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Review

Nature-Inspired Design: Biomimicry and Cradle to Cradle

Azra Kekic, Ljiljana Stojanovic Bjelic, Dragana Neskovic Markic
Pan-European University Apeiron

Abstract: Rapid science and technology development, as well as population growth and solving global problems require a different approach to considering and solving these problems by including many scientific disciplines or technologies. The growing amount of waste and unsystematic depletion of natural resources impose new concepts and tools in creating new environmental products. The existing linear economy, based on the 'take, make and dispose' principle, is being replaced by a new approach, the 'circular economy'. A circular economy seeks to sustainably manage natural resources, extend product lifecycle and reduce waste. Some of the directions or tools in a circular economy are biomimicry and cradle to cradle. Biomimicry seeks to solve problems by imitating natural processes, while cradle to cradle tends to reduce waste using knowledge obtained from nature. Understanding of nature, its systems and cycles will provide analogies and models for creation of innovative solutions to global problems.

Keywords: waste, circular economy, biomimicry, cradle to cradle

INTRODUCTION

Waste as we know it is created only by man and it is a problem of modern society that affects human health and the environment (Kaiser et al., 2001). Since the Industrial Revolution, the global economy has been characterized by one significant model, the 'linear model of production and consumption'. The linear economy model operates under the 'take, make and dispose' principle, where all products that are no longer needed by man end up as waste (Ghisellini et al., 2015). It is common practice for products to be created at low prices, used and discarded. Such linear economy approach results in unsustainable consumption of natural resources and accumulation of pollution (Park & Chertow, 2014; Su et al., 2013). Such approach, not only from the economic point of view, triggered consideration of the unsustainability of the model, i.e. the unsustainability of modern civilization. On the other hand, the Earth's resources are not infinite and they are increasingly threatened. Technology growth and development have led to a decrease in production and selling prices, an increase in the standard of living of the population, and an uncontrolled imbalance between the economic and environmental systems (Korhonen et al., 2018).

A circular economy seeks to operate on a product-to-waste-to-product principle, i.e. to ensure sustainable resources management, product lifecycle extension, waste reduction, and renewable energy use. With this new approach, waste is almost non-existent, i.e. it is reduced to a minimum (Geissdoerfer et al., 2017).

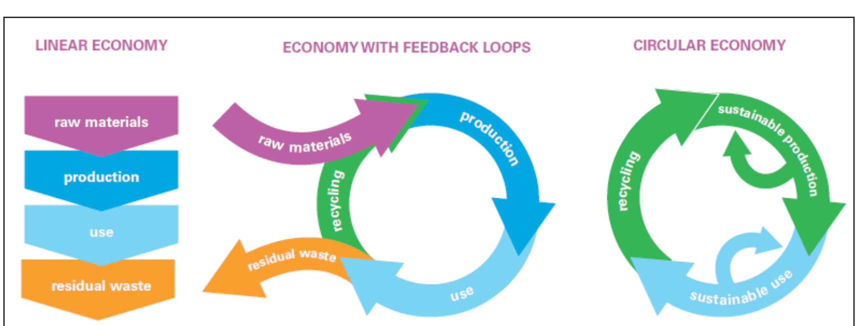

Figure 1. Linear and circular economy (Moula et al., 2017)

As shown in the figure 1, every phase in a circular economy tends to diminish costs and dependency on natural resources, as well as to reduce waste. This model replaces the 'end of life' concept with restoration, use of renewable energy sources, and elimination of the use of toxic chemicals. A product is produced, used, and once it has reached the end of its useful life, its constituent resources are reused, that is, the process restarts from the beginning. For example, factory waste becomes valuable to another process, products can be repaired, reused or upgraded rather than thrown away

The objectives of circular economy are (Ghisellini et al., 2015):

- Lower consumption of natural resources,
- Extended lifecycle of products and components of the materials used,
- Growing consumption of renewable resources,
- Reduced noxious gas emissions.

A circular economy aims to improve the quality of life of citizens, use resources more efficiently, increase competitiveness, create new jobs through the development of new technologies, innovations, designs, modular products manufactured in a way that they can be easily upgraded and processed, and a new way of company organization. The companies embracing the circular economy model means operating for the benefit not only of the society and the environment, but also of the consumers and investors.

A linear economy generates a large amount of waste, and in the long run increases the cost of solving various environmental problems, consumes large quantities of resources, leading even to the scarcity of some resources. Circular economy means moving towards 'zero waste' and changes in product design and packaging and promoting the idea that waste can become a resource again. Transition from a linear to a circular economy seeks to have all economic actors consuming as little natural resources as possible, to move towards regenerating by recycling, introducing innovative technologies, etc.

In accordance with the objectives of a circular economy, the European countries that have taken national-level initiatives to implement circular economy are the Netherlands, Finland, Germany, Portugal, Italy, France and Slovenia. At local and regional level, green economy and circular economy are promoted in the regions of Catalonia (Spain), Scotland and London (United Kingdom), Amsterdam (Netherlands), Paris (France) (Avdiushchenko & Zajac, 2019). Also, circular economy development is not limited to Europe, but covers other countries of the world, especially China (Welfens et al., 2017; Yuan et al., 2006), Japan and Canada (Korhonen et al., 2018).

We view the circular economy as a complex holistic approach consisting of several development directions or tools (Bruel et al., 2019; Lewandowski, M. 2016) (Figure 2).

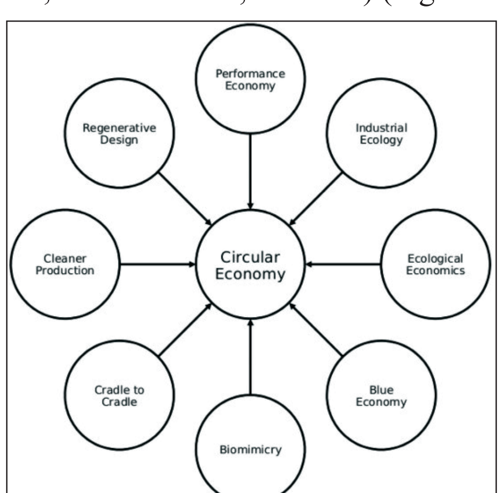

Figure 2. Key concepts closely related to the circular economy (Bruel et al., 2019)

NEW NATURE-INSPIRED CONCEPT

Biomimicry

Biomimicry (bios – life and mimesis – imitate) is an adaptive way of solving the problems of life and economy, which can be found in nature, i.e. by imitating natural phenomena and processes. Biomimicry can also be defined as a set of innovations inspired by nature. Nature has always been an inexhaustible source of inspiration for scientists, experts and artists in various fields (Kennedy et al., 2015).

In nature, every organism is unique and fully adapted to its environment and life and survival in all conditions. We can observe a tree growing from seed using nutrients and solar energy during its growth and development, and eventually dying and becoming food for a new life and beginning. Through evolution, nature has solved a number of problems, that is, plants, animals, and microorganisms function in a harmony or equilibrium (Eadie & Ghosh, 2011). Study of organisms, i.e. the adaptations and processes that unfold in each organism individually and through interactions with other organisms and the environment, yields knowledge and new ideas to be applied in various fields of human creation such as architecture (Rao, 2014; Singh & Nayyar, 2015), medicine (Ahadian et al., 2013; Zhang, 2012), robotics (Habib, 2011), textile technology (Das et al, 2017; Ellison, 2013), etc.

Biomimicry is determined by three key principles (Stevens et al., 2019):

- Nature as a model – where, by studying nature's models, mimicry evaluates these models into new forms, processes, systems or strategies for solving technical problems,
- Nature as a measure – serves biomimicry to use ecological standards to judge the sustainability of innovation,
- Nature as a mentor – serves to biomimicry to observe and grasp nature as a source of knowledge.

Biomimicry is increasingly advancing with the development of technology, synthesis of bio-sustainable and environmentally friendly materials, obtaining of new scientific knowledge and achievements. The principles of biomimicry are based on the laws of nature (Oguntona & Aigbavboa, 2017):

- Nature acts under the influence of sunlight,
- Nature uses only the energy it needs,
- Nature recycles everything,
- Nature operates on the principle of diversity,
- Nature is founded on diversity,
- Nature fits form to function,
- Nature does not allow wastage.

The application of biomimicry in architecture and design is revolutionary. Man adapts to nature, enhances his existence and survival in difficult conditions such as harsh climate, poor geological soil characteristics, hard to access terrain etc. Designing and building facilities on biomimicry principles makes it easier for people to overcome natural disasters such as earthquakes, floods, strong winds, increased radiation due to ozone layer damage. New ideas and innovative solutions in architecture seek to ensure healthy working and living conditions in sustainable design and eco-efficient facilities (Kennedy et al., 2015, Rao, 2014).

Biomimicry examples in practice

The lotus flower or, more specifically, some of its features have long been used in architecture and design. German botanist Barthlott noticed, while studying the lotus plant, that the leaves were perfectly clean or that the impurities did not stay on the leaf. At first glance, lotus leaves seem smooth, but surface analysis showed that the surface was rough. The water that falls on the leaf in the form of droplets, slides off the leaves together with impurities. This effect on the surface of the lotus leaf is due to its micro- and nanoscopic surface architecture, which reduces adhesion of dirt particles. The surface of the lotus leaf is superhydrophobic, repelling water. Water falling on the leaf forms balls, i.e. it does not adhere to the surface of the lotus (Solga, et al., 2007). Other plants, such as nasturtium (Tropaeolum), reed (Phragmites), cabbage (Brassica oleracea) or columbine (Aquilegia) demonstrate this effect, as do some animals (many insect wings).

The self-cleaning ability of water-repellent nanostructured surfaces was discovered in the 1970s by Wilhelm Barthlott with protected 'Lotus Effect' trademarks. This desired property of micro- and nano-structuring of superhydrophobic surfaces is a purely physicochemical phenomenon and can be bionically transferred to technical surfaces (Marmur, 2004). This phenomenon of lotus leaf cleaning was used to produce façade paints based on hydrophobicity and special microstructure to achieve less adhesion of dirt and impurities, and to protect the façade from microclimatic influences. Initially, the intent was to make façades as smooth and even as possible (Xuan-yi, 2005). Another option for application of the lotus effect is in making self-cleaning awnings, tarpaulins and sails based on the principle of the lotus effect, since they typically dirty easily and are difficult to clean. Furthermore, there is producing hydrophobic glass surfaces. There is a Lotus Building in China, which is currently a gem of modern architecture, and most importantly this facility is a low-energy facility.

Cradle to Cradle

There is no concept of waste in nature, i.e. everything is food for other organisms or systems. Materials are reused in cycles, and there are no durable and bio-accumulative materials. And biota is created on the planet by solar energy activity.

Manufacturing systems of the Industrial Revolution are based on a one-way or linear cradle-to-grave stream of materials - a model that takes, makes and consumes. Materials are taken from nature and refined, products are assembled, distributed, used by consumers and then discarded to landfills or incinerators. Each step in this stream typically creates unintended environmental and health impacts. The advent of modern industrial processes has had the added consequence of making many processes and materials more toxic. Today, they are the legacy of the linear model that affects profoundly the air we breathe, the water we drink, the climate we live in, the diseases we suffer from, and global politics (Michelini, et al., 2017; Bonviu, 2014).

In response to widespread environmental degradation, governments and industries have adopted a strategy known as 'eco-efficiency' - minimizing waste, pollution and natural resource depletion. Many companies have realized significant cost savings and reduced environmental impacts by embracing eco-efficiency. But long-term prosperity depends not on the efficiency of a fundamentally destructive linear model of the economy. It depends on the effectiveness of processes designed to be sustaining, healthy and renewable (Bach et al., 2018).

Cradle to Cradle Design (C2C) offers an alternative. It rejects the assumption that human industry inevitably destroys the natural world, or that the demand for goods and services is the ultimate cause of environmental ills. Instead, it embraces abundance, human ingenuity and positive aspirations. Today, owing to a growing knowledge of the living earth, our designs can reflect a new spirit. Cradle to Cradle Design incorporates this new ecological awareness at every level of human endeavor. Its principles are built on the intelligence, abundance and effectiveness of natural systems - the flows of energy and nutrients that support the Earth's biodiversity (Reay et al., 2011).

Nature's ecosystems function on some key principles that human design can emulate. First, there is no waste in nature; the waste from one organism provides nutrients for another. Second, all life on earth is fueled by solar energy. Third, life thrives on diversity, constantly adapting to fill niches. Cradle to Cradle Design models human industry on these natural principles. It envisions a world powered by the sun where growth is good, waste nutritious, and productive diversity enriches human and natural communities (Figure 3) (Reay et al., 2011; Toxopeus et al., 2015; Peralta-Álvarez, et al., 2015).

The application of cradle-to-cradle principles to industry creates cyclical material flows (cradle-to-cradle, rather than cradle-to-grave) that, like the Earth's nutrient cycles, eliminate the concept of waste. Each material in a product is designed to be safe and effective, and to provide high quality resources for subsequent generations of products. All materials are conceived as nutrients, circulating safely and productively in one of two 'metabolisms' (Braungart et al., 2007):

- biological metabolism and
- technical metabolism.

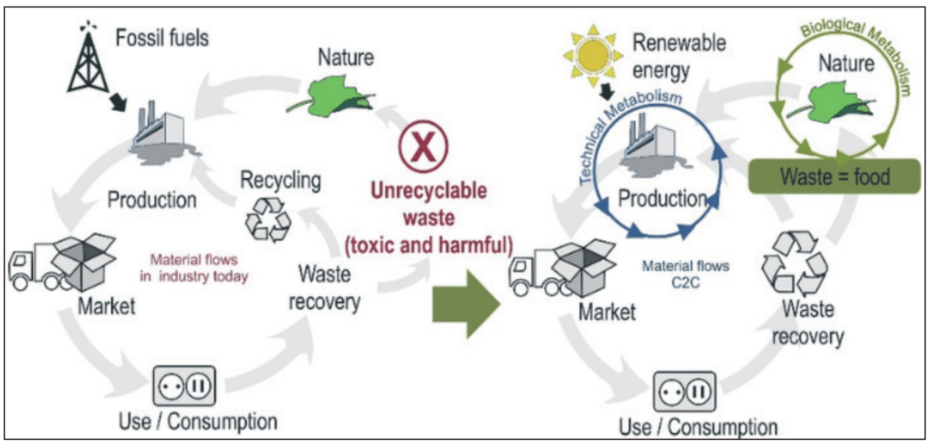

Figure 3. Cyclical Metabolisms in C2C (Peralta-Álvarez, et al., 2015)

The biological metabolism is the system of natural processes that support life. These processes include the degradation of organic materials and their incorporation into organisms - cyclical, and ultimately fueled by sunlight. Materials that contribute to the productivity of the metabolism are biological nutrients. Ideally, products of human industry designed from biodegradable, ecologically safe materials, participate in the biological metabolism after use through decomposition.

Technical metabolisms exist within the natural world as material releases to ecosystems are inevitable, and technical nutrients ideally should pose little or no hazard to the biological metabolism. Lead is universally recognized as being so toxic that even minor releases damage human and ecological health. For car batteries, there are safer alternatives (e.g. lithium, zinc) that provide comparable performance. Though these alternatives are currently more expensive, they do not carry the associated environmental and health costs of lead.

The concept of C2C is a new concept of economy modeling through processes similar to nature, where materials are seen as nutrients that circulate within a biological or technical metabolism to a healthy or safe metabolism. This healthy metabolism enables reuse, material optimization, recycling and nature conservation. The C2C concept shapes materials and objects on the model of natural processes. This new concept considers artificially created materials, obtained in other industrial processes, as nutrients that circulate perpetually in the healthy metabolism of the living world. This creates an infinite lifecycle of nonliving matter, modelled on the living world, where the biosphere is equated with the technosphere (Peralta-Álvarez, et al., 2015; Toxopeus et al., 2015).

C2C Design is a system of thinking based on the belief that human design can have a more effective approach by learning from nature and incorporating its patterns. Industry can be transformed into a sustaining enterprise - one that creates economic, ecological and social value - through thoughtful design that mirrors the safe, regenerative productivity of nature and eliminates the concept of waste. C2C design is key to creating a regenerative economy inspired by natural systems, which benefits the society, the economy and the environment. C2C is based on the following principles (Kopnina, 2011; van de Westerlo et al., 2012):

1. Waste is food.
2. Use renewable energy sources
3. Promote diversity

Waste is food - The first principle calls for the elimination of the very concept of waste and encourages to be inspired by nature's endless nutrient cycles. Instead of the eco-efficient approach of trying to reduce the amount of waste, the focus should be to design systems with outputs that can be taken up as nutrient by other processes. This goes both for emissions during the production stage of a product and for the product itself once it reaches the disposal stage. To ensure that such emissions can undergo 100% closed loop, recycling materials should be defined as either technical or biological nutrients. Technical nutrients should be designed for industrial recycling, whereas biological nutrients should be designed to return to the soil and feed the environment. Biological and technical nutrients should not be mixed. Otherwise a product is created which fits into neither the biological nor the technical 'metabolism'. Such a product can never be truly recycled, but merely downcycled into a product of lower quality and value (Kopnina, 2011; Bach et al., 2018).

Use renewable energy sources - The second principle dictates that the energy required for fueling a closed loop C2C cycle must come from what is termed 'current solar income', defined as photovoltaic, geothermal, wind, hydro and biomass. These sources correspond with the general understanding of renewable energy sources (Kopnina, 2011; Bach et al., 2018).

Promote diversity - The main point of this last principle is to avoid one-size-fits-all solutions and instead design products and systems with local environment, economy and culture in mind. The aim should not be to reduce negative impacts on the environment as suggested by the eco-efficiency concept, as this would result in isolation from other species (Kopnina, 2011).

C2C example in practice

Upholstery fabrics which wear out with use, can be designed from biological nutrients that can be returned to ecosystems after use. Climatex® Lifecycle™ fabric is an example of this type of product. The fabric is a blend of pesticide-residue-free wool and organically grown ramie (a nettle family plant), dyed and processed entirely with non-toxic chemicals. All product and process inputs were defined and selected for their human and ecological safety within the context of a biological metabolism. Currently, the fabric trimmings (process 'waste') are used by garden clubs as a mulch for growing fruits and vegetables, returning the textile's biological nutrients to feed new growth. The return of Climatex Lifecycle's nutrients to the biological metabolism depends on its application and post-use handling. The design must facilitate the clean separation of the fabric from materials that cannot function as biological nutrients, like synthetic foams. Substances used to treat and clean the fabric should also be compatible with the biological metabolism. Finally, the cycling of the fabric's nutrients will likely rely on a well run composting system (Braungart et al., 2007).

The technical metabolism industry can also be modeled after natural processes to create technical metabolisms, systems that productively cycle industrial materials. These materials, valuable for their performance qualities and typically ‘non-renewable’, are technical nutrients, designed to circulate safely and perpetually through cradle to cradle product lifecycles of production, use, recovery and re-manufacture. The processes of the technical metabolism are industrial rather than natural, but ideally fueled by the energy of the sun in the form of renewable energy.

Another example is the well-developed system for lead-acid battery recovery as a model for the development of technical metabolisms. Car batteries are valuable to customers for storing and providing electricity, but incidentally pose risk to customers and the environment as a result of the hazardous materials they contain. To reduce the risk of the release of hazardous materials, economic incentives have been built in to encourage the return of old batteries to authorized locations with credit towards a new battery. Old batteries are sent to secondary smelters where the material value of the lead, plastic and the acid is recovered for use in new batteries. Over 95% of all lead and plastic from recovered car batteries is recycled, making it the most recycled consumer product in the US.

Swiss company Rohner uses 16 dyes for its fabrics which do not contain any toxic substance. Mixing these dyes can produce any shade. The waste resulting from the production process of cutting out is made into biodegradable felt. This felt is used in agriculture in the winter and is completely decomposed by spring to produce nutrients (Kopnina, & Blewitt, 2018).

Since 2017, C&A started gradual phasing out of models of garments made from non-renewable materials, with a focus on biological materials that can be reused, recycled and finally decomposed safely (Cattermole, 2018).

The concept of circular economy is increasingly applied in construction, and innovations are being increasingly introduced in this branch in using and revitalizing old materials, and re-incorporating them in a new shape. Urban agriculture is increasingly used within self-sustaining urban areas. Fruit and vegetables are being grown on rooftops, i.e. food is being grown in cities thus eliminating food transport in containers from other areas.

Another example of application of the C2C concept in construction is reconstruction of the Ford car factory roof in the US. Ford opted for construction of a green roof instead of construction of a water treatment plant. The green roof covers the area of 40,000 m2, where grass on the roof of this industrial complex collects, purifies atmospheric water outdoors (Dijk, 2014).

The SPARK architecture house in Singapore is another example of the application of the C2C concept through construction of vertical aquaponics agriculture. This building has an established system of circulating waste nutrients from the bottom of the building to the top, processing waste substances to obtain heat and electricity, as well as saving by building a modern lighting system. The system is completely self-sustaining. In addition, elderly persons are living in several residential units of this building. These people work in the garden, socialize and learn about growing plants in urban vertical agriculture, which has an important social component.

CONCLUSION

In recent years, the world has been faced with the need to find new models of production and consumption by increasing the efficiency of resource use and reaching ‘zero waste’. The concept that leads to the achievement of these goals is circular economy. Circular economy as a global solution should reconcile the constant diminution of natural resources with the increased demand for them, population growth, intensified consumption, etc. Circular economy uses various tools such as: blue economy, green design, biomimicry, cradle to cradle, performance economy etc. This paper focuses on biomimicry and cradle to cradle because both of these concepts are founded on nature, by grasping and using natural processes, emulating nature in creating new products and services. For a long time, man has been creating products, new materials that are not in harmony with nature and processes in nature. Various artificial materials have been created, unmatched by nature, so we have such artificial materials decomposing in nature for very long periods, hundreds of years. The new approach, which is based on nature-inspired design, seeks to bring man and his actions back within the limits of natural processes and living in harmony with nature.

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