order to analyze the use of materials, it is possible to notice that around 1940 and most-likely associated with World War II, materials reached their trough relative importance, which was inverted in the following decades by a growing trend in all materials linked with the mass investments in research and development in the Cold War period. Within this context, a relevant phenomenon occurred in 1950: the emergence of resins facilitating the design of new composites (Figure 1 [18]), beginning a growing trend of use and application of composite, polymeric and ceramic materials.

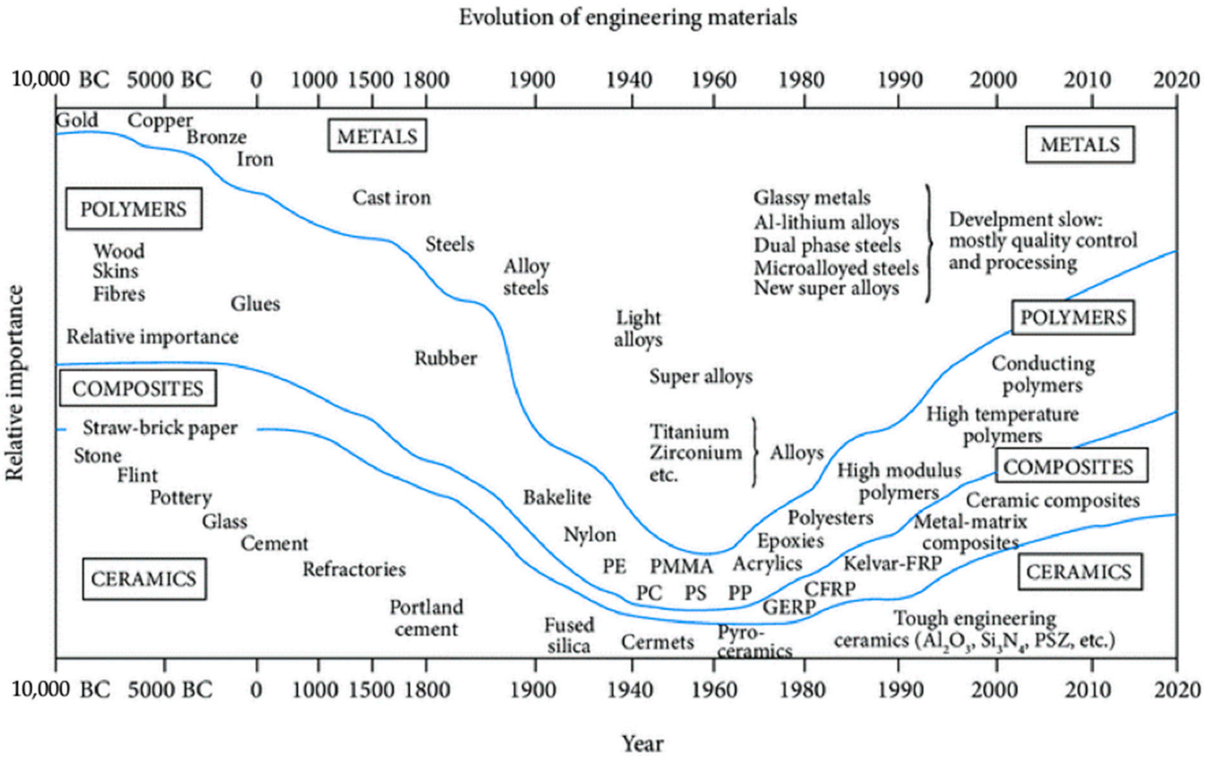


Figure 1. Brief timeline of the relative importance of engineering materials worldwide (adapted from [18]).

The growing relevance of fiber reinforced polymers worldwide is reflected by the market production indexes of their constituents. For instance, the annual global demand of carbon fibers [19] has been rising exponentially from 33 thousand tons in 2010 to 98 thousand tons in 2020, with an expected demand of around 120 thousand tons in 2022. In these same years, the global demand for carbon fiber reinforced polymers was 51 in 2010, 160 in 2020 and is expected to be nearly 199 thousand tons in 2022 [19].

Figure 2 [20] compares the Young Modulus and Density of different materials. Each material has a range of values for each property, depending on the exact composition, grade, etc. The huge range is covered by using logarithmic ('log') scales, where each major step on the axes represents a factor of 10. The main materials used for research and engineering applications have been shifting from monolithic metallic materials to composite materials since the mid-20th century [21]. Particularly, composites reinforced with fibers have shown many advantages due to the combination of key properties of its constituents (i.e., matrix and reinforcement). Lightweight and high-performance are the characteristics that most motivate the use of those materials in several engineering areas, such as aerospace and automotive industries, and the cost-driven consumer goods market [18].

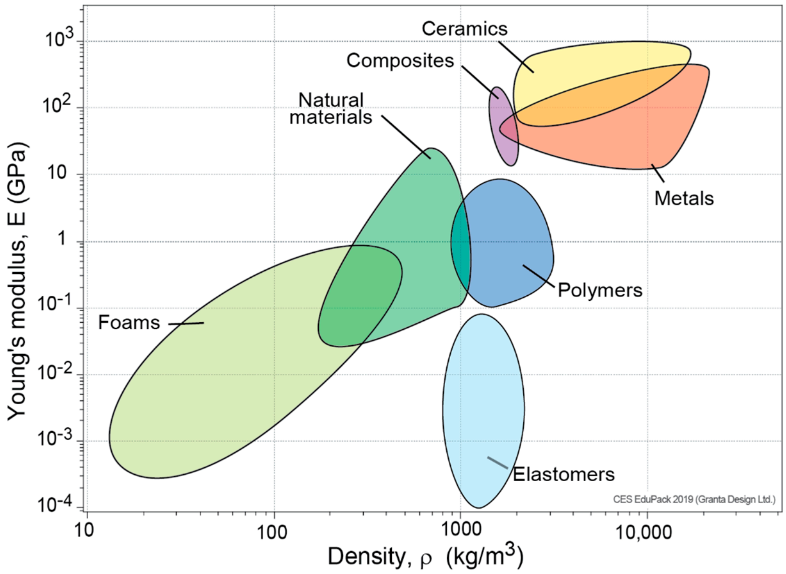


Figure 2. Young's Modulus vs. Density Ashby Chart for different materials [20].

1.3. Potential of the Automotive Industry for Application of Bio-Inspired Composite Parts

In emerging economies such as Brazil, for instance, the road industry accounts for 81.3% of national companies, representing around US$ 15.15 billion of the country's Gross Domestic Product (GDP) from January to March 2019 [22,23]. Of its 1,720,700 km of highways, only 12.4% are paved, 78% are unpaved and 9.1% are only planned. Furthermore, from the 12.4% paved roads, only 30% are in good condition. The legal control of cargo is governed by the balance law, which allows 10% overcharge without penalty, circulation with up to 12.5% overcharge under penalty and the requirement of overfilling from over 12.5% excess. So, tackling both concerns of carrying more cargo and yet avoiding overweight penalties, and circulating mostly on bad condition roads with safety, carriers have started an incessant search for vehicle weight reduction and tough designs simultaneously.

As a key element to achieve such goal, industry has focused on alternative materials that could meet the same structural requirements of metallic products but with lower weight, while keeping costs reasonable. It was at this point that polymeric composites arose as a potential solution. At first, the design of novel parts was based in the practice known as "black metal", transferring the design of the metallic part to the alternative material without any design suitability study. However, black metal assumes that continuous-fiber-reinforced composites (e.g., glass and carbon fiber reinforced epoxy) mechanically behave in the same isotropic way as a metal, which is not true. In this way, material properties are depreciated, and the product does not become competitive because it is economically unfeasible, even though it has less weight when compared to the metallic part.

For that reason, new design approaches have been looked into, and biomimicry has demonstrated to be an effective method to enhance the properties of auto-parts made with composite materials. The engineering skillset required to achieve such bio-inspired designs also deserves merit, after all, the isotropic mindset is deeply rooted within any engineer, and being able to correctly embrace the biomimetic concept to create composite materials solutions is still an emerging ability in industry as a whole, being mostly restricted to a few high-end applications such as aerospace and motorsport.

Focusing on polymeric composites, the present work embraces a thorough state-of-the-art review on how biomimicry has been applied to address the environmentally concerning issue of mobility, which is responsible for a great deal of GHG (greenhouse gases) emissions, not only through the design of vehicles but also as a result of the materials with which they are made. It is shown that, once most material solutions found in nature are based on composites, the potential of synthetic composites to solve engineering endeavors through biomimicry is formidable, with a lot yet to be explored.

2. Biomimicry in Composites

Composite materials have been widely used in many engineering applications in the last decades given the unique combinations of shape, mechanical and physical properties only achievable with such materials. However, the design and fabrication processes constitute a field undergoing evolution, thus making it challenging to develop certain projects [24]. Among the techniques applied to address this issue, biomimetics became an interdisciplinary methodology with high potential and acknowledged successful cases such as Velcro and its hook-like structure, anti-slip shoes with grooves resembling those of dog paws, and swimsuits inspired by shark skin [25]. Hence, it is impossible to address design and biomimetics without mentioning manufacturing solutions, which may be a considerable barrier to be overcome given the intrinsically complex designs and shapes of some natural structures.

2.1. Manufacturing Challenges

Indeed, the application of biomimicry design concepts is much more suitable to composite materials than metals because, for instance, there is a higher level of freedom in designing intricate shapes and because several solutions found in nature are made with actual composites (i.e., the combinations of two or more materials). Some examples are wood, which is basically a composite made with cellulose and lignin, insect cuticles that consist of a glassy protein matrix reinforced by crystalline chitin fibers [26], teeth, horns, ivory and even seashells [27].

As pointed out by Mark [27], even though synthetic and biocomposites have a similar structural principle, they differ in many relevant aspects that either cannot be entirely imitated by the synthetic version or cannot be manufactured at all due to technology limitations. Structurally, for instance, biocomposites are able to achieve up to 95% in reinforcement mass; their crystallinity is carefully controlled regarding amounts, size, orientation and distribution, and high loads of precipitated phases can be achieved [28].

The contrasting structural properties of bio and synthetic composites could be attributed to the time that each one has to be formed. While in nature, time is hardly an issue in the growth of bones, plants and shells, in industry, time is often the essence of a manufacturing process aiming at supplying a given demand while maintaining low production costs. The first case allows better mechanical properties once time allows more effective diffusion kinetics such as mass diffusion and heat flow.

Traditional manufacturing via autoclave or resin infusion techniques result in high in-plane uniaxial or biaxial mechanical properties. The advantages of the in-plane properties are offset to some extent by the lower out-of-plane properties such as the interfacial shear strength and inter laminar fracture toughness. Delamination or interlaminar fracture is commonly observed, and finding ways to mitigate this mode of failure has been a topic of research since the inception of structural composites [29,30]. Fiber-reinforced composites are heterogeneous by nature and thus the stress–strain fields associated with failure are non-uniform. Damage can be initiated in several ways: impact, excessive loading, compression, all of which produce high strain that leads to microdamage within the laminate [31].

Another manufacturing aspect that has been imposing challenges in the development of complex and/or large composite structures is the definition of a joining technique that inflicts the lowest stress concentration possible. Until recently, it was common to find, in industry, cases in which joining techniques usually applied for metallic structures (e.g., bolts and rivets) were used in polymeric composite materials. Even though there are textbook standard techniques to design such joints in composites [32], the ideal would be to avoid these joints given that load-bearing fibers are destroyed in the process, thus impairing load distribution and causing high local stresses [33]. Glued joints are a common process to solve this issue, although the method demands the usage of a second and often expensive material.

2.2. Applications with Synthetic Composites

Recently, researchers have been looking at biology to understand how the natural world has evolved to produce examples of structures that can endure large stress/strain events. All these studies demonstrate a common theme, namely that of a hierarchy of structures combined to achieve a uniform strain across the joint/structure. The advantage of this approach is that the lack of a node of stress/strain concentration makes premature failure less likely.

Keeping the aforementioned joint issue in mind, there have been several studies on how a hierarchical layup of the tree branch–trunk joint and bird bone's joint can improve the performance of a composite T-joint. Burns et al. [34] have used the biological design of tree branches embedded into the center of the trunk to address aerospace joints, since aircrafts are typically assembled with thousands of joints, which constitute the weakest regions of the structure [35]. The author, inspired by tree T-joints (*Pinus radiata*) that offer an elastic-plastic response with high toughness even though wood is intrinsically brittle, compared conventional and bio-inspired joints made with carbon fiber and epoxy. The biomimetic T-joint showed an improvement of up to 27% in bending strength, while keeping the same tensile and compressive resistance. This result was attributed to the 3D fiber placement of the structure; the wood density varies across the joint, with higher fiber volumes in the most solicitated areas. In another study, Akrami [36] used a bio-inspired design concept based on the optimized topology of a bird bone's joint to improve the strength-to-weight ratio and damage tolerance of TC35-carbon fiber fabric/SR5550 epoxy resin composite T-joints. As shown in Figure 3, better structuring the constituents' materials near the sharp bends results in re-distribution of stress over a larger area and reduces the stress concentration. The quasi-static bending and tensile tests revealed that the bio-inspired T-joint design is very advanced compared to a conventional T-joint in terms of the absorbed mechanical energy (over 130%), elastic stiffness (over 60%) and peak load (over 40%). The fatigue results show a considerable improvement for the bio-inspired T-joints as well.

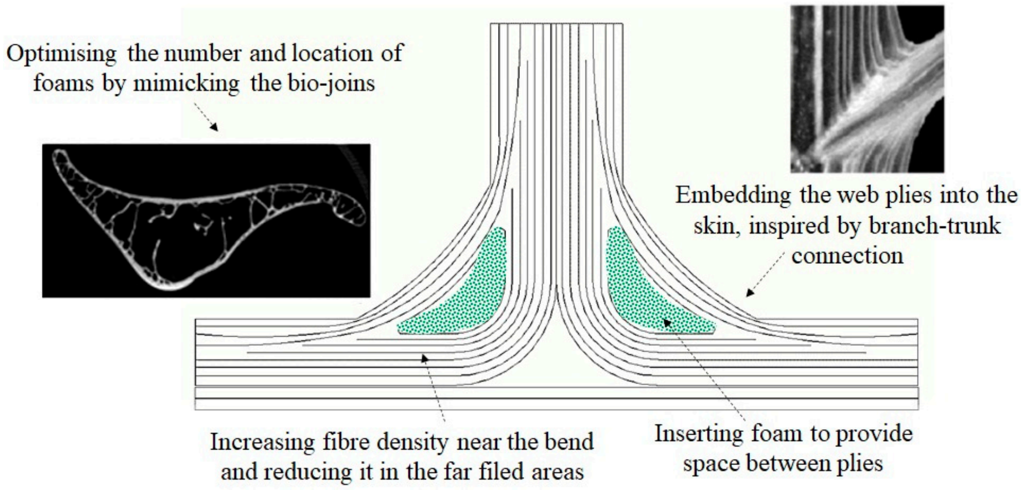


Figure 3. Design examples for future developments of composite T-joints.

In another study, Li [24] analyzed how bamboo-inspired composite parts can have improved properties, especially because bamboo is a more typical long-fiber natural composite than wood. Although the chemical compositions of both bamboo and wood are similar, the latter is a solid cylinder made of spring and summer wood, while the first is a hollow non-linear cylindrical structure with several nodes, with vascular bundles and thin-walled cells. The study showed that the interlaminar shear strength of glass fiber reinforced laminates actually increased by 15% due to the introduction of an inter-layer transition zone similar to the one found in bamboo bast fibers.

Converging both issues of barriers imposed by standard manufacturing techniques and the need to improve impact absorption capacity in composites, Svensson [25] used biomimicry concepts to improve impact-absorbing liners of helmets through additive manufacturing. The effect of bio-mineralization [37] found in sponges and mollusks [38] can be used as a source of inspiration so that minerals are deposited in regions that need higher strength and stiffness and are in detriment of fracture resistance. In other words, the polymer of the composite that better suits an impact load condition would preferably have low mineral content. Furthermore, nature has perfected several other structures to withstand impact solicitations such as multi-layered bones, teeth and horns; or a hard outer shell to distribute impact and retain strength, such as in the case of the toucan's beak [39] or the armadillo's armor [40], which can be applied, for instance, in a state-of-the-art helmet with fiberglass outer skin and a soft polyurethane inner layer [41].

The unique toughness of conch shells has been looked into by Gu et al. [42], who demonstrated the importance of its cross-lamellar structure for crack arresting mechanisms through the manufacturing of a biomimetic design made by additive manufacturing and impact tests. The second level of cross-lamellar hierarchy increases impact performance up to 85% in comparison to a single-level hierarchy, which is attributed to the generation of pathways for crack deviation.

Impact-resistant composites are designed inspired by the mineralized dactyl club of the smashing predator stomatopod (*Odontodactylus scyllarus*), which can withstand thousands of high-velocity blows that it delivers to its prey [43]. The helicoidal design strategy observed in the stomatopod club was mimicked to the fabric of high-performance carbon fiber–epoxy composites. The bio-inspired concept showed reduced through-thickness damage propagation during an impact event and resulted in an increase in toughness.

A great example of an optimized natural composite structure is the rostrum of the North American paddle fish. The rostrum consists of a combination of hard and soft cartilage, the soft material running down the center of the rostrum surrounded by a mesh of hard cartilage. The supporting bone structure is shown in Figure 4 [44]. Deang et al. [45] undertook high and low strain rate testing of the midline cartilage of the paddlefish. Finite element modelling was used to mimic the tests, and an excellent fit with experimental data was achieved. The work by Riveros et al. [46] modelled and compared the performance of the rostrum and a homogeneous material. The results suggested that the rostrum had better energy dissipation characteristics and could take a higher load before being damaged than the homogeneous structure. This excellent behavior is attributed to the topologically optimized structure of the rostrum.

It is important to highlight that even though most structural materials found in nature are polymers or composites of polymers and inorganic particles, biomimicry can be a complex notion to be applied in engineering since the functionality of natural structures is not always what is seems to be, which may mislead the designer [47]. For instance, a natural structure that evolved for thousands of years may yet not be optimized, be it because the environment in which it is encountered has a limited number of chemical elements available, because it would work only for the particular set of temperature and pressure conditions in which it evolved, or simply because the natural structure is so complex that it cannot be adequately reproduced with current manufacturing techniques.

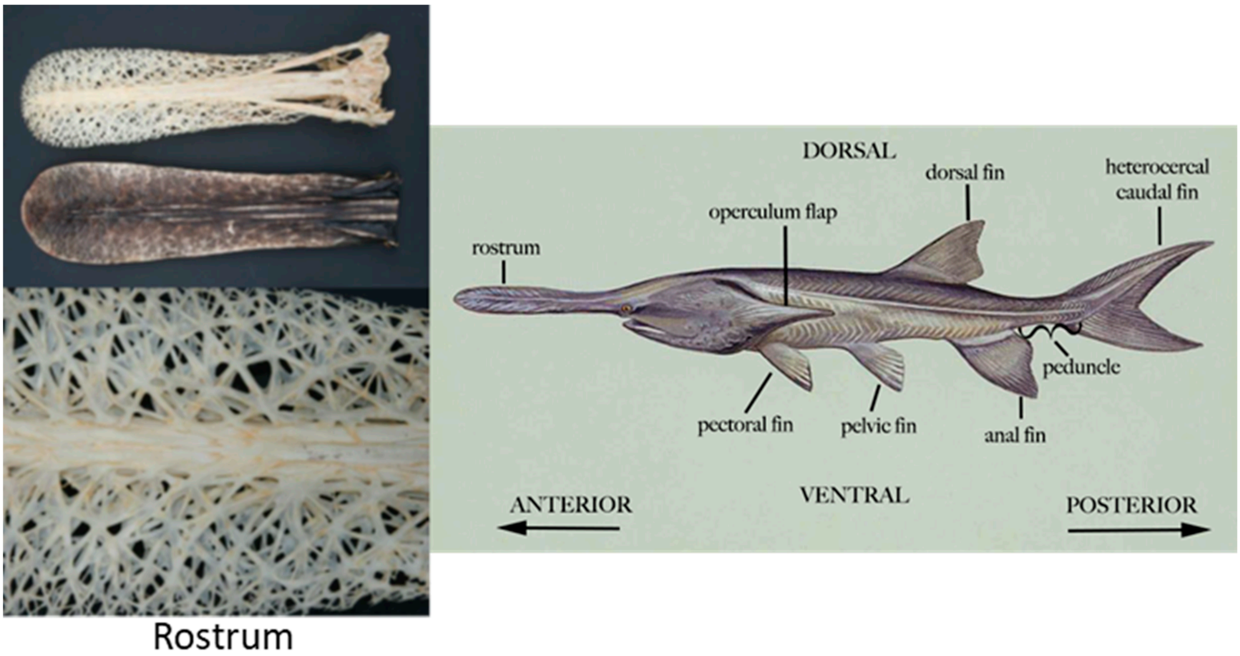


Figure 4. Paddlefish rostrum and stellate bone arrangement [44].

3. Biomimicry in Mobility

In agreement with the predictive statement of Margolin in 1998 [48], the role of designers in shaping how society lives, interacts and consumes goes beyond producing mere commodities; it is to act as agents toward a more sustainable way of living. It is not different with the mobility sector, which plays a key part, as relevant for the economy as it is demeaning for the environment, due to the currently dominant fossil fuel power source.

Within this scenario, biomimicry rises as a powerful tool to achieve shapes that are more efficient, spending less energy to cover a certain distance, to maneuver due to a bio-inspired aerodynamically efficient shape, or to allow an enhanced force transmission mechanism. Although biological designs generally embrace resilient, adaptable, regenerative and zero-waste features [49], it is important to highlight that not every bio-inspired design is sustainable. To support such statement, Bogatyrev [50] demonstrated, through a complex algorithmic network, that in technology, 70% of design solutions are energy-saving-oriented, whereas in biology, this premise accounts for less than 5% of design solutions. After all, according to Benyus [51], if a designer aims to develop a sustainability-driven biomimetic design, the three levels of form, process and ecosystem must be well covered.

The following subsections provide a brief overview of how biomimicry is successfully being applied in the mobility sector as a whole in terrestrial, marine and aerial vehicles.

3.1. Terrestrial Vehicles

To address the urban GHG emissions, the usage of aerodynamically efficient shapes found in nature have been applied in studies regarding cars, with the intent of decreasing drag resistance and, consequently, fuel consumption. For instance, Chowdhury et al. [52], inspired by the boxfish (family *Ostraciidae*) shape, which efficiently travels through water spending low amounts of energy, evaluated how the drag coefficient of a passenger car is affected if its shape is designed after a boxfish in comparison with a regular design. By carrying numerical simulations and wind-tunnel experiments, it was proven that the drag coefficient of the bio-inspired vehicle is around 0.24 against 0.56 of a regular car, demonstrating an aerodynamic performance two times more efficient and inferring a significantly lower fuel consumption. In contrast, the first boxy cars, such as Model A by Ford in 1928 [53] did not have this concern at all, reaching a drag coefficient of approximately 0.70. The aforementioned comparison demonstrates how engineering, particularly through biomimicry concepts, is able to improve designs.

From a different point-of-view to address energy efficiency, Salgueiredo [54] has focused on how human cells have more than one type of energy storage system and at least two metabolic pathways to recharge these storages. In fact, energy can be released in different ways during sportive running depending on the training routine the athlete has. These notions were the base for a study regarding energy consumption of multi-energy vehicles that proved that, in some cases, a controlled variation of speed could mean a lower energy consumption than a constant speed. It is worth underlining that this study was recently carried out by the automaker Renault, which shows the interest in biomimicry by a relevant automotive company to improve the performance of passenger vehicles.

As in most high-end technological applications, the military also demonstrated interest in the biomimicry concept. The work of Shyian et al. [55] presents the development of a combat vehicle based on the scolopendra's (family *Scolopendridae*, genus *Scolopendra spp.*) shape and articulation mechanisms, looking into its influence on the principles of modularity, protection, mobility, system of movement and firepower. Beyond the vehicle itself, Ng [56] produced effective improvements on the automation of road feature surveys inspired by the human visual system. The novel technology proposed mimics the role of the eye, the visual cortex and the neural networks in the video cameras, image processing and artificial intelligence of the system, respectively. This automated technology was proven noticeably more effective than the previous one on a 50 km field trial experiment on a highway.

3.2. Marine Vehicles

Contrary to what one might think, terrestrial vehicles are not the main topic of interest regarding the volume of research produced, in which marine vessels prevail. This could reflect the probable interest of the military on innovative designs that outperform regular and long-time used ship and submarine shapes.

The origin of life is related to the marine environment, and in it, a large variety of species have evolved and adapted to their challenges over 600 million years ago. The wide range of environments required adaptations in body design, physiological processes and even behavioral mechanisms from these organisms, ensuring that the challenges of the ocean were overcome. Thus, this environment can serve as a great source of inspiration for biomimicry since animals have specialized their bodies and metabolisms to face challenges such as water pressure and water drag by producing armor for protection, stability mechanisms and increased speed, among others [57].

Studying the field of autonomous underwater vehicles (AUVs), Roper et al. [58] provide a comprehensive review on the subject. As a matter of fact, AUVs play an important role in modern sub ocean operations such as subsea cables, pipelines and deep-sea oil drilling, in which cutting-edge technology is required to assure fast and maneuverable designs. For that, aquatic animals are used in many studies as a fruitful inspiration once they present levels of maneuverability that exceed those of conventional engineering designs.

The locomotion mechanics principles of aquatic animals are categorized in two subgroups: body and/or caudal fin (BFC) and paired and/or median fin (PMF) swimming, as proposed by Siochi et al. in a study carried at NASA [59]. The first refers to the generation of great thrust force through a translational wave propagated along the body and translated onto the caudal fin; and the latter to precision maneuvering with six degrees of freedom, station keeping and reversing maneuvers.

The tuna (family *Scombridae*, genus *Thunnus* spp.) is seen as a rich source of inspiration for its ability to outperform any man-made vehicle relative to its size in both speed and turning ability [60]. Its hydrodynamic-drag-reducing features were primarily analyzed by Barret [61,62] and then by Anderson and Kerrebrock [63], resulting in the empirical observation of drag force reduction of an AUV prototype and finding an impressive response of turning rates up to 75°/s against 4°/s of conventional AUVs.

In other studies, the sea bream (family *Sparidae*) was selected as an inspiration source for a robotic fish for its large side profile area and carangiform swimming style, which favors a uniquely fast turning ability [64]. Further, an AUV modeled after a dolphin has demonstrated higher propulsion efficiency than regular AUVs [65]; and subcarangiform robot swimmers [66] were proven able to perform a body bending of 9° in 0.2 s [67].

As in most high-end applications that demand low weight, composite materials are also applied to bio-inspired AUVs. For instance, carbon nanotube composites have shown great performance on actuators given their enhanced electrical properties generating high levels of stress with low voltages (640 MPa at 7 V) [68].

3.3. Aerospace Vehicles

Given the constant seek for new technologies regarding lightweight structures and shape optimization inherent of the aerospace segment, biomimicry has been applied as a promising tool to generate efficient aerial vehicles.

Inspired by the flight of birds, Galantai et al. [69] have applied the concept of wing morphing (i.e., the ability of the wings to change their shape to adapt to different flight conditions) for unmanned aerial vehicles (UAVs). Once the airfoil shape is determinant for the lift and drag forces the vehicle experiences, the main goal was to provide a solution that allows a dynamic adaptation of the wing profile during flight instead of the current wings, which depend on complex hydraulics and servo motors (inferring a weight penalty to the structure). This concept yielded a UAV geometry with high adaptability, efficiency and maneuverability supported by adaptive spars and ribs on a deformable structure that is fixed to the fuselage. The performance improvement allowed a decrease in power requirement to sustain flight at a maximum speed of up to 12%.

In another recent study, Rashidi et al. [70] successfully demonstrate how a structure built with a composite material through additive manufacturing and with a design inspired on the armadillo (order *Cingulata*) carapace allows the design of high strain articulating cylindrical shells for aerospace applications. The composite material mimics the interaction of the soft collagen and rigid bone structure in alternating sections, with two 3D printing materials of Young moduli and Poisson ratios of 1 MPa and 0.48 and 2 GPa and 0.35, respectively.

Depicting the cutting-edge aspect of biomimicry, Pohly et al. [71] designed a 5-g hover flight vehicle for Mars exploration based on flapping wing flight of insects of Earth. This technology is seen as vital to understand the red planet through aerial surveillance considering its ultra-low-density environment and was made possible due to the employment of the advantages of the unsteady lift enhancement found in insects.

A general overview of the topics approached above is portrayed in Figure 5.

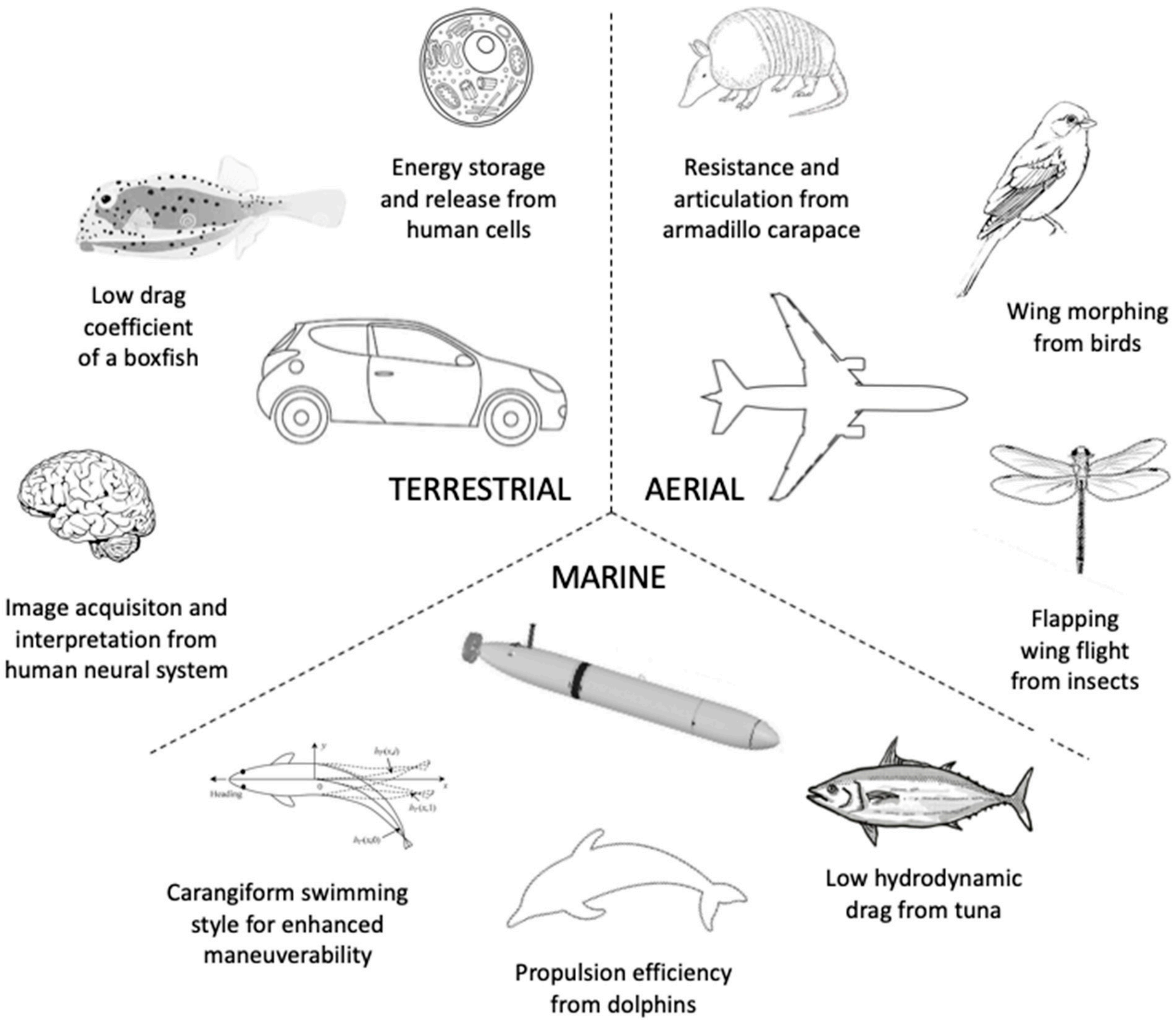


Figure 5. Bio-inspirations of some of the works approached in this section.

3.4. Heavy Vehicles

For some time, nature has been inspiring solutions to problems rising from transport, whether for cargo or passengers. Some examples can be found in the bullet train whose front is based on the Kingfisher [72] and the bus based on the Beluga whale [73,74].

An example of problem-to-solution approach relies on the bullet train case [72]. In its original design, a great level of noise was inferred to the train when it entered a tunnel due to a turbulent flow that also caused structural damage from air shock waves.

With that in mind, the Kingfisher (family *Alcedinidae*) represented a perfect example of how nature overcomes the same issue. The bird needs to perform dives in an aquatic environment without generating wave excitement, so as not to scare off fish. The beak of these birds has an ideal aerodynamic profile for "silent" dives (Figure 6), that is, there is almost no water disturbance, providing a more efficient hunt. This biomimicry solution is one of the most successful cases so far: the new nose proposed for bullet trains has drastically reduced the noise problem in addition to reducing the energy consumption by 10–15%.

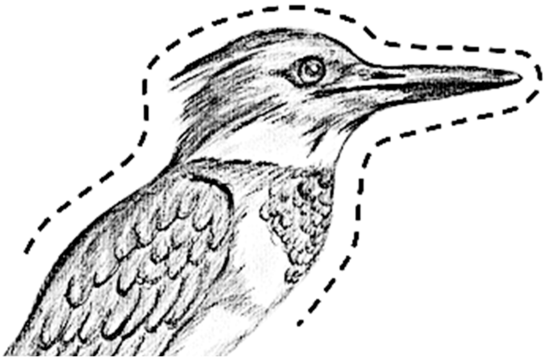
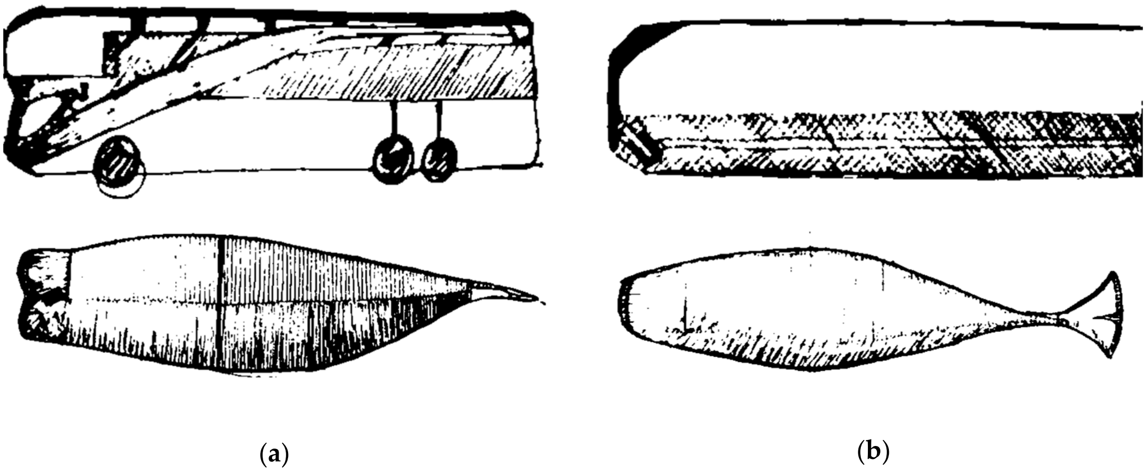


Figure 6. Aerodynamic profile of the Kingfisher.

Arabaci et al. [73,74] studied the design improvement for buses based on the hydrodynamic shape of the Beluga whale (Figure 7) (family *Monodontidae*—Scientific name *Delphinapterus leucas*). Design variations were established by computational means until the options that allowed aerodynamic gains in the order of 21% and a consequent reduction in fuel consumption of up to 12.6% were reached.



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

Figure 7. Hydrodynamic profile of the Beluga whale applied to a bus in side view (**a**) and top view (**b**) (adapted from [73,74]).

Biomimicry is also strategically applied for components and subsystems of heavy-duty cargo vehicles, mainly for safety parts such as tires. Goodyear [75] has launched the Eagle-360, a special kind of tire mimicking the pattern of a brain coral (*Mussidae* or *Merulinidae* families). The tread design of this tire has multidirectional blocks and grooves, which help it to secure a safe contact patch no matter which direction the tire moves. In nature, the structure of the brain coral ensures optimal water distribution independently of the direction of the surrounding water currents, which guarantees optimal nutrient availability for the organism. In addition, the design of the coral increases its resistance and guarantees its safety against predators and weather [76]. Thus, a product can mimic a natural design aiming at a different function from the original. Furthermore, the tire groove bottom compound imitates a natural sponge that stiffens when dry and softens when wet. This texture absorbs water of the road, then ejects it through centrifugal force thus resisting to aquaplaning.

The truck manufacturer Volvo is also investing to increase environmental care, using biomimicry as a tool to approach innovation that seeks sustainable solutions to human challenges [77] by emulating nature's time-tested patterns and strategies. Studies involving internal process improvement projects and products already follow the concept of bionics, as in the case of the modular support with flexible bulkheads, which has the function of absorbing the different part formats without the need to change the basic platform.

For cargo vehicle combinations, such as Truck and Trailer, Volvo presented a very bold concept, the Volvo Ants [78]. The Design and concept, based on actual ants (*Formicaridae* family), go beyond the previously presented quest to reduce energy consumption as the project has points for cooling the electric energy storage system (battery packs), multi-load capacity and, most importantly, an "intertrucks" communication network that allows combinations to form trains and seek route optimization, a skill widely used by ant colonies in their daily activities.

Within the truck industry, FL IR is a new concept truck launched by Isuzu manufacturer, which applied bio-design strategies to optimize aerodynamic performance and route [79]. Externally, the machine would look like a "mighty shark" (*Carcharodon carcharias*), and technically, the engineers focused on the behavior of marine animals that use ultrasonic sound waves to communicate underwater. It is believed that the new FL IR trucks can, independently, form a platoon while moving in unmanned position. The car in the caravan head is able to communicate with each subsequent truck and transmit to the convoy participants all the necessary information.

4. Conclusions

The present review clearly demonstrates that nature has found its way to overcome the most diverse problems through the evolution of sophisticated structures, which are mostly possible due to the combination of two or more materials as in a natural composite. Hence, synthetic composites, which have already proven their value for their inherently enhanced strength-to-weight ratio, could be used to address complex situations by taking advantage of their tailoring possibilities, even though, in some cases, being limited by current manufacturing techniques and cost-related restrictions. Sometimes, even though composites might be the ideal mechanical solution for a design, they might just not be practicable. Hence, suitable design guidelines, such as biomimicry, need to be found and correctly applied.

Biomimicry has been widely applied in innovative vehicle designs, demonstrating great potential in increasing their energy efficiency due to either lower aerodynamic drag, lower weight, or both. Particularly, given the relevance of cargo transport on roads worldwide and the relatively high amounts of energy spent to deliver truck cargo in comparison to the ship and train modals, the improvement of energy efficiency in transporting goods by truck would significantly contribute to a more eco-friendly supply chain. Hence, bio-inspired designs made with polymeric composite materials have risen as an important tool for achieving such step toward sustainability.

Although this work approaches distinct topics of biomimicry and composite materials for vehicles, it is important to underline its limitations. For instance, the application of biomimetics can be extended to several other fields of study not related to structural engineering. The present work demonstrated that this concept can be a powerful ally for energy efficient designs, especially considering lightweight materials such as polymeric composites. However, like any design tool, it may not be appropriate for certain applications. Particular caution is advised since the manufacture of specific biomimetic shapes may infer an elevated cost for a given part, making it potentially unfeasible.

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