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The Art of Imitating Life: The Potential Contribution of Biomimicry in Shaping the Future of Our Cities.

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Abstract

This paper discusses the significance of biomimicry as a design methodology within the context of urban infrastructure planning and design. The application of biomimicry principles to urban infrastructure problems is examined by analysing case studies that used biomimicry inspired designs rather than 'mainstream' infrastructure approaches. Biomimicry is presented as an ontology of the city that fosters innovative and collaborative urban infrastructure design and management, supplements dominant future city paradigms like the 'smart' city, and is worthy of further, detailed study.

Keywords: Biomimicry; Sustainable urban infrastructure; Transdisciplinarity; Design methodology; Ontology; Innovation; Integrated Infrastructure

Introduction

Biomimicry extracts design principles from nature to apply to human challenges and is utilised in engineering, product design and architecture, stimulating innovation and 'transdisciplinarity' (Helms et al., 2009; Mcgregor, 2013). This paper discusses the significance of biomimicry for inspiring innovation within urban infrastructure planning and design. It aims to provide an overview for practitioners, city decision makers and academics attempting to shift city paradigms. As such, it is part of a movement reviewing ontological conceptions of the city and how urban planning and design practice fit into these.

We have moved from the modernist ideal of urban infrastructure conquering nature to an ecological age that embraces rather than eradicates urban nature. This is represented globally by the Gaia hypothesis (Lovelock and Margulis, 1974) and at the urban scale by ontologies that challenge the view that cities are the antithesis to nature (Braun, 2005). Cities as ecological spaces can be traced to Ebenezer Howard, who proclaimed cities '*a product of the earth…a fact in nature'* (Howard, 1902). The 1920 -1930's Chicago School sociologists used biological concepts and metaphors to describe the city's social, cultural and spatial patterns. Raymond Williams argued that city and countryside are inextricably connected (Williams, 1973); David Harvey asserts there is nothing 'unnatural' about New York City (Harvey, 1996). Matthew Gandy and Sarah Whatmore claim the city is fully part of nature, with nonhuman nature present everywhere (Gandy, 2002; Whatmore, 2002). Heynen's discussion of 'urban forests' focuses on specific ecological interactions between elements of nonhuman nature (Heynen, 2003); Swyngedouw's 'socionature' concept (Swyngedouw, 2004), evolved into 'cyborg' cities (Swyngedouw, 2006). Mimesis theory in architecture states imitation is a form of adaptation central to the human condition (Leach, 2006) that identifies and empathises with the external world, alluding to the creative, constructive reinterpretation of an original (ibid).

If cities can be conceptualised as natural entities there may be advantages to designing and managing them accordingly. Biomimicry offers one potential route, although its urban scale usage poses several questions, such as identifying whether biomimicry is best seen as a metaphor or a technical framework, and precisely how biomimetic approaches differ from current urban planning and design approaches and whether or not they provide novel concepts of the city.

This paper argues that biomimicry is an ontology that can support the planning and design of cities' urban infrastructures. As a valid problem-solving methodology, it has been employed successfully in other fields to foster innovative and collaborative designs. It supplements dominant paradigms such as the smart city, reconnects citizens with nature, and regenerates ecosystems (Zari, 2012). It potentially accesses 'pathways of least resistance' (Mathews, 2011) and challenges our descriptions of cities. It poses questions about whether infrastructure should be steadfast, resisting nature, or malleable enough to adapt to transient conditions, i.e. the move from fail-safe to safe-fail infrastructure systems (Matczak et al., 2015). The hope is to contribute to the conceptualisation of biomimicry within urban infrastructure, by examining how it is applied to urban infrastructure problems with reference to case studies and stakeholder interviews.

The paper first outlines key 21st century urban challenges and the theoretical basis of biomimicry and its successful application in other fields. Case studies exploring urban biomimicry principles are then presented, followed by a thematic analysis of the empirical material. The conclusions and research agenda for deeper understanding of biomimicry's role in urban planning and design are then discussed.

Background of Problem

Global urbanisation, climate change and resource constraints combine to create major challenges in the 21st century. Urban pressures include shifting demographics, traffic congestion, resource depletion, flooding, and overheating. Half of the world's population live in urban areas (United Nations, 2007b), which is predicted to increase to nearly 70% by 2050 (United Nations, 2011). Cities are responsible for 75% of global energy consumption, and 80% of carbon emissions (United Nations, 2007a).

Academic research and industry efforts to commercialise city-scale technological solutions to these challenges have increased exponentially, although most attempts suffer from a lack of coordination between disciplines operating at the city scale (Taylor Buck and While, 2015). Accordingly, responses to infrastructural challenges are typically fragmented and reactive technical approaches (HM Treasury, 2011). Design is often based on inaccurate supply and demand computer models (e.g. Department for Transport, 2013) that discount or underplay future climate change impacts. Current urban infrastructure approaches often aim to overcome and disconnect nature rather than embrace it, are blind to environmental limits, and ignore behavioural impacts. For example, building more roads does not reduce congestion, but increases car use (Noland and Hanson, 2013).

It has been argued that the growing disconnect between city dwellers and nature has negative impacts on our well-being (Gullone, 2000) and capacity to combat climate change (Nisbet et al., 2008). Some believe a relationship with nature is essential to child development, with modern children at risk of suffering from 'Nature Deficit Disorder' (Louv, 2010), causing them to be environmentally and nutritionally illiterate.

Theoretical Basis of Solution

What Is Biomimicry?

Designers have used biology as an inspiration for thousands of years (Helms et al., 2009), viewing the natural world as 'a living encyclopaedia of ingenuity' (El-Zeiny, 2012). Leonardo Da Vinci (1952) wrote: *'The genius of man…will never discover a more beautiful, a more economical, or a more direct [approach] than nature's, since … nothing is wanting and nothing is superfluous'*.

Biomimicry (from *bios*, 'life', and *mimesis,'* to imitate') is one approach to drawing inspiration from the natural world (Spiegelhalter and Arch, 2010). It is an applied science that emulates nature's forms, processes and ecosystems to solve human design problems (Shu et al., 2011), employing strategies refined over 3.8 billion years of evolution (ibid). Janine Benyus (1997) popularized biomimicry in the late 1990's by discussing product design, engineering and manufacturing applications. She later wrote, 'the built environment is the most fertile ground for biomimicry' (quoted in Klein, 2009). Biomimicry fundamentally differs from both bio-utilisation (the harvesting of a product / producer, such as harvesting silkworm silk in the wild) and bio-assisted technologies (the domestication of an organism, such as selective breeding of silkworms to maximise silk production) (Baumeister, 2013). In contrast, biomimicry would emulate the silkworm's manufacturing process.

Such emulation engages three levels of mimicry: form, process, and ecosystem (Benyus, 2008). This differentiates biomimicry from similar concepts such as Biophilia, Biomorphism, and Ecological Design. Biophilia is the inherent desire for humans to 'affiliate with natural systems and processes' (Wilson, 1984). Biomorphic designs focus on the aesthetic properties of naturally occurring shapes, forms and patterns (Wünsche, 2003) without reference to biological processes or ecosystems. Ecological Design attempts to minimise environmental damage, integrating ecological processes (Van der Ryn and Cowan, 1996) but may ignore biological form and process. Therefore biomimicry is the 'technology of biology' (Baumeister, 2013), a holistic approach, not designing *with* nature, but designing *as* nature. Human technology relies on external inputs, assembly, and ongoing maintenance. Nature relies on sunlight and growth, curbs excesses from within, recycles materials, and can self-repair (Quinn and Gaughran, 2010).

In problem solving, it has been argued that exposure to biological examples increases the novelty of solutions generated in contrast to human-engineered examples, which decrease variety (Wilson et al., 2010). This may be due to the high level of abstraction required and the inherent characteristics of biologically inspired design, which are (after Helms et al., 2009):

1. Inherent transdisciplinarity
2. Communication challenges between biologists and designer-engineers
3. Different investigative methods between biologists and designer-engineers
4. More multi-functional, interdependent designs
5. Different resources/materials between the natural and engineering domains

How Is Biomimicry Applied to General Design Problems?

Examples of successful biomimicry exist across many fields. In textile manufacture, hydrophobic materials and drag-reducing swimwear have been inspired by lotus leaves (Guo et al., 2011) and shark skin (Smith, 2007) respectively. Mechanical designs include low-gravity drills based on wood wasp ovipositors (cited by Shu et al., 2011); velcro, inspired by cocklebur seed pods (Mueller, 2008); and adhesive mimicking gecko feet (Yang, 2008, cited in Klein, 2009). In ICT, bee forager allocation behaviour inspired dynamic server allocation (Nakrani & Tovey, 2004). Material innovations include paints that mimic butterfly wing colours (Smith, 2007) or self-clean (Vartan, 2006); super-tough ceramics mimicking mother of pearl (Heintz, 2009); and 3-D printed, fracture-resistant, bone-like materials (Brehm, 2013). In chemistry, much work focuses on artificial photosynthesis (Benniston and Harriman, 2008). Architectural biomimicry includes the FAZ Pavilion in Frankfurt, which uses a pinecone-inspired skin that passively opens on sunny days and closes during rain, providing shelter (El-Zeiny, 2012) and the

Eastgate Centre in Harare, Zimbabwe, which emulates the cooling mechanisms of termite nests (Deshpande et al., 2013)

Biologically inspired design processes typically begin from one of two starting points: Solution-to-Problem, where a known biological solution is applied to suitable problems; or Problem-to-Solution, where a particular problem is tackled by searching for biological solutions to analogous natural challenges (Pandremenos et al., 2012). Helms et al. (2009) provide a framework for the Problem-to-Solution design approach:

- **Step 1: Problem Definition** - functional decomposition splits a complex function into sub-functions.
- **Step 2: Reframe Problem** - use questions with broadly applicable biological terms, such as ‘How do biological solutions accomplish xyz function?’
- **Step 3: Biological Solution Search** - See Table 1.
- **Step 4: Define Biological Solution** - using functional decomposition to determine sub-functions
- **Step 5: Principle Extraction** – after understanding the solution
- **Step 6: Principle Application** - translate principle into new domain

Table 1. Solution Search Heuristics Search. After Helms et al. (2008)

Search Technique	Technique Description
Change Constraints	Broaden narrow problem definition, increasing search space, e.g. “keeping cool” to “thermoregulation”.
Champion Adapters	Find organism or a system that survives in the most extreme case under review. For instance, for “keeping cool”,

	look for desert or equatorial organisms.
Variation within a Solution Family	Find organism "families" that face and solve the same problem in slightly different ways,e.g., the many variations on bat ears suggest deeper echo location solution principles.
Multi Functionality	Find organisms or systems with single solutions that solve multiple problems simultaneously.

Several authors suggest such design processes should be based on common principles (Tsui, 1999; Van der Ryn and Cowan, 1996). In particular, the biological solution search stage is difficult for those with little or no biological training, and attempts to create classifications for categorising known biomimetic solutions and streamlining the search process continue (Goel et al., 2014; Vincent et al., 2006).

Biomimicry and Urban Infrastructure Design and Management

In the built environment, biomimicry could reduce embodied energy in construction products; reduce materials use; improve resource efficiency; reduce weight and complexity; produce novel designs; and reduce maintenance (BRE, 2007). For example, Exploration Architecture are developing a algorithm-based flow optimisation tool for infrastructure that mimics nature's minimal use of material and energy to move liquids and gas about a body (Pers.Comm.).

Biomimicry of genetics and evolutionary processes has the potential to deliver 'living' cities. An organism's sphere of influence extends beyond its physical boundaries to include the environment it modifies (Turner, 2004, 2009). This 'extended physiology' concept makes possible a built environment that does not simply imitate biology, but actively tends towards homeostasis - i.e., recovering from disruptions to an adaptive state (Turner & Soar, 2008). For cities, the algorithmic recipe stored within genes provides an alternative model to replicating exact developmental designs (Fratzl, 2007). This could foster dynamism and adaption, in the same way that two branches growing on opposite sides of a tree grow differently in response to environmental conditions, despite sharing the same genetic code (Jeronimidis et al., 1995).

Biomimicry also offers a fresh perspective to solving urban challenges that differs from the dominant sustainability paradigm. Whereas sustainable urbanism has traditionally involved mitigating negatives, biomimicry is much more about trying to create positive regeneration. It therefore has enormous potential to stimulate innovative and adaptable city solutions (Bonser & Vincent, 2007).

Empirical Examples of Urban Scale Biomimicry

Methods

A scoping review of the literature pertaining to biomimicry and urban infrastructure design took place to identify projects which either mimicked the dynamic interaction of two or more organisms with their environment in an ‘ecosystem’ arrangement (Type 1) or mimicked strategies exhibited by single organisms (Type 2). From this review four Type 1 and five Type 2 case studies were selected. Cities can be conceptualised as a system of systems (Keating et al., 2003), and the case studies were chosen to provide evidence for each of six key city systems: Energy & Carbon; Water; Waste; Food; Transport; Buildings & Infrastructure. Each case study was analysed to identify the theoretical biomimicry design paths. Results were tabulated in a

‘Problem-to-Solution’ design format (Helms et al., 2009), alongside a typical ‘mainstream’ infrastructure solution to emphasise the difference in approach (See Tables 2 and 3).

Another key selection criteria for the case studies was their explicit use of nature-inspired design. A case study was considered biomimetic when the design’s primary function depended upon or was enabled by the integration of biological knowledge (Baumeister, 2013). In this way, the use of case studies demonstrating ‘bio-coincidence’, or accidental biomimicry, was avoided.

To deepen the understanding of the impact of biomimicry on the infrastructure design process, four potential interviewees who had been directly involved with the selected case studies were initially identified and approached using a reputational method (Fainstein, 2001; Jackson and Watkins, 2011). These individuals were selected based on them either being a design team member or client in one or more of the case studies. Four further respondents were then selected using a snowball method (Edwards et al., 1999; Schoenberger, 1991) where interviewees were asked to supply the names of others who could provide useful insight on the case studies.

As a result interviews were carried out with eight key international actors in urban biomimicry - one academic theorist, three specialist urban biomimicry consultants, three built environment designers using biomimicry in their work, and one client in a major new mixed-use development employing biomimicry. Interviewees commented directly on the projects they were involved in, which included all Type 1 case studies and 1 Type 2 case study, allowing the gathering of multiple perspectives. The remaining Type 2 case studies are intended to demonstrate the breadth of biomimicry's potential contribution to various city infrastructure systems, and are either product-based or theoretical. As such it was deemed that interviews with their manufacturers / designers would not provide any further insight into the actual practice of incorporating biomimicry into the urban infrastructure design process.

It is recognised that eight is a small number of individuals, though it should be noted that several interviewees had been involved in multiple case study projects. The consistency in responses also suggested that the saturation point (Levy, 2006) had been reached, and further interviews were deemed unecessary.

The semi-structured interviews were conducted over the telephone or using video-conferencing software, using a pre-determined topic guide. Questions covered topics such as definitions and understandings of key terms, limitations of biomimicry, and experience of the design process. The interview quotes used have been anonymised by giving each interviewee a number due to the commercial sensitivity of some of the comments made during the interviews.

Type 1 Ecosystem-Based Biomimicry Case Studies

1. Lavasa, India, is one of the few current urban-scale examples of biomimicry. This 12,500 acre mixed-use development (HOK, 2013b) illustrates the importance of strong leadership regarding innovation. An interview with one of the project team highlighted that biomimicry was adopted due to the long-standing relationship between the client and the principle in charge of design, who was promoting biomimicry. A biomimicry approach helped the business case by reducing the likelihood of pollution-related fines, and resulted in highly integrated conversations between the clients and different members of the design team.

The design process, heavily influenced by biomimicry, involved a 2-3 day ‘eco-charrette’ that involved everyone from the client-group chairman down to every designer and consultant on the project. The team identified six ‘ecosystem services’ provided by the local moist deciduous forest: water collection, solar gain, carbon sequestration, water filtration, evapotranspiration, and the nitrogen and phosphorus cycle. Emulating these ‘services’ drove the urban design.

One aim was to eradicate the soil erosion caused by 9 metres of annual monsoon rainfall. The intention was to break the rains with a ‘structural canopy’, slowing drainage off buildings and allowing it to be collected; the city-wide water storage is inspired by the ‘Hydraulic Redistribution’ local trees display, whereby the roots draw rainwater into the soil to ‘bank’ it for the dry season - ‘rainwater harvesting at the city level’.

This strategy had significant implications for the success and operational costs of the scheme’s non-architectural elements, and while the green infrastructure component of the development has increased by 20-25% , the associated maintenance costs have decreased by more than 90% (interviews).

However, even with such a forward thinking team, the economic case for the biomimetic architecture is problematic, and the prohibitive cost of prototyping has prevented implementation, despite the ongoing commitment to biomimicry (interviews).

2. The Mobius Project

Exploration Architecture's proposed Mobius Project in London is an urban farm, closed-loop ecosystem. It comprises: greenhouse; community allotments; restaurant serving seasonal food, grown in and around the greenhouse; fish farm; food market; wormery composting system; mushroom farm, utilising waste coffee grounds; anaerobic digester and biomass CHP; accelerated carbonation technology (ACT); and a 'Living Machine' water treatment system. 'Living Machines' or 'Eco-Machines' use a complex ecosystem of specific bacteria, plants, zooplankton, and fish to mimic wetlands, efficiently treating and reusing wastewater with low or no odour (Todd and Josephson, 1996). These systems have been successfully employed at large scales, including the Urban Municipal Canal Restorer in Fuzhou, China (Todd, 2002), and the USA's Omega Center for Sustainable Living (Todd, 2003). This approach avoids transporting waste water to remote energy-intensive processing plants, before releasing it into watercourses. The increasing threat of extreme weather events and ageing water infrastructure makes intra-city water recycling of this kind crucial to reduce reliance on such centralised infrastructure. For example, treating wastewater for irrigating greenhouses, aquaponic systems and vegetable gardens maximises food security. There are three main cycles at the Mobius project: food production, energy generation and water treatment. The building is designed to process local biodegradable waste via composting and anaerobic digestion (AD). AD provides electricity and heats the greenhouse; flue gases are transformed into building materials via ACT. Restaurant scraps are fed to fish or composted, black water solids are processed via AD, and the remaining water treated for potabilty or toilet flushing. Crucially, the project has an explicit community role of education around nutrition, food production and closed loop systems. The interaction with nature is seen as a good way to break down cultural and social barriers and integrate people around a positive message.

3. 4000 years ago, the original pre-development local ecosystem of Langfang, China, was a mixed deciduous forest (Lazarus and Crawford, 2011). Deforestation means the city no longer effectively captures rainwater, and has depleted the local aquifer. Consequently, land subsidence occurred, and citizens meet UN water scarcity measures, despite the city's three channeled rivers. Supplementary water is pumped from the Yangtze River, which is costly and reduces city resilience. In response, the HOK design team used Biomimicry 3.8's 'Genius of Place' analysis of the site's unique natural systems attributes, alongside the Fully Integrated Thinking (FIT) living systems design tool to comprehensively change the city's architectural plan to emulate natural water cycles. The concrete storm channels were redesigned, referencing the paleo-channels that illustrate how water once moved across the landscape. The city now has a comprehensive plan to direct water into the aquifer through strategic planting, providing attractive, green, city-corridors (Interviews; Lazarus and Crawford, 2011; Peters, 2011).

4. Urban Greenprint Seattle

The Urban Greenprint project uses predevelopment ecosystems as inspiration for solving urban challenges. In Seattle, Phase 1 identified metrics for carbon flows, biodiversity, and water flows. Evapotranspiration in Seattle region forests is 50%, and at the heart of the region, Puget Sound wetlands is highly polluted. At the core of the project is the intention to mimic natural evapotranspiration cycles at the building level to reduce polluted runoff into Puget Sound. The process of reconciling the current and predevelopment metrics involved several public brainstorming events involving diverse attendees.

Table 2: Biomimicry Design Approach for Type 1 Ecosystem-Based Urban Scale Biomimicry Case Studies

City System	Step 1: Problem Definition	Example of typical mainstream approach	Step 2: Reframe Problem	Step 3: Biological Solution Search Result	Step 4: Define Biological Solution	Step 5: Principle Extraction	Step 6: Principle Application	Case Study Ref.
Energy & Carbon	Overuse of energy in urban areas	Increase efficiency of appliances, processes and buildings	What properties allow natural systems to operate within local resource limits?	Ecosystem recycling of resources	Using the waste products of one part of the ecosystem to feed a different part of the ecosystem	Employ closed loop approach	Use the various waste streams of the city as energy sources	2

Food	Overuse of remote, mono-cultured agri-cultural land	Increase land productivity via intensive farming technology	What properties allow natural systems to operate within local resource limits?	Ecosystem recycling of resources	Using the waste products of one part of the ecosystem to feed a different part of the ecosystem	Employ closed loop approach	Use bio-degradable waste steams to provide food	**2**
Waste	Overuse of physical resources in urban areas	Increase efficiency of recycling plants	What properties allow natural systems operate within local resource limits?	Ecosystem recycling of resources	Using the waste products of one part of the ecosystem to feed a different part of the ecosystem	Employ closed loop approach	Use the various waste streams of the city to feed other processes	**2**
Water	Providing water - depleted aquifers	Pump water from remote rivers	What features of natural systems circulate and conserve water?	Tree roots and wetlands	Natural water cycle	Emulate natural water cycle	Pervious green corridors	**3**
	Providing a consistent supply of water in monsoon areas	Wash monsoon water away quickly; pump water from remote rivers during dry season	What features of natural systems circulate and conserve water?	Tree roots and wetlands	Natural water cycle	Emulate natural water cycle	Inter-seasonal water storage; Pervious green corridors	**1**
	Water treatment	Remote treatment plants	What properties allow natural systems to remove toxins from water?	Wetlands	Ecosystem of specific bacteria, plants, zooplankton, and fish purify water	Use ecosystem processes	Create artificial ecosystem of specific bacteria, plants, zooplankton, and fish to mimic wetlands	**2, 3**
	Polluted Run-off	Interceptors, Remediation	What properties allow natural systems to reduce run-off?	Forest Water Cycle	Evapo-transpiration of up to 50% of rainfall	Recreate evapo-trans-piration in the built environ-ment	Adapt rainscreens on buildings to enhance evapotranspiration and reduce runoff	**4**

Type 2 Single-Organism Based Biomimicry Case Studies

5. Dye-sensitive solar cells are cheaper and more flexible than PV panels; they mimic photosynthesis found within plants and algae (Dyesol Ltd, 2014; Tulloch, 2011) and can be incorporated into a variety of architectural and infrastructural elements like window panes, paints, textiles or cladding. Though in their infancy, they can potentially reach grid parity due to low-cost operability under a wider range of light and temperature conditions (Dyesol Ltd, 2014). They were successfully demonstrated in the House of the Future at Sydney Olympic Park (Tulloch, 2011).

6. Carbon Capture and Storage (CCS) is a commonly cited technical solution for reducing atmospheric carbon. This involves capturing waste CO_2 at source (such as fossil fuel plants), transporting it to a storage site, and depositing it where it cannot reach the atmosphere, typically an underground geological formation. CCS is unproven and is likely to be expensive (Boot-Handford et al., 2014). Salps, seashells, the Saguaro cactus and coral all sequester environmental carbon, fixing it in solid media where it is atmospherically inactive (Barnes and Ramsden, 2013). This process was mimicked by Calera, producing a Portland cement replacement that locks away atmospheric carbon (Calera, 2014). This is significant, as current global cement production is around 2.8 billion tonnes annually and could increase to 4 billion tonnes per year by 2050 (Schneider et al., 2011). Similarly, buildings and infrastructure could be 'grown' using light sensitive bionanorobots that formulate atmospheric carbon into Carbon Nano Tubes, which are then 3D printed into a structure (Rebolj et al., 2011).

7. Urban surfaces are typically impermeable; and rainwater is carried away from them via high capacity drainage systems. However, serious flooding results once the drainage infrastructure is inundated. Indian harvester ants protect nests by building a series of spiraling channels, slowing the monsoon rainfall to reduce erosion (Ritter, 2012). This approach has been mimicked in Lavasa, where multipath, low-grade channel designs of underground storm-water infrastructures and street layouts take a similar form (interviews).

8. Analogies are often drawn between natural vascular structures and planned transport networks. Vascular structures are core elements for most biological systems, facilitating transport of fluids and nutrients throughout the organism (Wang et al., 2005). Studies of *Physarum polycephalum*, a slime mould, revealed that when the location of food piles mirrored the layout of Tokyo and the surrounding cities, the mould created a network of vascular tubes connecting each pile, in a layout remarkably similar to the carefully designed Tokyo rail system (Tero et al., 2010). Without any central organisation system, the mould self-organised, spread out, and formed a network of comparable efficiency, resilience and cost to the real-world infrastructure. A mathematical model mimicking *Physarum*'s behaviour was created to inform the design of real-world, cost-efficient, robust transport networks (ibid).

9. Contemporary designs for bridges use computer models to predict forces from intended use and environmental impacts. 'Head-room' is designed-in above the expected maximum loads, but recent extreme weather events demonstrate that when the head-room is breached, infrastructure fails. Designs for new 'Tensegrity' bridges sense structural compromise and alter their structure to compensate (Korkmaz, 2011). This is achieved via sensors and actuators, allowing them to morph, much like an animal adjusting its stance, accommodating the stresses of changing environments, including wind, heat and heavy loads (Korkmaz et al., 2011).

Table 3: Biomimicry Design Approach for Type 2 Single-Organism Based Urban Scale Biomimicry Case Studies

City System	Step 1: Problem Definition	Example of typical mainstream approach	Step 2: Reframe Problem	Step 3: Biological Solution Search Result	Step 4: Define Biological Solution	Step 5: Principle Extraction	Step 6: Principle Application	Case Study Ref.
Energy & Carbon	Capturing Solar Energy	Photo Voltaic panels	What strategies allow organisms to capture solar energy?	Photo-synthesis	Chemical process stimulated by photons	Use chemical process stimulated by photons	Dye-sensitive solar cells	**5**
	Sequestering Carbon	Carbon Capture & Storage	How do organisms lock away carbon?	Salp, seashells, and the Saguaro cactus	All sequester carbon from their environment before fixing it in solid media	Sequester atmospheric carbon into building materials	Calera process produces a concrete that locks carbon away	**6**
Water	Preventing Flooding	High capacity drainage	What features allow natural systems to reduce the impact of flash floods?	Indian Harvester Ants	Nest entrance on slope with surrounding spiral channels to slow and redirect water	Redirect and slow water	Landscape features increase flow path and direct water toward pervious surfaces	**7**
Transport	Transporting People	Grid based system	How do organisms transport things efficiently?	Slime Mould	Network that maximises efficiency and tolerance to interruption or failure at	Continuous Integrated transport network	Design infrastructure to mimic capacity hierarchies, bifurcation	**8**

					reasonable cost		angles and minimal disruption of flow	
Buildings & Infrastructure	Adapting to Extreme Weather	Fixed bridges	How do organisms cope with damage?	Human body adapts to damage	Active compensation, e.g. limping to reduce weight on damaged leg	Infrastructure senses structural compromises and alters structure to compensate	'Tensegrity' bridges	**9**

Analysis of Case Study Literature and Interviews - Key Factors in the Adoption of Urban Biomimicry

The literature pertaining to the specific case studies and the interviews reflecting on these case studies were analysed using thematic analysis. Three main themes were identified: 1) Advantages of Urban Biomimicry, 2) The Design Process, and 3) Barriers to Adoption. These will each be discussed in detail below, along with evidence from the wider literature.

Theme 1: Advantages of Urban Biomimicry

Transdisciplinarity

There was agreement amongst all interviewees on the value of biomimicry in helping to align design teams around a common goal, whilst eroding traditional disciplinary siloes:

> We had launched a whole planning firm … in 17 [global] locations [with] about 200 people. I was trying to find something that could tie [them] together from a philosophical point of view. I flew everyone … to a

> conference [about] bio-inspired [design]. We just aligned as if it was meant to be…we were all really focused on…coming up with the holy grail of performance criteria that we could judge our projects by [Interview #6]

> We've learned … that when you start … listening to people from outside our discipline…we actually enrich our own discipline [Interview #7]

This ability to unify efforts by allowing participants to discard all preconceptions spreads beyond the design team to also include wider stakeholder groups, including businesses, non-profit organisations, scientists, environmentalists and municipal authorities:

> They loved it - they wouldn't leave; it was amazing. People were coming up with ideas that wouldn't have otherwise happened. People are really eager; they are hungry. [Interview #2]

Business Case

The interviewees stressed a growing business case for the adoption of a biomimicry approach. For example, some developers realise biomimicry is a useful tool in community engagement and helps to secure planning permission by getting buy-in from the local community and planners.

There is also growing awareness of urban biomimicry's positive impact on property value. The biomimicry consultants interviewed stated that most of their clients are profit driven, and see biomimicry as one route to creating a unique product that results in market differentiation and higher rental income.

As highlighted in the Lavasa case study, Biomimicry can help to reduce infrastructure maintenance costs, and can be beneficial in reducing liability to environmental fines, taxes and levies. Evidence from outside the case studies highlights that occasionally biomimicry can also result in radical technological breakthroughs that have significant cost implications, as in the UK's Eden Project. Using a bamboo inspired hex-tri-hex structure for the 'biome' domes (Pawlyn, 2011: 11), allowed glass to be replaced with ETFE cushions, resulting in factor 100 material savings (Interviews).

Scale

Currently, the best-known applications of urban-scale biomimicry are Type 1 Ecosystem 'closed loop' examples because urban areas mirror ecosystems, with interconnected components such as buildings, streets and infrastructure, each of which is intrinsically complex. Many believe that conceptualising cities as such complex, integrated 'systems of systems' is vital to the success of future cities, and biomimicry fits well with this approach. The business case for biomimicry in urban infrastructure, particularly closed-loop or circular-economy models, grows in tandem with shifts in project boundaries towards cities or a regional scale.

Behaviour Change

There is a fundamental need for positive behaviour change to realign our relationship with the natural and built environments, which is something biomimicry appears to be good at fostering. The Mobius project has an explicit community education role to align people around a positive message, to foster greater awareness and behaviour change. It is apparent that exposure to nature both physically and as an inspiration can have a profound effect on people:

> The thing that I think has had the greatest impacts are actually … the transitions I've seen in people [Interview #4]

This notion is supported by the experience of The Biospheric Foundation urban farming project in Salford, UK. A derelict mill was converted to combine food production and waste systems, using nutrient cycling to support production of fish, chickens, mushrooms, fruit, vegetables and honey. The premise was that to create behavioural change, 'infrastructure right in the heart of the communities' is needed (Perry, 2013). Local tenants began volunteering at the site and learning about the nutritional content and source of their food. The project includes providing fresh fruit and vegetables for residents, resulting in high levels of community vigilance and engagement. Anecdotally, local crime rates and antisocial behaviour dropped by over 70% and local drug abuse dropped by 90% (Vincent Walsh pers.comm).

Biomimicry could also help to crystallise efforts around a shared vision of future cities for 25, 30 or even 50 years from now:

…that's where everybody agrees - there's not one person that's not going to say they want clean water, clean air, access to nature, a place where they're going to want to hold their grandkids' hand and listen to the birds … we have to say what are the steps … to get there? That galvanizes people, maybe people on opposite sides of the argument… [Interview #2]

Theme 2: The Design Process

Comparison of Different Design Approaches

The interviews highlighted that the urban biomimicry design process varies amongst consultants and designers. Biomimicry 3.8's 'Design Lens' methodology is flexible enough to overlay onto existing design processes, 'delivering solutions and providing goals at any phase' (interviews). The Design Lens methodology is a collection of diagrams that visually represent the key parameters to be iteratively referred to throughout the design process. These are: 1. Essential Elements (Ethos, Emulate, (Re)Connect); 2. Life's Principles (Be locally attuned and responsive, Use life friendly chemistry, Be resource efficient (material & energy), Integrate development with growth, Evolve to survive, Adapt to changing conditions (Baumeister, 2013)); and 3. Biomimicry Thinking (Define, Identify, Integrate, Discover, Abstract, Brainstorm, Emulate, Measure) (Biomimicry 3.8, 2015). These diagrams were used as visual references to guide thinking and ideas during the Puget Sound workshops. Exploration Architecture uses research-based design methods developed in tandem with the project brief (interviews). The project begins with divergent research looking at any number of organisms or ecosystems that face similar challenges to the project being designed. The analogy search converges towards the end of each design phase, when inappropriate organisms or ecosystem models are eliminated. At the start of the subsequent design phase, design criteria are refined and the analogy search is initially widened slightly to accommodate the refined criteria before further convergence. In this way, each design phase narrows the range of solution models being considered until a preferred option is arrived at. HOK and Biomimicry 3.8 attempted to integrate natural system thinking and Life's Principles into design processes by developing the Fully Integrated Thinking (FIT) tool. Used on the Lavasa and Langfang projects, FIT encourages cities to be regenerative, resilient and accountable. The tool incorporates multiple triple bottom line lenses, including ecostructure, water, atmosphere, materials, energy, food, community, culture, health, education, governance, transport, shelter, commerce and value. It also goes beyond traditional site analysis by incorporating a 'deep understanding of the local ecologies' (HOK, 2013a), known as the 'Genius of Place' approach. Genius of Place can address a range of scales and challenges, including infrastructural ones (Biomimicry Oregon, 2013). The process mirrors that described by Helms et al., (2009) above, and involves studying local organisms to provide models for establishing locally attuned and sustainable design strategies (Biomimicry Oregon, 2013):

- Identify local design challenge(s)
- Conduct biological research to ascertain how local organisms and ecosystems address the challenge
- Translate the biological research into design principles that architects, engineers, planners, and policymakers can use

- Generate locally attuned design strategies based on the design principles

This understanding is then used to mimic appropriate place-based design principles, and produce a design framework for setting goals, benchmarks and performance indicators. One example cited in the interviews is the Durban Umbilo River Catchment Project, in South Africa, where a Genius of Place design methodology has provided a design framework with the following Ecological Performance Standards metrics based on local reference habitats:

- Runoff (Gallons / minute)
- Albedo (%)
- Carbon sequestration (Tonnes / acre)
- Pollutants captured from water (%)
- Evapotranspiration (%)
- Nitrogen and phosphorous cycling (Tonnes / acre)
- Diversity of native species
- Soil created (mm)
- Cooling (°C)

At Lavasa an 'eco-charrette' format was also employed to collectively brainstorm and populate infrastructure design solutions within a matrix with required infrastructure functions on one axis, and 'Life's Principles' on the other axis. The team identified multiple local organism and ecosystem strategies, and selected the most appropriate for further in-depth research in order to fully understand the mechanisms involved.

In summary it seems that there are many variations on the urban biomimicry design process. The key point, however, is that sufficient tools, guidance and exemplars exist to elevate urban biomimicry from a metaphor to a technical infrastructure design exercise.

Pitfalls of the Biomimicry Design Process

It is important to note that there are some significant potential pitfalls to the biomimicry design approach. A summary of those described by Helms et al. (2009) is presented here. First, poorly defined problems are too vague to yield functional descriptions, making solutions difficult. Poor problem-solution pairing is another pitfall, when problems are matched to biological solutions based on vague or superficial similarity. Designers may oversimplify complex biological functions, missing the significance of an underlying principle. Designers may also fixate on a single biological function, failing to understand complex, competing functions. Another possibility is designers focusing strictly on the initial source of inspiration, rather than searching for better models:

> People get lost in the 'biomimetic promise' and don't do any greater analysis of outcomes…and the dialogue just stops right there [Interview #4]

Analogies can be misapplied to problems, leading to sub-optimal or flawed solutions, and only the applicable elements of the biological inspiration should be transferred to the problem, as not every solution will be biomimetic (interviews).

Theme 3: Barriers to Adoption

Despite the benefits outlined in Theme 1 above, there are a number of important barriers to innovation.

As with any innovation, early adopters are subject to higher costs until methods and supply chains mature, but these costs tend to be technology based rather than resulting from extra design time:

> … I would probably guess the projects we've worked on have been …more expensive than traditional projects…a tiny... fraction of that [cost] is design time… [Interview #5]

The role of organizational cultures is critical to any innovation process. The interviews indicate that urban biomimicry helps tackle the siloes that blight city planning and management. However, true integration cannot yet be claimed. In some instances, biomimicry has been reduced to little more than a marketing gimmick to win work or create positive publicity before reverting to business-as-usual:

> …we sold it to the client, and then we were…pushed out of the process…the lead architect wasn't very bought-into including us in the process [Interview #4]

> Sometimes the client wants us there to validate what they're doing, but not to push them too hard [Interview #7]

This problem partly stems from the fact that biomimicry consultants are often employed as sub-consultants to the designers; they do not report directly to clients and have limited influence on design team members. Construction and design are very different cultures, and only having a direct line of communication to designers will limit the ability to apply biomimicry principles.

Buy-in to innovative processes like biomimicry is also not necessarily homogenous within an organisation, and while upper management may be enthusiastic, this doesn't always pervade the rest of the company:

> the manager was like, 'biomimicry's great, we should use this…' and then when they won the project, they gave it to a more junior architect who [said] 'this is my building, and now you landscape architects put a skirt around it' [Interview #4]

Sub-consultants to design firms encounter particular challenges around timescales and ingrained practices. Time pressures often lead to innovative ideas being 'value- engineered' out, and there can be a cultural reluctance to take external advice:

> …we're sort of trained to be the creator, and the idea of quieting your cleverness and listening to nature, or anyone else, telling you what to do is not embedded in our normal DNA [Interview #6]

There is an apparent disconnect between decision makers, who are chiefly concerned with getting a job completed efficiently and profitably, and innovators in the built environment. This is exacerbated by the trend for increasing levels of specialisation within the construction industry, which runs counter to the need for a holistic appreciation of city-system interconnectivity. In contrast it has been claimed that biomimicry practitioners tend to be polymaths, with knowledge outside of their own field (interviews).

Unreceptive designers and managers form another potential barrier to adoption. However, although there are usually conservative members of any design team, the interviews reveal a positive reception from designers and clients:

> we show … new approaches to traditional problems, and people get very excited [Interview #5]

In many cases, however, inertia makes converting this enthusiasm to actual projects difficult. Indeed, some mainstream clients can find the idea of biomimicry-based innovation a concern:

> …you can really turn people off because it's not normal… [Interview #7]

All interviewees concurred that improving urban biomimicry's adoption requires more completed explicit biomimicry projects that act as case studies and lower the perception of risk associated with innovation:

> …seeing is believing…then there is conviction [Interview #8]

The current short-to-medium-term investment horizons prevalent in the built environment are also significant obstacles. Industry Return On Investment (ROI) calculations focus on short term build costs, whereas a lifecycle perspective considers operational, maintenance and legislative costs, along with the positive impact of climate change mitigation strategies on, for example, insurance premiums. The business case for biomimicry in urban infrastructure is much stronger with a lifecycle approach to ROI, but an organisation utilising an established profit-driven methodology may be unwilling to change unless forced by regulation (interviews).

This longer-term thinking is slowly manifesting within the investment sphere; the World Bank now uses resilience measures as part of its due diligence (World Bank, 2013). However, the inclusion of such language within business plans is still a novelty, and not at the forefront of the minds of most developers (interviews).

For any effective change in regulation, regulators must also become better trained in actual risk versus perceived risk to address their perceptions and biases.

One of the greatest challenges for urban biomimicry is the cost associated with the research and development (R&D) time required to translate the metaphor into the science:

> … not many people have the money to invest in that kind of research [Interview #6]

Exploration Architecture demonstrates one model for overcoming this constraint by absorbing some of the R&D costs themselves. For each paying project they have, they have another non-paying side project that allows them to develop ideas:

> so we are ploughing…our…profits into ourselves…staying as much as possible on the cutting edge... It means that we can then use our research in a project when we are required to come up with ideas [Interview #5]

Many interviewees agreed that another potential barrier to the adoption of urban biomimicry is the biomimicry label itself. Concerns were expressed that it may suffer from over or inappropriate use (such as ‘greenwashing’), and that it might degrade over time in the same way that the term ‘sustainability’ fell prey to politicians. Interviewees also stressed that the term needs careful management to promote clarity by ensuring tangible connections between design function and biological models.

The issue of the different language and approaches used by designers, engineers and biologists was also raised as an important barrier to adoption. For biomimicry to reach its full potential as a city infrastructure tool it will be critical to reconcile these different fields through improved training and understanding of the benefits of urban biomimicry within each field. It appears there may also be a role for independent third parties who can act as 'translators' between the fields in the short to medium term, until the biomimicry approach is better understood and cultural norms have shifted towards transdisciplinarity within the construction industry.

However, this process will not be quick, as the construction industry is conservative in terms of risk (Batty, 2013; Bueren and Priemus, 2002) due to the volatility of material costs and market values. This means that in contrast to the automotive and aeronautics industries, which spend billions on research and development in the certainty that they will gain appropriate returns on that investment, the construction industry is much more reluctant to innovate, and the pace of change can be glacial unless mandated through regulation.

Conclusions and Research Agenda

The aim of this paper has been to examine the use of biomimicry to inspire innovation within urban infrastructure planning and design. It has demonstrated that biomimicry is potentially a critical perspective in informing future city infrastructure strategies from multiple perspectives: design; governance; and citizen.

A biomimicry ontology represents both metaphors and technical approaches for extracting design principles and inspiring novel urban space and infrastructure design – complex, messy problems that require reorienting our relationship with nature (Kenny et al., 2012; Mcgregor, 2013). The case studies have shown that high levels of abstraction are required when conceptualising problems and solutions, stimulating design team creativity and stakeholder engagement, and placing transdisciplinary work as the core design process component (Mcgregor, 2013). The systems-based teams needed to implement this process differ from current urban planning and design approaches by challenging disciplinary boundaries and the trend for splintered service provision (Graham and Marvin, 2001), shortening feedback loops and broadening the potential solution space (Baumeister, 2013). A growing business case also supports biomimicry's adoption. Despite some inherent pitfalls that require careful management, biomimicry could significantly improve the quality and resilience of urban infrastructure.

Through re-establishing our connection with nature urban biomimicry has the potential to stimulate positive individual behavioural change and help to develop a shared vision for the future of our city infrastructure (interviews, Graham Wiles, Pers.Comm.).

Realising this vision could involve Ecological Performance Standards, which several interviewees describe as powerful tools to guide the development of future cities, providing a solid design framework for how infrastructure should perform in a particular place.

There is also strong alignment between the dominant 'future city' paradigms such as the smart city and biomimicry. Biomimicry can help to inform analytical, communication and infrastructure design strategies. Many of the algorithms that are making cities smarter are already based upon biomimetic strategies and knowledge (e.g. Batty et al., 2012, interviews), and smart cities are often described as being capable of self-healing (Doherty, 2013). The smart city movement also stresses quality of life as a critical metric. The case studies demonstrate that given biomimicry's philosophy that people and nature inhabit the same socio-ecological system, urban biomimicry could realign economic, environmental and social factors for greater quality of life. Similarly, the multi-functional nature of many biomimetic solutions means that there is a natural fit for scholars and infrastructure designers who are examining the potential of 'Integrated Infrastructure' for transforming the form, function and resilience of our cities.

Biomimicry could be systematically incorporated into future city design and management, although there are significant barriers. The adoption of such transdisciplinary solutions requires significant changes to city powers and cooperation between city systems, utility providers and stakeholders. Additionally, designers, developers, local authorities and the public need to adapt their mindsets to fully exploit its potential. Providing successful case studies that demonstrate value for money is essential, as is developing mechanisms for offsetting R&D costs. It is important to incorporate biomimicry consultants at project inception, elevating their status to influence the client directly, or as seen in HOK, train designers in biological principles.

This paper provides an overview of the potential of urban scale biomimicry for practitioners, city decision makers and academics who are exploring ways to shift city infrastructure design paradigms. In doing so, it has also exposed the wider issues of organisational, cultural and investment barriers to innovation within the built environment.

Research is now required on the process of incorporating biomimicry into urban planning, design and decision making and how it compares with 'conventional' approaches, quantitatively and qualitatively assessing design coherence and wider societal benefits. Examining the success of large scale urban biomimicry in Langfang and similar projects will be revealing, as a gulf often exists between intention and application. Active research is also required on the application of community-scale biomimicry using a range of project types, and how infrastructure research and development, investment models and business cases can be adapted to exploit its benefits.

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