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Biotechnologies and Biomimetics for Civil Engineering

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I am confident that humanity's survival depends on all of our willingness to comprehend feelingly the way nature works

Buckminster Fuller

I dedicated this book to my wife Adriana, and to late Tico and Tucha, my companions of writing, sources of all my drive, inspiration and mental integrity, ever present memories of our common Earthling condition

Foreword

Although human ingenuity makes various inventions it will never discover inventions more beautiful, appropriate and more direct than in Nature because in her nothing is lacking and nothing is superfluous.

Leonardo da Vinci

In Nature there is an economic use of energy and materials. Water and air are vital for the plant and animal kingdoms to live and much of architecture is about how these are channelled in various climates in order to provide the best environment for the organism's survival. Much of our aesthetic is derived from the organic and fluid language that you find in Nature. It involves complex, three dimensional geometries but there is always a rigorous logic behind them. Animals, including humans, and plants have evolved various strategies for dealing with control to suit the local changing conditions such as thermal insulation, cooling via radiating surfaces, blood flow. In addition, plants are unique in being able to convert sunlight into integrated functionality in the process of photosynthesis.

The words *optimisation* and *integration* are often used by building design teams but often without any idea about how these can be achieved, even though there are methods in operational research such as dynamic, integer or linear programming available. Integration and optimisation in Nature appear as completely natural processes.

Now many researchers and designers believe in sustainable solutions for architecture using lessons from the natural world. The attraction of biomimetics for building designers is that it raises the prospect of closer integration of form and function. It promises to yield more interaction with the user by for example, learning from the sophisticated sensor systems in animals including the insect world. However, there are barriers including ever changing standards; the fragmentation of the construction industry at educational and professional levels; the persistent traditional culture with regard to matters like innovation and sacrificing value for cheap capital cost.

This book presents a true galaxy of ideas from biomimetics and how they maybe applied in engineering and architecture. The ideas here will have radical consequences for architecture. New materials can make not only low energy but also more beautiful facades that can produce healthier climates for people to work in. Energy systems using bacterial fuel cells, self-cleaning and self-healing materials and many other ideas are presented here by a distinguished group of international authors.

Not least biomimetics makes us think laterally. We can think the unthinkable because Nature is full of remarkable surprises and yet simplicity too. Our education in schools and universities needs to embrace all the creativity and wonder that Nature can show us. Biomimetics is at the interfaces of biology, engineering, material science, and chemistry and encourages an open dialogue, which can bring enlightenment about problems as displayed in this book.

Derek Clements-Croome

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Chapter 1
Introduction to Biotechnologies and Biomimetics for Civil Engineering

F. Pacheco-Torgal

Abstract This chapter starts with an overview on the sustainable development crucial challenges. The ones directly or indirectly related to the field of civil engineering are highlighted. These include greenhouse gas emissions (GHG) related to the energy consumption of the built environment, aggravated by urbanization forecast expansion, and the recent increase in building cooling needs due to climate change. It also includes the depletion of nonrenewable raw materials and mining-related environmental risks in terms of biodiversity conservation, air pollution, and contamination of water reserves. Some shortcomings of engineering curriculum to address sustainable development challenges (especially civil engineering) are described. Possible contributions of biotechnologies and biomimetics to sustainable development and the rebirth of civil engineering curriculum are suggested. A book outline is also presented.

1.1 Sustainable Development Challenges

Four decades ago several investigators used a computer model based on the fixed-stock paradigm to study the interactions between population, food production, industrial production, pollution, and the consumption of nonrenewable resources. As a result, they predicted that during the twenty-first century the Earth's capacity would be exhausted resulting in the collapse of human civilization as we know it Meadows et al. (1972). Two decades after that an update of this study was published showing that some limits had already been crossed (Meadows et al. 1992).

Rockström et al. (2009) recently proposed a new approach to global sustainability defining nine interdependent planetary boundaries within which they expect that humanity can operate safely. This include:

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(1) climate change (CO_2 concentration in the atmosphere <350 ppm and/or a maximum change of +1 W m^{-2} in radiative forcing);
(2) ocean acidification (mean surface seawater saturation state with respect to aragonite ≥80 % of pre-industrial levels);
(3) stratospheric ozone (<5 % reduction in O_3 concentration from pre-industrial level of 290 Dobson Units);
(4) biogeochemical nitrogen (N) cycle (limit industrial and agricultural fixation of N_2 to 35 Tg N yr^{-1}) and phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P);
(5) global freshwater use (<4,000 km^3 yr^{-1} of consumptive use of runoff resources);
(6) land system change (<15 % of the ice-free land surface under cropland);
(7) the rate at which biological diversity is lost (annual rate of <10 extinctions per million species).

Two additional planetary boundaries for which a boundary level was not yet determined are chemical pollution and atmospheric aerosol loading.

According to Rockström et al. (2009) "transgressing one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger nonlinear, abrupt environmental change within continental- to planetary-scale systems". These authors estimated that humanity has already transgressed three planetary boundaries for climate change, rate of biodiversity loss, and changes to the global nitrogen cycle. And a recent study (Garcia et al. 2014) confirms the devastating impacts of climate change on biodiversity loss. As a consequence of this worrying status, it remains crucial to act in order to address those problems in a context in which urban human population will almost double, increasing from approximately 3.4 billion in 2009 to 6.4 billion in 2050 (WHO 2014). Other authors also agree that this is the most vital challenge of the twenty-first century (Griggs et al. 2013; Gerst et al. 2014). As Spence et al. (2009) have showed this increase in urban population is economically motivated. The higher the urbanization rate of a country, the higher its GDP. Countries high a GDP per person over \$10.000 have a urbanization rate over 60 % while countries with a GDP per person over \$30.000 have a urbanization rate around 80 %. Internally the economic importance of working in cities can be assessed by the urban–rural income gap. In China the urban–rural residents' income ratio surged from 2.57:1 in 1978 to 3.13:1 in 2011 (Li et al. 2014a, b).

Climate change is one of the most important environmental problem faced by the Planet Earth (IPCC 2007; Schellnhuber 2008) being due to the increase of carbon dioxide (CO_{2eq}) in the atmosphere, for which the built environment is a significant contributor, with around one-third of global carbon dioxide emissions. In the early eighteenth century, the concentration level of atmospheric CO_{2eq} was 280 parts per million (ppm) at present it is already 450 ppm (Vijayavenkataraman et al. 2012).

Keeping the current level of emissions (which is unlikely given the high economic growth of less developed countries with consequent increases in emission rates) will imply a dramatic increase in CO_{2eq} concentration to as much as 731 ppm in the year 2130 leading to a 3.7 °C global warming above pre-industrial temperatures (Valero et al. 2011). Even if all the greenhouse gas emissions suddenly ceased, the amount already in the atmosphere would remain there for the next 100 years (Clayton 2001). Meaning the rise in the sea level, ocean acidification and the occurrence of extreme atmospheric events will continue. Hansen et al. (2013) are even more pessimistic believing that the climate has already been changed in an irreversible manner. A worrying sign that justifies Hansen's view comes from a recent study (McMillan et al. 2014) based on the measurements collected by the Cryosat-2 satellite which reported an annual loss of 159.000 million tons of the Antartic ice sheet. This represents a 200 % ice loss rate when compared to the 2005–2010 previous survey. This means that adaptation to climate change as well as mitigation of GHGs should be a priority to the built environment (Kwok and Rajkovich 2010; Varias 2013; Boucher et al. 2014; Reckien et al. 2014; Georgescu et al. 2014). Even because buildings are responsible for almost 40 % of energy consumption and energy efficiency improvements show the greatest potential of any single strategy to abate global GHG emissions from the energy sector (IEA 2012). And especially because as a consequence of climate change in the last two decades building cooling needs have increased in an exponential trend going from 6 TJ in 1990 to 160 TJ in 2010 (Balaras et al. 2007). According to Crawley (2008), "the impact of climate change will result in a reduction in building energy use of about 10 % for buildings in cold climates, an increase of energy use of up to 20 % for buildings in the tropics, and a shift from heating energy to cooling energy for buildings in temperate climates". Other authors mention that depending on the climate zone cooling loads are likely to increase by 50 to over 90 % until the end of the century (Roetzel and Tsangrassoulis 2012). Cooling needs will also be aggravated because of urban heat island (UHI) effect, which is one of the major problems in the twenty-first century posed to human beings as a result of urbanization and industrialization of human civilization (Rizwan 2008). And this scenario will get even worse due to the expected increase in urban population and also of predict number of deaths due to heat waves (and their synergic effects with air pollution) that may reach 89,000 deaths/year by the 2050s if no adaptation measures are taken (Pacheco-Torgal et al. 2015). This means that the energy efficiency of the built environment should and must constitute a priority in the field of civil engineering. However, only some parts of the world, like for instance Europe, are now start implementing ambitious building energy efficiency policies like for instance the "nearly zero-energy building" concept to be in effect beyond 2020 (Li et al. 2013; Pacheco-Torgal et al. 2013a, b). Since only several years ago, civil engineering curriculum starts giving this issue some attention. This means that the majority of civil engineering curriculum around the world are obsolete concerning building energy efficiency or the holistic and broader concept of green building (Zuo and Zhao 2014; Li et al. 2014a, b).

Another sustainable development serious problem which is directly related to the field of civil engineering concerns total resource inefficiency. Over the twentieth century, the world increased its fossil fuel use by a factor of 12, whilst extracting 34 times more material resources (COM 2011). Also during the last century, materials use increased eightfold and, as a result, Humanity currently uses almost 60 billion tons (Gt) of materials per year (Krausmann et al. 2009). The global construction industry alone consumes more raw materials (about 3,000 Mt/year, almost 50 % by weight) than any other economic activity, which emphasizes its unsustainable character. Also, in the next few years, the construction industry will keep on growing at a fast pace. China alone will need 40 billion square meters of combined residential and commercial floor space over the next 20 years—equivalent to adding one New York City every 2 years (Pacheco-Torgal and Jalali 2011). Recent estimates on urban expansion suggests that until 2030 a high probability exist (over 75 %) that urban land cover will increase by 1.2 million km^2 (Seto et al. 2012). This is equivalent to an area about the size of South Africa. The forecast urban expansion could lead to the loss of up to 40 % of the species and of 88 % of the global primary vegetation land cover had been destroyed in "biodiversity hotspots" (Pim and Raven 2000; Myers et al. 2000).

The most important environmental threat associated to materials production is not so much the depletion of nonrenewable raw materials (Allwood et al. 2011), but instead, the environmental impacts caused by its extraction, namely extensive deforestation and top-soil loss. In 2000, the mining activity worldwide generated 6,000 Mt of mine wastes to produce just 900 Mt of raw materials (Whitmore 2006).

This means an average use of only 0.15 %, resulting in vast quantities of waste, whose disposal represents an environmental risk in terms of biodiversity conservation, air pollution, and contamination of water reserves. It is worth mention that around 1.2 billion people live in areas of physical scarcity and 500 million people are approaching this situation. As a result, since the 1970s there were 30 serious environmental accidents in mines, 5 of which occurred in Europe (Pacheco-Torgal and Jalali 2011) like for instance the 2010 toxic red mud flood in the town of Kolontar (Hungary). This is rather disturbing because Europe has high environmental standards which mean that countries in which such high standards do not exist environmental disasters could happen much more frequently. Since materials demand will double in the next 40 years, the environmental impacts will therefore increase in a drastic manner (Allwood et al. 2011). Consequently, the World Business Council for Sustainable Development estimates that by 2050 a 4 to 10-fold increase in resource efficiency will be needed (COM, 571). Alwood et al. (2011) recognizes that part of the problem is related to the fact that so far researchers have paid too little attention to the crucial issue of materials efficiency. A possible explanation for that gap relates to the fact that sustainable development principles have not yet been apprehended by University curricula. In recent years, several authors theorized about the way to embed sustainable development in higher education and several institutions made some efforts on this issue (Lozano 2006; Pacheco-Torgal and Jalali 2007; Holmberg et al. 2008; De Vere et al. 2009; Lozano 2010; Waheed et al. 2011). Data from a recent survey completed by final year engineering students in three Irish Higher Education Institutions shows that the engineering students' knowledge on this subject is still deficient (Nicolao and Colon 2012).

Salcedo-Rahola and Mulder (2009) state that "If engineers are to contribute truly to sustainable development, then sustainability must become part of their everyday thinking. This, on the other hand, can only be achieved if sustainable development becomes an integral part of engineering education programs, not a mere "add-on" to the 'core' parts of the curriculum." As a result, the validation of any discipline in any engineering curriculum must be put to a test in which the one million dollar question is "How can your discipline contribute to sustainable development?" (Salcedo-Rahola and Mulder 2009). A more holistic approach is defended by Al-Rawahy (2013) who state that sustainable development has concentrated mainly on physical and tangible issues and assets and that that the most pressing ingredient and the most scarce resource facing the sustainability concept is the ethical and moral values that universities need to proactively and aggressively "infuse" into their respective curricula. This position was already defended by other authors. According to Dator (2005) "engineering is not more important than ethics... and science is not more important than policy and law" therefore a new kind of engineering education is therefore needed to address sustainable development principles. Grasso et al. (2010) mention that "a new kind of engineer is needed, one who can think broadly across disciplines and consider the human dimensions that are at the heart of every design challenge". This is especially important in the context of climate change, which raises many questions with ethical dimensions rooted in the human condition (Willis 2012; Kaklauskas et al. 2013).

1.2 Civil Engineering: The Rebirth of an Obsolete Curriculum Through Biotechnologies and Biomimetics

Recent studies show that students of civil and environmental engineering were reluctant to have sustainability integrated sustainability into existing classes (Watson et al. 2013). One of the latest trends concerning the update of civil engineering towards sustainable development is related to the inclusion of life-cycle assessment (LCA) skills in the education curriculum (Glass et al. 2013). Unfortunately, since almost all construction products are not environmentally friendly, this is the same as choosing between the less of two evils. Another drawback of LCA is the fact that it does not take into account the possible future environmental disasters associated with the extraction of raw materials. This means that, for instance, the LCA of the aluminum produced by the Magyar Aluminum factory, the one responsible for the toxic red mud flood in the town of Kolontar (Hungary), should account for this environmental disaster. Only then construction products will be associated with their true environmental impact. Since that it is almost impossible to put in practice this means that new and truly environmentally friendly construction materials are needed. However, not only is important that civil engineering curricula are updated so they may give future graduates appropriate skills to tackle the sustainable development challenges but it is also important that enough students are interested in following a career as civil engineers. Unfortunately, in the last decade, several Western countries have reported a severe applications reduction to civil engineering. A 50 % reduction was reported on undergraduate applications to civil engineering in UK (Byfield 2001; Edwards et al. 2004). In the UK, a shortfall of 9,000 civil engineers is predicted to occur until 2013 (Byfield 2003).

Nedhi (2002) also confirms that civil engineering is not traditionally viewed as "high tech" engineering and, as a result, student quality and enrollment have been declining across North America. The same also applies in the case of research funding in civil engineering programs. This also reduces the possibility of attracting high grade students. Also in my own country (Portugal) the reduction on the enrollment ratio exceeded 80 % in the last 5 years. To make matters worse, in the last 5 years, the grade of the last student to be admitted has fallen in all the top three Portuguese Universities meaning that civil engineering is less and less capable of attracting high grade students.

In the beginning of the twenty-first century, Yurtseven (2002) already mentioned that a general problem was common to all engineering professions thus affecting negatively the student recruitment. He stated that engineers were viewed as dull individuals by contrast "to the image of a true renaissance engineer, Leonardo da Vinci who was creative and literate… an accomplished painter, architect and scientist."

The explanation for that can be found in the words of Zielinski (2003) who states that "the traditional narrow technical formation produces graduates that are, using the German language expression "fachidiot." It is then of no surprise that engineers are often satirized as persons with zero social skills. For Hamill and Hodgkinson (2003), the responsibility lies in the "invisibility" of the civil engineering profession, the absence of positive role models, low starting salaries, and unattractive working conditions. Lawless (2005) mentions that South Africa faces the same recruitment problem. Adeli (2009) also mentions that the low enrollment ratio of students in civil and environmental engineering at many US universities constitutes a problem to be dealt with. This constitutes a strange fact in a country where civil engineering is viewed as a profession with high industry demand. India, a crucial worldwide player, is also facing a severe shortage of civil engineers to achieve its huge infrastructural development targets. Again, as it happens in the US, the demand is not the problem (construction industry in India needs civil engineers). This reason, however, however seems insufficient to motivate Indian students. Part of the explanation for the low attraction capability of civil engineering relates to the fact that, in India this course is viewed as "brick and mortar engineering" (Chakraborty et al. 2011). Even the "the word "civil" in "civil engineering" is anachronistic and does not represent the works of the so-called civil engineer." As a consequence, civil engineering is "the only engineering discipline to have a name that does not represent the works it undertakes" (Shings 2007). All of what was wrote can be seen as a proof that this curriculum is an obsolete one, which constitutes a worrying issue in the context of future of twenty-first century sustainable development challenges.

However, "recent" nanotechnology achievements regarding the replication of natural systems may provide a solution to solve some of the aforementioned sustainability challenges related to the field of civil engineering. Nanotechnology deals with an atom scale (1 nm $= 1 \times 10^{-9}$ m). A hydrogen atom has a diameter of about one tenth of a nanometer and it takes six bonded carbon atoms to reach a nanometer width. In Nature there are innumerous examples of the nanoscale but one of the most interesting in the "civil engineering context" is the 1–2 nm hydrophobic wax crystals that cover lotus leaves and are responsible for their self-clean ability (Varadan et al. 2010). This new field encompasses a holistic way of perceiving the potential of natural systems (Martin et al. 2010) in which traditional and predominant anthropocentric views are replaced by more eco-centrically approaches (Hofstra and Huisingh 2014) as prerequisite in order to build a sustainable future. It is worth mentioning that this ecological imperative is very far from the 1828 Royal Charter of the Institution of Civil Engineers main purpose, which defined civil engineering as the art of "directing the great sources of power in nature for the use and convenience of man..." (Muir-Wood 2012). Strangely as may seems most civil engineering curriculum and most civil engineering departments in the world still live by this two century outdated and unsustainable motto and some even went to the paradox extreme of try to marketing it as a curriculum forged in sustainable development principles.

The crucial importance of Nature's lessons relates to the fact that it always uses ambient conditions with minimum waste and no pollution, where the result is mostly biodegradable by the contrary man-made materials are processed by heating and pressurizing generating enormous hazardous wastes (Bar-Cohen 2006). On her inspired book Benyus (1997) quoted Mehmet Sarikaya, Professor of material's science and engineering at the University of Washington who wrote: "We are on the brink of a material's revolution that will be on par with the Iron Age and the Industrial Revolution. We are leaping forward into a new age of materials. Within the next century, I think biomimetics, will significantly alter the way in which we live. Learning from nature can become a great challenge for future management". And in fact some more or less recent papers on biological materials (Sarikaya et al. 2003; Sanchez et al. 2005; Chen et al. 2012; Yang et al. 2013; Amini and Miserez 2013) especially the highly cited papers of Markaya et al. (with 823 Scopus citations by May of 2014) and of Sanchez et al. (with 517 Scopus citations by May of 2014) and the extensively detailed paper of Chen et al. serve as a confirmation of the 1997 Saikaya's predictions.

The Biomimicry Institute, founded in 2006 by Janine Benyus, was precursor in this field providing the AskNature online library of research articles on biomimetic design indexed by function. The term biomimetics was used by the first time by Otto Schmitt during the 1950s and relates to the development of novel technologies through the distillation of principles from the study of biological systems. This author made a distinction between an engineering/physics approach to the biological sciences, which was termed "biophysics," and a biological approach to engineering, which he termed biomimetics (Vincent et al. 2006; Lepora et al. 2013). However, the study of biological systems as structures dates back to the early parts of the twentieth century with the work of D'Arcy W. Thompson, first published in 1917. In this work that some authors considered the first major one on this field D'Arcy W. Thompson looked at biological systems as engineering structures and obtained mathematical relationships that described their form (Chen et al. 2012).

According to Vincent (2001), biomimetics is the "technological outcome of the act of borrowing ideas from nature" and this concept would have also been termed as "biomimesis", "biognosis," and "bionics." For this author, the term "bionics" was coined in 1960 by Jack Steele of the US Air Force. In German-speaking countries, the term "Bionik" has become widely accepted for the corresponding field to "Biomimetics." "Bionik"—combining biology and technology (Gebeshuber et al. 2009).

Figure 1.1 gives an overview of the history of biomimetics research. Terms such as "biomimicry," "bioinspiration," and "bioinspired" are derived words from "biomimetic," and "bioinspired" is sometimes used to connote a presumed heir of the word biomimetic (Shimomura 2010).

The publications on the field of biomimetics have experienced an amazing increase from a few 10 papers per year in mid-1990s to the present, doubling every 2–3 years and reaching an annual production of 3,000 papers in 2011 (Lepora et al. 2013). A recent search on Elsevier's Scopus revealed that in 2013 the number of

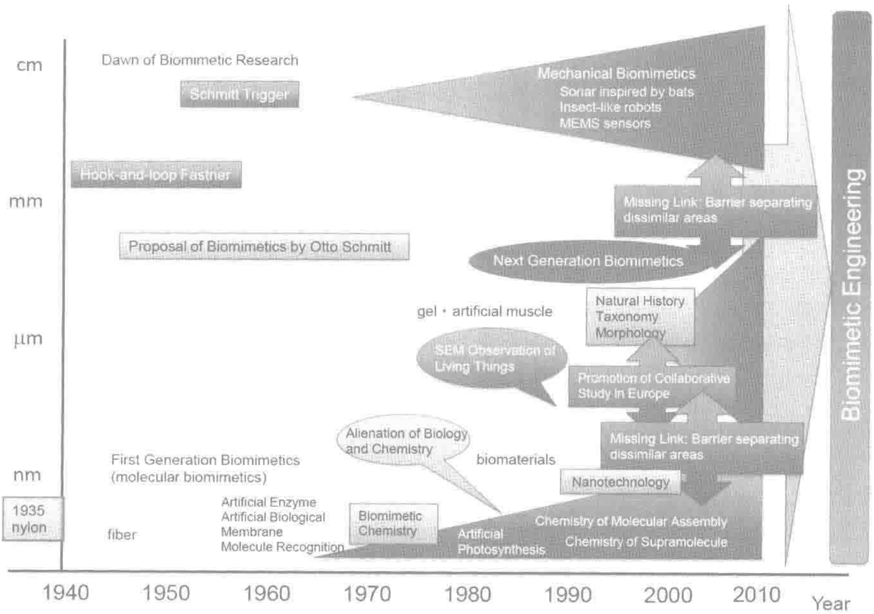

Fig. 1.1 History of biomimetics research (Simomura 2010)