BIOMIMETIC ENGINEERING TO COMBAT CLIMATE CHANGE

Shafiat Islam Dewan

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"...I learned first-hand that truth can be found in the way life exerts itself in order to persist and carry on in this world. From then on, 'learning from nature' became a recurrent theme for me."

Eiji Nakatsu (McKeag, 2012)

What is Biomimicry and Why You Should Care?

Whether you enjoy a casual stroll through Hyde Park, religiously watch Attenborough documentaries, or are (God forbid) a biologist, there is no denying the beauty of the nature that surrounds us. It seems logical then, that one might want to mimic natural processes and entities to advance our technology and engineering solutions. Inspiration has been drawn from the structure of the Golden-fronted woodpecker's skull to design shock absorbers that reduce the failure rate of microdevices to 0.7% withstanding shocks up to 60,000g (Park, 2011). Formula One engineers now look to the woodpecker-shock-absorber to protect the driver from large forces from severe deceleration and increasing the efficiency in braking (Marks, 2011).

There are many examples where scientists have looked to nature and to help solve crucial problems like the woodpecker. Arguably the most crucial problem facing us today, though, is climate change; and arguably, there is no better place to look to help combat climate change than the Earth and how its organisms have adapted to survive so many millennia. This article will give you examples of biomimetic engineering at its finest inspired by the sky, the sea and the land to give you an understanding of biomimicry as a thought process.

Inspiration from the Sky – The Owl and the Kingfisher

The Shinkansen 500-series bullet train is one of the fastest trains in the world, travelling up to 300 km/hr (Biomimicry Institute, 2017) and has one of the strictest noise regulations in the world (Nakatsu, 2005). These stringent noise regulations caused a big problem for the Shinkansen during its design, the faster the engineers tried to run it, the more noise it would make, causing complaints to be sent to the engineers during testing. Aerodynamic noise, from the air hitting the pantographs (the current collectors that get electricity from overhead wires), and a 'tunnel boom' that could be heard 400m away (McKeag, 2012).

The aerodynamic noise came from Karman vortices (depicted in Figure 1). These are produced as a result of vortex shedding, which is an effect of fluid flow being disturbed by an object when the width of the wake of the object approaches the diameter of the object itself. There is an imbalance of fluid speed to the sides of the object with the fluid speed inside the wake (see figure 3), causing a Karman Vortex street or Karman vortices to be formed, which cause an oscillating lateral force on the object by Bernoulli's principle. Mr Nakatsu sought to remove the effect of these vortices by analysing the noiseless flight of owls.

Figure 1 A satellite image of Karman Vortices produced by the Canary Islands (Schmaltz, 2015)

Owls have tiny comb-like serrations on the leading edges of their primary feathers called fimbriae (Mckeag, 2012; Sheppard, 2012). These fimbriae break down the fast-moving air that rushes over them into micro vortices to reduce the effect of turbulence caused by Karman vortices reducing noise (McKeag, 2012). The engineers reshaped the pantograph into a ‘wing-graph’ that allow the train to travel at 320 km/hr while still meeting the noise regulations.

The next challenge was to minimise the sonic boom that came from the transition into tunnels. It is caused by a large atmospheric pressure wave propagating down a tunnel at the speed of sound, exiting at 0.001atm. (McKeag, 2012). Ever the ornithologist, Mr Nakatsu tried to identify any animal that regularly experiences a rapid medium density change, which lead him to the kingfisher. He surmised that the shape of the beak is what allowed the bird to dive at such a high speed from air into water (800 times denser (McKeag, 2012)) with barely a splash. After testing, the engineers created a new nose for the Shinkansen 500-series with a 15m long nose with a round cross-section which reduced the air pressure by 30% (Nakatsu, 2005). The product of all of this is a quiet Shinkansen bullet train, that runs 10% faster and consumes 15% less electricity (Rowley, 2013).

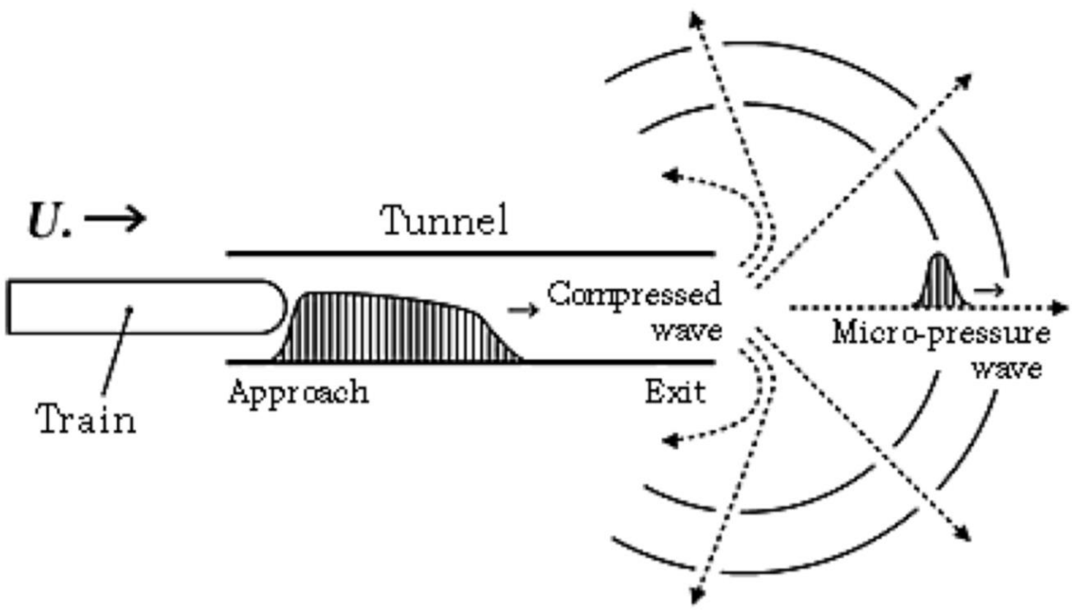

Figure 2 A diagram of how the tunnel boom is produced (McKeag, 2012)

Inspiration from the Sea – Humpback Whales

Wind power. It is a staple of renewable energy, that convert the kinetic energy of the wind into electrical energy through a wind turbine and is a good alternative to fossil fuels. But, as anyone who has been in Britain for all of two minutes will tell you, there are issues to do with the weather. Wind turbines are not reliable as wind speeds are variable and don’t perform well in turbulent or unsteady air (Kumar, 2012). They are also noisy. Therefore, wind turbines need to be made much more efficient and aerodynamic to be viable.

When designing something to be as aerodynamic as possible, taking a turbine for example, the objective is to maximise the aerodynamic coefficient defined by the ratio of lift to drag. Therefore, one must keep the lift as high as possible, and the drag as low as possible when designing things like wings and turbine blades. Despite their massive weight and significant length, humpback whales have been observed swimming in tight circles to catch their prey. The dexterity of the whale is attributed to its unique flippers which have irregular bumps on the leading edge called tubercles. It seems counter-intuitive that having bumps and ridges on a flipper would increase mobility in a fluid because they seem less aerodynamic: cars are made to be as smooth as possible, likewise with high-speed jets. The reason that tubercles are the secret of the humpback whale's agility is due to the resistance to stalling.

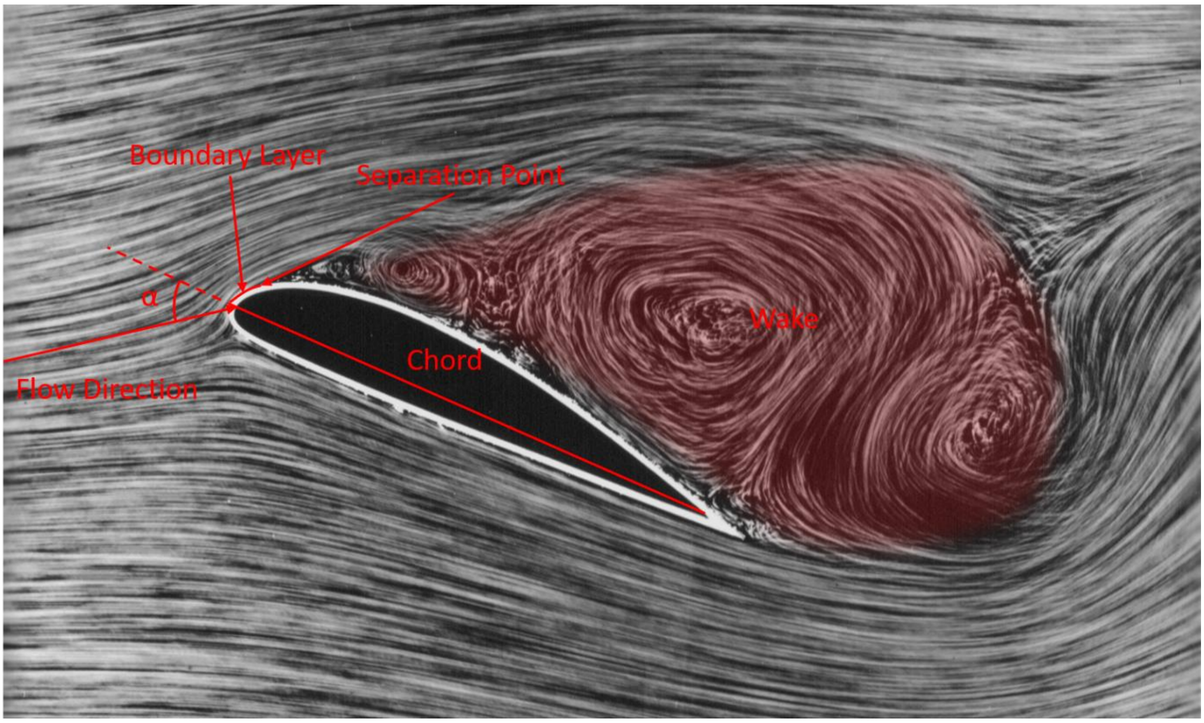

Figure 3 Separation of airflow from an airfoil at a high angle of attack α, adapted from DLR (1915)

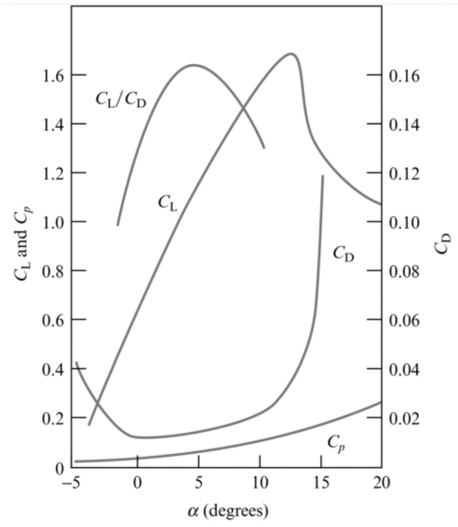

Figure 4 Typical profile of an airfoil where C_L is the lift coefficient, C_D is the drag coefficient, and C_P is the pressure coefficient (John F. Douglas, 2005)

To visualise stall, it is helpful to envisage a flow of a fluid around an airfoil (any object placed in a moving fluid, and the fluid is a gas), like figure 3, with the angle of attack, α, increasing from 0°. As you might expect, the angle of attack determines the lift coefficient, C_L, and thus the lift for the airfoil. In fact, $C_l \propto \sin\alpha$ giving a profile of figure 4 for small α (John F. Douglas, 2005). For small angles of attack, the experimental relation for C_L and α follows the theoretical. This is due to the boundary layer and the top surface having little to no separation for small α. As α increases however, the separation become larger, reducing the rate of increase of lift. As α increases further, the separation point moves further towards the front of the airfoil, widening the wake, hence increasing the drag. At some point, an increase in α no longer increases C_L: this is stall. For scenarios involving wind and air, dynamic stall is much more of an issue. It lives up to its namesake as it can occur at any windspeed meaning that wind turbines need to be adaptable to dynamic stall (Aeronautics, 2013). But then you might ask 'How do tubercles increase resistance to stalling?'

Seen easily from figure 3, water breaks up into turbulent vortices as they cross a smooth wing at a high speed and angle of attack. The velocity of the water is therefore reduced and the pressure on that side of the wing is increased. Whereas, water that passes between a humpback's tubercles on its flipper maintain even channels of fast-moving, low-pressure water. These areas of low and high pressure create a pressure gradient, and by Bernoulli's principle generate lift. This allows humpbacks to execute these tight banking and turning manoeuvres. Miklosovic et al. (2004), discovered that adding turbucles to a scale model of a whale flipper reduced the drag and increasing the lift while also delaying the stall angle by 40%. It has been found that increasing the amplitude of the turbucles on a turbine delays stall further, but the stall delay is also insensitive to the wavelength of the bumps (Ernst A. van Nierop, 2008). A company called WhalePower Corp has already designed and implemented a turbucle based turbine (see figure 5) that has a higher steady electrical output power than a standard turbine (Howle, 2009; Fish, 2011). A patent filed by WhalePower Corp outlines a design that allows the turbine blades to operate at a larger range of wind speeds (increasing the power that can be produced) and reduces the noise of the turbine by reducing the turbulence produced that the tip (Fish, 2005).

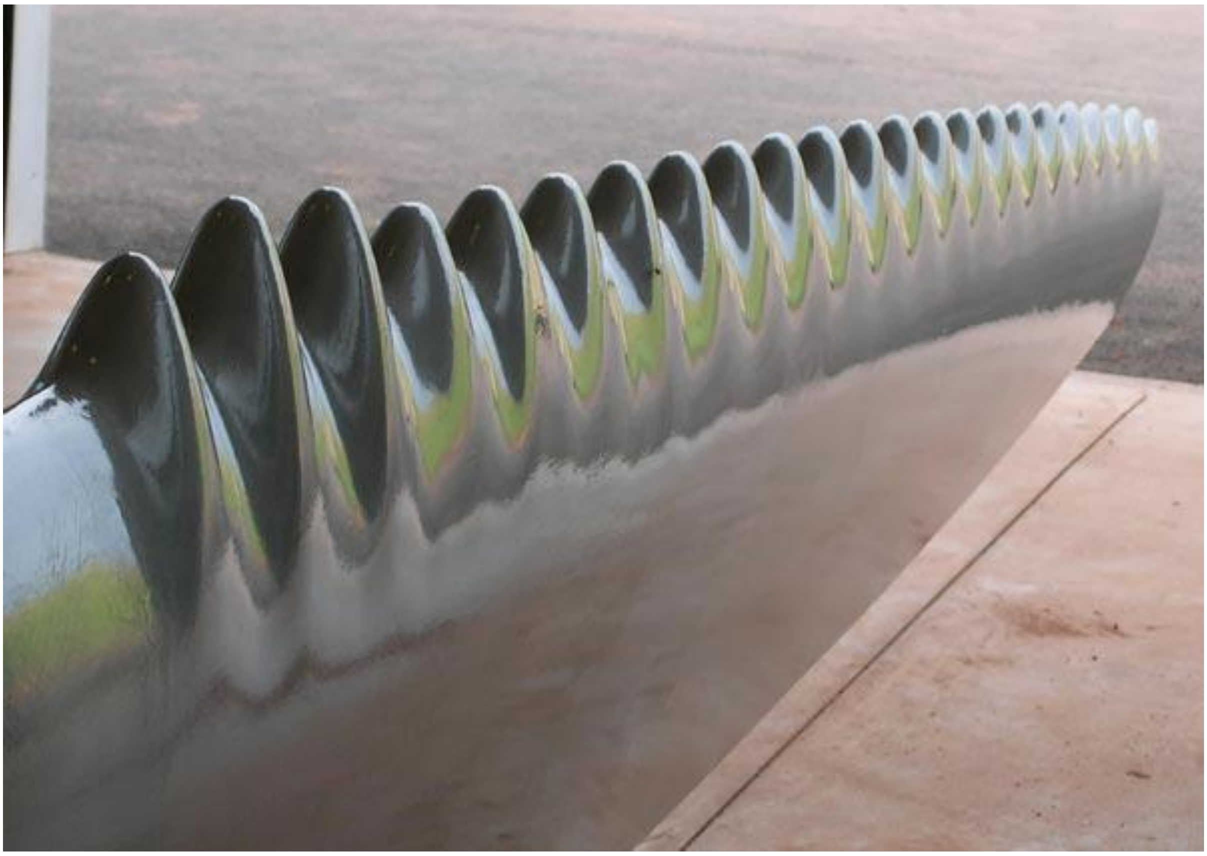

Figure 5 Image of a Wind Turbine blade produced by WhalePower Corp (Subirana, n.d.)

Inspiration from Land - Termites

Air conditioning units are a lifesaver in hot countries, but they are also a vicious circle. Not only do they use up huge amounts of electricity for cooling, about 6 % of all of America's residential energy use (U.S. Energy Information Administration, 2013), but they also increase the emission of air pollutants from power plants (Tracey Holloway, 2018). You might think that the solution is get rid of all air conditioners forever and brave the heat for the sake of the planet, but not necessarily; the humble termite has a unique method of beating the heat, and it relies upon the iconic desert structure: the termite mound.

Constructed out of soil, saliva, and dung, termite mounds in Africa measuring up to several meters high generally resembling chimneys. They vary in structure, with some having large open vents inside, and others having porous walls, but inside, termites can create intricate arrays of tunnels living in nests, below ground, in colonies up to a million strong (Biomimicry Institute, 2018).

Figure 6 Picture of a termite mound (Biomimicry Institute, 2018)

Initially, mound ventilation was thought to happen through two effects in two scenarios: the stack effect for an open-topped 'chimney' mound, or thermosiphon flow for a closed top chimney. The stack effect is the unidirectional Venturi flow of air up through the mound, due to high wind velocities drawing air out of the top of the mound, with the input of air at openings near the base of the mound (Soar, 2008). Whereas thermosiphon flow (Lüscher, 1961), is a cycle of hot air created by the termite's nest rising, due to buoyancy, to the top of the mound, being replenished with water vapour and exchanging heat and respiratory gases through the porous walls with the atmosphere, and then falling down due to an increased density. Now, termite mounds are thought to be more like a functional analogue of a mammalian lung because there is no evidence that termites regulate temperature, in fact, the temperate is thought to vary closely with the high thermal capacity soil that surrounding and buffering the mound (Soar, 2008).

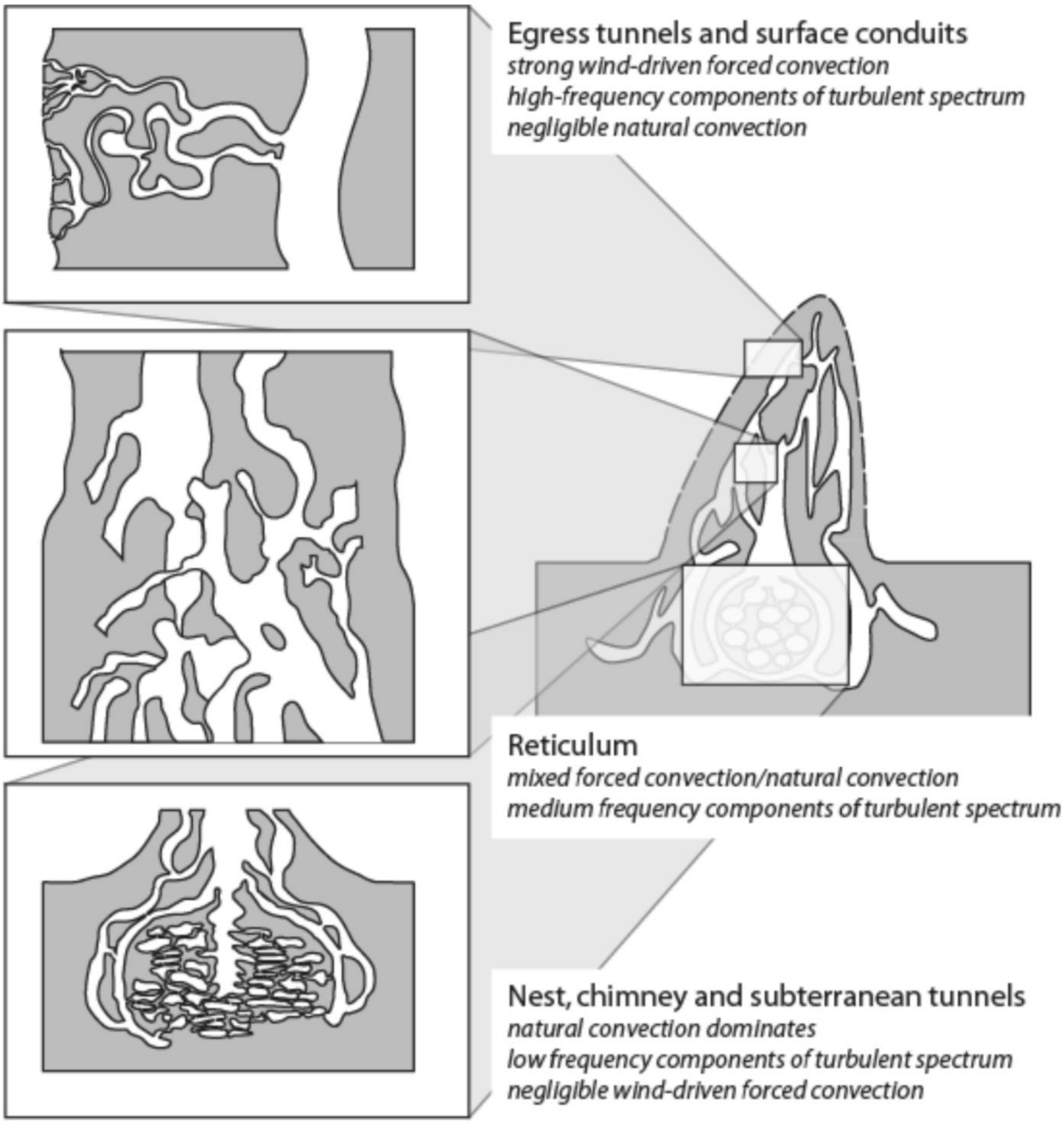

Figure 7 Termite mound structure (Soar, 2008)

Temperature gradients form between the periphery of the mound and the centre due to the varying temperature and position of the sun. Therefore, currents of rising and falling air develop throughout the mound that constantly change direction with the temperature gradients. Since the walls are porous, wind may play a secondary role in ventilation (Biomimicry Institute, 2018). Turbulent winds have a broad spectrum of AC transients, but the mound acts as a low-pass filter, where, at surface conduits, there is a broad spectrum of wind speed, but in the nest, this broad spectrum of transients is completely damped out by the network of tunnels causing impedance (Soar, 2008). There is a mixed-phase that allows the colony to respire, which occupies the lower parts of the chimney above the nest. There are a couple of mechanisms that drive gas exchange in the mixed-phase region: Pendelluft ventilation and resonance mixing (Soar, 2008). Pendellufts (literally air pendulums) are caused by pressure on air deep within the mound (which originate from the gradient of transients within the mound) which cause quasi-tidal air movements, enhancing gas exchange (Soar, 2008). Resonance occurs due to the organ-like (instrument) nature of the tunnels and at a certain frequency of ventilation, diffusion is enhanced (Soar, 2008).

The Eastgate Centre in Harare, which opened in 1996 was designed using biomimicry of termite mounds to create a passive cooling system that does not use any air conditioning. Low power fans in the building pull in cool air during the night and disperse it throughout the porous walls in the building, and during the day the fans force warm air up through the chimneys of the Eastgate centre. Using up to 50% less electricity than other air-conditioned buildings in Zimbabwe (Pearce, 2016), the building is made from high thermal capacity bricks (like the soil in a termite mound), maintaining an internal temperature of 24°C with an outside fluctuation of 19-29°C (Fred Smith, 1996) by the manipulation of airflow underneath the building. This piece of biomimetic architecture saved over $3.5 million within the first five years of it being opened (Michael Hacker, 2010).

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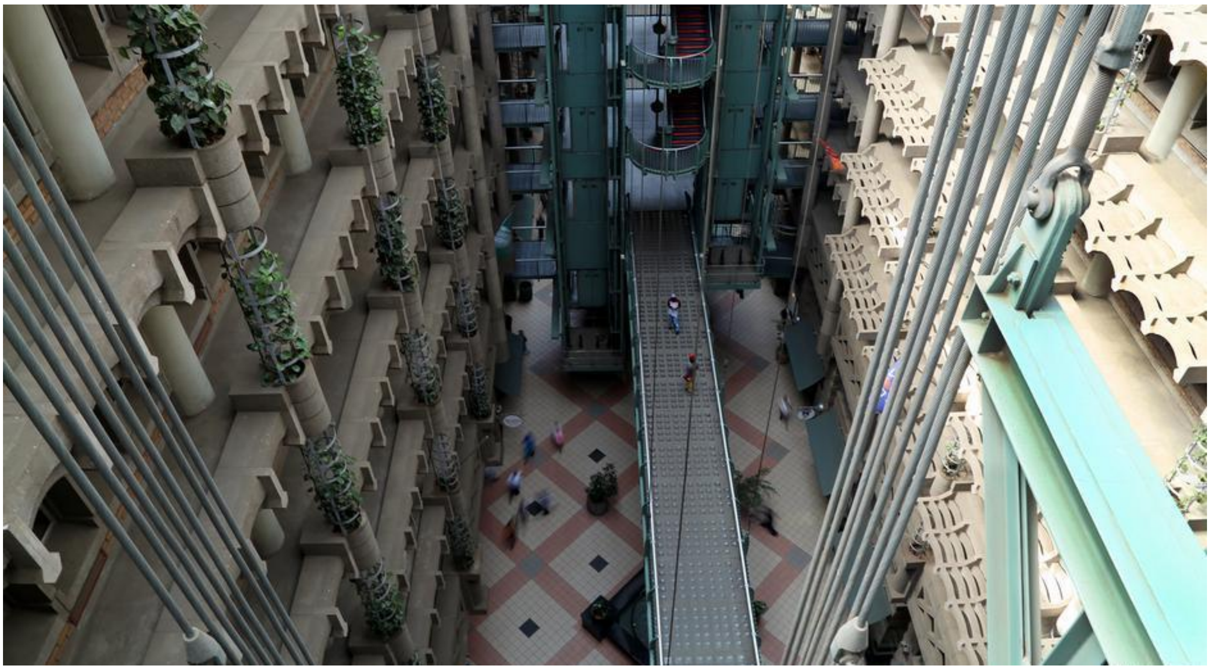

Figure 8 Picture of the interior of the Eastgate Centre in Harare (Pearce, 2019)

Have we Exhausted Inspiration from Nature?

Not yet. There are still so many animals and processes that we can learn from and have to do research on before they are ready for the market: slug slime, although revolting, could be used to revolutionise how surgical wounds are closed because of their non-toxicity, and sticking strength (Biomimicry Institute, 2019). In the same way, plants photosynthesise, engineers at the Universities of Chicago and Michigan are producing a bionic leaf that is ten times as efficient at photosynthesis as the real thing (Biomimicry Institute, 2019). Oriental hornets have photovoltaic pigments that power their metabolic functions which could increase the efficiency of industrial photoelectric cells (Marian Plotkin, 2010). There are so many more examples of extraordinary behaviour that has the potential to solve a lot of climate problems (Biomimicry Institute, 2015), the list is nowhere near exhausted by this article.

Conclusion

The Biomimicry Institute defines its namesake as “a practice that learns from and mimics the strategies found in nature to solve human design challenges — and find hope along the way.” (Biomimicry Institute, n.d.) The worrying yearly trend of ‘hottest year on record’ isn’t going to go away with the current dependence on fossil fuels. Renewables have gone from providing a small percentage towards our electricity needs to being almost a third of the UK’s electricity generation (Government Digital Service, 2018) and this is, in no small part, thanks to innovations in the field. There is a lot still to research though, but there is a lot of hope that fossil fuels consumption will be overcome.

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