ISSN: 2717-5626 (Online)
Volume 5 · Issue 3
September 2023

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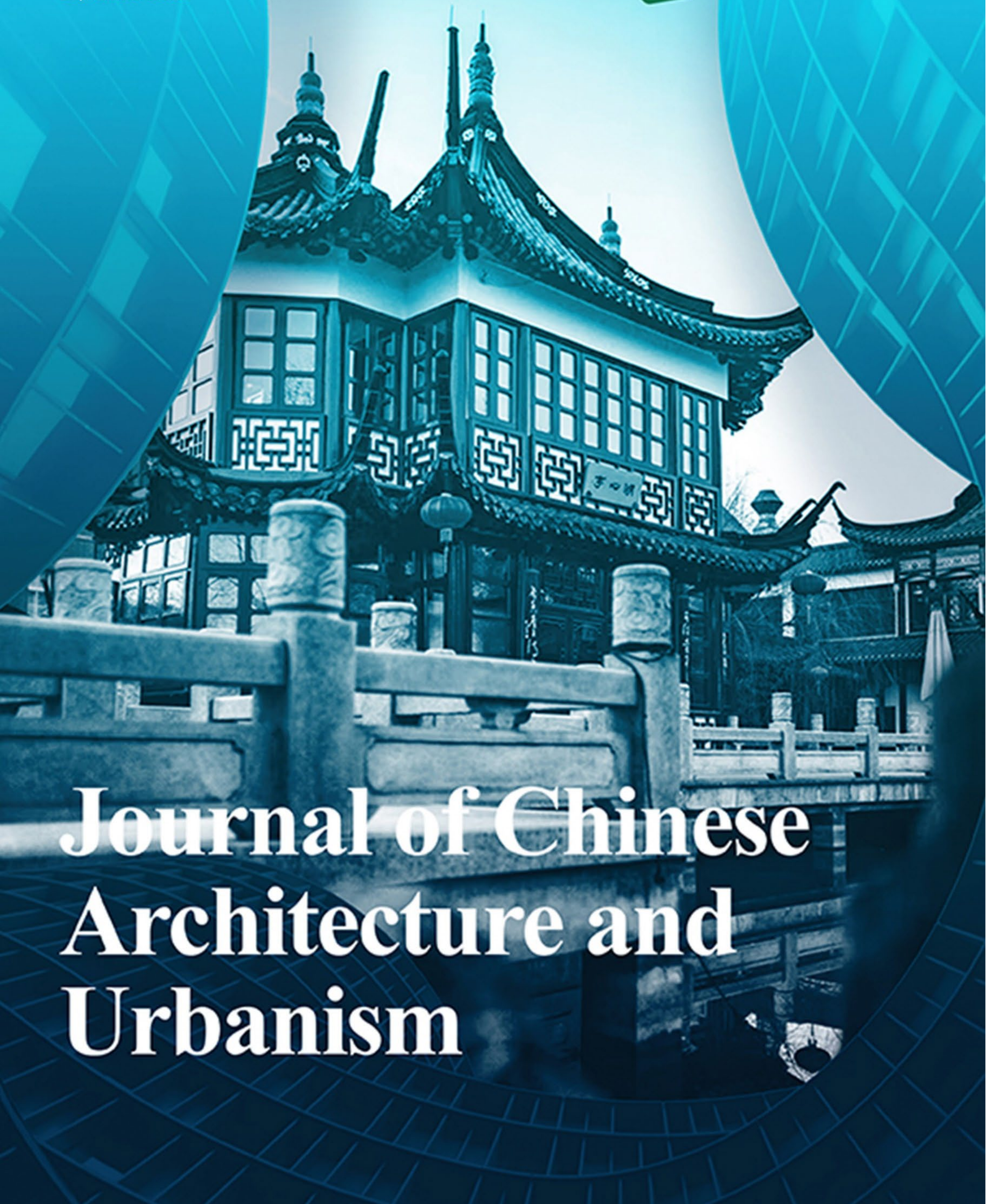

Journal of Chinese Architecture and Urbanism

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Volume 5 • Issue 3 • September 2023
ISSN 2717-5626 (online)

Journal of Chinese Architecture and Urbanism

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JOURNAL OF CHINESE ARCHITECTURE AND URBANISM

ISSN: 2717-5626 (online)

Editorial and Production Credits

Publisher: AccScience Publishing
Production Editors: Ian Wong, Chi Tat Poon
Special Issue Commissioning Editor: Felicia Wang
Article Layout and Typeset: Sinjore Technologies (India)
Cover Design: ProPub (China)

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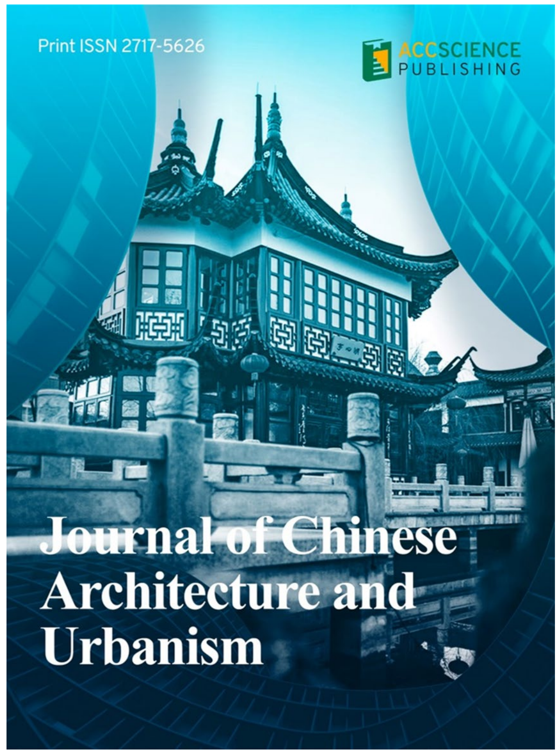

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A typical Chinese-styled building

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VIEWPOINT

Synthetic biology enabling a shift from domination to partnership with natural space

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(This article belongs to the *Special Issue: Regenerative Architecture*)

Abstract

Synthetic biology is a field of science that examines biological systems through the lens of engineering with the explicit objective of rationally designing live objects for either fundamental or biotechnological purposes. Yet, the same conceptual frame also embodies its exact counterpart: the biologization of engineering, i.e., looking at rationally designed systems through the lens – and with the tools – of biology and evolution. Such a creative tension between technology-driven design and biological processes has one of the most conspicuous battlegrounds in modern architecture. Such an edge occurs in a time dominated by the evidence of climate change, ramping environmental deterioration, and the ensuing instability and mass migrations. The most recent influences of biology in architecture have moved from the adoption of biologically inspired shapes and forms in many types of buildings to the incorporation of new biomaterials (often functionalized with qualities of interest) as assembly blocks, to the amalgamation of live materials with other construction items. Yet, the possibility opened by synthetic biology to redesign biological properties *à la carte*, including large-scale developmental programs, also unlocks the opportunity to rethink our interplay with space, not as one more step in the way of domination, but as a win-win conversation with the natural environment. While various contemporary architectural tendencies clearly move in that direction, we propose a radical approach–exemplified in the so-called *Biosynthetic Towers Project*–in which complex buildings are designed and erected entirely through biological programming rather than assembled through standard construction technology. To make this scenario a reality, we need not only tackle a dedicated research agenda in the synthetic biology side, but also develop a new attentive mindset toward the environment, not as a space to be conquered for our exclusive own sake, but as one scenario of sustainable co-existence with the rest of the natural world.

Keywords: Synthetic biology; Bionic architecture; Evolution; Adaptability; Sustainability; Partnership

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Citation: de Lorenzo, V. & de la Ossa, M. (2023). Synthetic biology enabling a shift from domination to partnership with natural space. *Journal of Chinese Architecture and Urbanism*, 5(3):0619.
https://doi.org/10.36922/jcau.0619

Received: April 19, 2023

Accepted: July 14, 2023

Published Online: August 4, 2023

1. Introduction

The history of architecture is one of human attempts to dominate tridimensional (3D) space for the sake of habitability (March & Stiny, 1985). Successive technological innovations have often contributed to this end. New materials and new mathematical tools have driven the progress of the field from the trial-and-error approaches of the pre-scientific times to the contemporary power of modern building materials and impressive computer-assisted design (CAD; Szalapaj, 2013), building information modeling (BIM; Abdelhameed, 2018) and artificial intelligence (AI; Debauche *et al.*, 2020) platforms. These tools enable robust prediction of basically any feature of a building much before it is materialized. But what we could call the purposely conquest of the 3D space is not exclusive to human-made architecture. The same process is reminiscent of another course ultimately driven by the same logic: the necessity of biological systems to arise and develop in a physical scenario with clear in or out boundaries, specialized functional assignments, and a coherent geometry for optimizing performance and durability (Lewis, 2008). Note that—unlike human-made buildings—such biological principles apply through different scales, from subcellular organization to very large structures (trees, termite nests, and beehives). Yet, while human-made architecture is most often the result of a rational planning, what we may call *biological architectures* are the outcome of billions of years of evolution. But can each other learn from their respective solutions to not altogether unrelated challenges? Given similar trials, it cannot come as a surprise that outcomes converge whether they are rationally planned or evolutionarily selected as the result of the random exploration of a solution space—as characteristically done by biological systems (de Lorenzo, 2018).

The interplay between technological design and live systems is the subject of what is now called *synthetic biology*, an interpretive frame of biological objects from an engineering perspective (Andrianantoandro *et al.*, 2006; de Lorenzo & Danchin, 2008). The key angle of synthetic biology is the assumption that the mechanical, physical, and chemical rationales that make live systems work as they do follow the same relational logic that engineers (electric, mechanical, computational) adopt for building complex objects (de Lorenzo, 2018). The advantage being that every biological property, including the development of physical structures in a 3D space, is ultimately determined by DNA. The main consequence of this state of affairs is that extant biological objects are already programmed through the sequences encoded in such DNA, which acts as the software of any live system (Danchin, 2008). The corollary of this narrative is that the growing affordability of DNA synthesis enables us to program live entities at our will (Gilbert & Ellis, 2018). We would need to qualify each of these assertions, but in general, the idea that one can program multi-scale biological systems with an engineering logic opens amazing opportunities to develop new products, assets, and–at long last–concepts with a potential to move architecture toward a different paradigm (Dade-Robertson, 2016).

2. Biology challenging the straight line

For many centuries, Western culture viewed humans as fundamentally distinct from and superior to the rest of the natural world. Given this belief, it was natural for the primary motivation behind architectural pursuits to be the desire to control and exploit any available resources for our own benefit. Biological items, especially trees and other plant products were just seen as mere construction materials, whether by themselves or in combination with stones and other building assets. Their merge with the scientific, mathematical geometry started by Euclid (Sbacchi, 2001) originated some of the most representative examples of classical Western architecture (e.g., the Parthenon; Figure 1). It is remarkable that such architectural icons are altogether governed by pure straight lines and flat surfaces, which allow for designing a precise, predictable connectivity between the parts, definition of the boundaries, and an accurate description of the final construct. Moreover, building materials were based on *hard* construction components and intended to be durable for a long time in the same shape they were first put together. All these features are in sharp contrast with the biological occupation of the environmental space. Straight lines and purely geometrical shapes are very unusual in live systems at the macroscopic level (Figure 1). With some exceptions, biological objects are generally made of soft, flexible, and even plastic matter. Furthermore, they tend

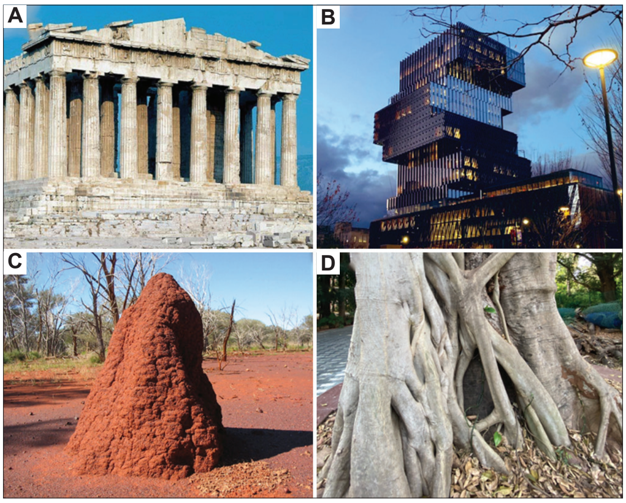

Figure 1. Geometry-driven architecture versus biological occupation of the 3D space. (A) The Parthenon is the most iconic example of historical buildings dominated by straight lines. (B) Center of Computer and data Science, Boston University, designed by KPMB Architects, an apotheosis of rectangular forms (credit: Ahmed Khalil). (C) A termite nest (credit: Australian Museum). (D) The roots of a banyan tree (Chennai, India)

to develop unexpected interactions with others and can age and evolve with time. It would therefore look as if the rational adoption of straight lines and compatible building materials were one of the most conspicuous manifestations of the human fondness to dominate nature, as they allow to suppress uncertainties associated with live counterparts. Other non-straight elements, which were later adopted (round and gothic arches, and domes), did not change the emphasis on Euclidean geometry (Sbacchi, 2001) as the core basis of any architectural project. Most often, non-linear forms were used almost exclusively for decoration.

Yet, one of the take-home lessons of contemporary systems and synthetic biology is the ability of evolutionary mechanisms (Morange, 2013) to solve complex optimization problems, which are not amenable to calculation from first principles (Krohs & Bedau, 2013). For example, assembling a new metabolic pathway for the synthesis or degradation of a target chemical compound typically starts with arranging a DNA sequence that encodes all the necessary enzymes, predicted either manually or with CAD resources (Hafner *et al.*, 2020). But this is just the beginning: the components of the route must be expressed in a specific stoichiometry through additional regulatory assets (*e.g.*, promoter sequences and ribosomal binding sites) to secure effective nesting of the construct in the pre-existing genetic and physiological network of the host, avoid toxic intermediates, and foster long-term performance (Stephanopoulos, 2012). Alas, such catalytic phenotypes are challenging to design, as the parameters involved in their optimization are either too high a number or they are simply unknown. One way is the application of what has been called *Gaudí's principle* (Porcar *et al.*, 2015) based on his hanging chain models (Figure 2). Under this frame, the starting point is a system which contains all necessary components to deliver a given function but lacks the proper connectivity and/or is endowed with unsuitable parameters and transfer functions. By letting the system fluctuate under an overarching selection criteria (for instance faster/better growth), the same biological object is made to evolve for finding solutions (Naseri & Koffas, 2020). Such an evolutionary and/or combinatorial approach typifies prime outputs to the initial challenge, regardless of the number of objectives that need to be simultaneously met. The process can in fact be entertained as a sort of physical computation, in which a complex metabolic problem is embodied in a material object, and the result is delivered as another physical entity endowed with the solution. If we were to do this rigorously, the large number of fine adjustments of the starting metabolic and regulatory devices could not be addressed through rational calculations. The best growers thus represent discrete attractors in a solution space which embody

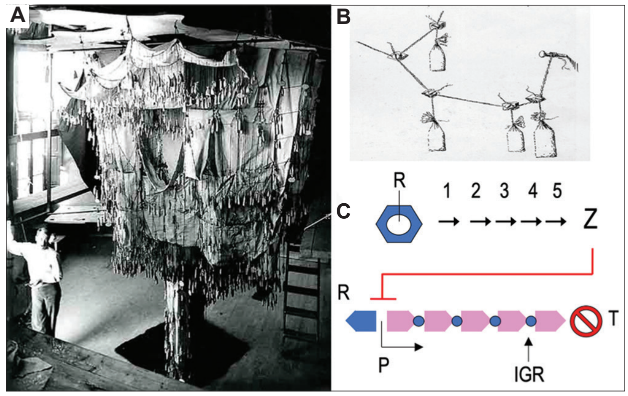

Figure 2. Gaudí's method for optimizing complex structures and its applicability to the genetic design of synthetic metabolic pathways. (A) String-weight engineering involves determining parameters for constructing a complex object where the interactions between nearby elements affect the entire system, and *vice versa*. Photo credit: Gaudí Museum, Barcelona. (B) Initially, a collection of components is physically connected to form an object. Weights are then attached to specific locations that will later become the peaks of the architectural piece. Through the force of gravity, the object undergoes deformation, resulting in an optimal distribution of angles and masses. Flipping the model upside down provides the stability parameters for the structure. (C) To achieve the best combination of enzymatic steps (1–5) for converting a substrate into a product (Z), various factors must be considered, such as appropriate gene expression levels controlled by the promoter P, the regulator, and the intergenic regions (IGR), as well as mRNA stability and termination (T). Introducing sequence diversification at these regulatory points and applying selective pressure to enhance Z production allows for exploration of the solution space until an optimum is attained (Adapted from de Lorenzo, 2018)

optimal genetic and physiological arrangements under given conditions. Therefore, in reality, biological systems can evolve and adapt to the environment capable of solving problems that are not yet amenable to straight engineering. As long as biological evolution cracks challenges that cannot be tackled otherwise, can we entertain also that biology empowers us to push architecture beyond the self-imposed limitations of what we could call *straight-line philosophy*?

3. Technification of biology *vs* biologization of technology

One common and implicitly accepted tenet of contemporary technology is that by applying mathematical methods, advanced physics/chemistry, and more recently computational approaches, humans can prevail over the uncertainties and threats of the natural world. In other words, for too long a time, the environment has been perceived as an adversary to submit to and a source of resources to exploit. Attempts of technological domination of the natural realm (and their associated narratives) are reminiscent of recurrent historical events when a self-perceived strong country or society conquers a militarily weaker but culturally more influential civilization or society. The typical outcome over time is that despite early successes of the invaders, the more elaborated culture of those invaded takes over and eventually prevails. Along the line, we entertain that technological attempts to subdue nature to our own benefit will eventually change to incorporate many of the strategies and solutions that biological evolution has already provided or can provide to complex problems that are beyond our current capabilities (de Lorenzo, 2018).

One archetypal example of technical leveraging of biological phenomena is the adoption of evolutionary algorithms for the optimization of antennas for NASA's spacecraft (Lohn *et al.*, 2005). The rational design of such antennas is challenging as so many parameters are at stake. However, evolutionary design techniques can provide workable solutions by exploring the design space and delivering automatically applicable results. Note that in these cases, the design principles are not rational but rely on massive diversification-selection cycles that recreate Darwinian evolution. In a different but related frame, the first synthetic biology wave ambitioned to dominate extant biological systems by adopting engineering concepts and methodologies. Yet, 20 years later it seems clear that such a straight projection of one thing on the other has not delivered as expected (Meng & Ellis, 2020).

Biological systems inherently mutate and evolve (Cardinale & Arkin, 2012), not only when submitted to changing environmental conditions, but also often through mere genetic drift. Moreover, the performance of biological devices is characteristically context-dependent, which leads to the emergence of new interactions and properties. Finally, living systems grow and reproduce. These qualities dramatically depart from those of human-engineered objects (Hanson & Lorenzo, 2023). One way to move ahead is trying to suppress such undesirable features for making biology easier to engineer (Calvert, 2010). This involves, for example, orthogonalization of genetic devices, mitigation of evolutionary potential, digitalization of regulatory components and others. However, we speculate that efforts to defeat such inherent characteristics of living systems will not ultimately solve the problem. What to do then? In this case, the advice attributed to Saint Lupe of Troyes (383–479 AD) when facing Attila the Hun on his way to the conquest of Rome could be applied here: "… *if you cannot defeat your enemy, join him…*". Instead of treating to suppress upfront undesirable qualities that are inherent to living systems, the way to go might be to make an alliance of what the other side has to offer and learning how such side has developed solutions by other means (Porcar *et al.*, 2015) and even tackled problems that were not anticipated before.

The time is ripe to move from *technification of biology* (as ambitioned by synthetic biology) towards *biologization of technology* (as we advocate will eventually happen). This trend is growingly making it in the synthetic biology literature (Castle *et al.*, 2021) and prospects of merging top-down genetic engineering with evolutionary tinkering are getting at hand. But how do all these affect modern architecture?

4. Biology conquering architecture

As mentioned above, after millennia of improvised utilization of naturally occurring construction materials for building short-lived human habitats on the mere basis of trial-and-error, the birth of Western architecture can be traced to the time when Euclidean geometry was incorporated to edifice design (Di Cristina, 2002). An additional and characteristically human attribute was also the integration of aesthetic features, so that (according to Vitruvius 80–15 BC), the functionality should be combined with durability and beauty (Kruft, 1994). Vitruvius also argued that architectural perfection is reached when buildings embody the laws and shapes of the natural cosmic order, as exposed by mathematics, physics, and geometry. No wonder that for much of history, buildings have been based on such principles. Native forms of natural materials are eligible as resources for construction, for example, stones, tree trunks, and so on, were reshaped to follow geometrical and physical standards necessary for fitting a preset assembly plan. Virtually nearly every building erected in the past 20 centuries has followed such norms, all submitted to straight lines and other purely geometrical shapes. Even the plastic exuberance of the baroque period limited utilization of non-linear forms to adornment of otherwise purely geometrical structures–to be soon replaced by an ensuing bare neoclassical style. At the core of the breach between such types of architecture and the occupation of the 3D space by biological structures lies the connectivity among the components. Purely geometrical forms entered in *hard* materials enable the capture and design of habitable space with a minimal number of elements and the least total of connections amid them. The downside of the same is frailty to environmental changes–as clearly shown by the sensitivity (and frequent collapse) of many classical buildings when facing natural calamities (Al-Momani & Harrald, 2003). In contrast, biological 3D structures are shaped by malleable and highly connected parts, which certainly complicate their rational design but often endow extraordinary robustness to the final object. Things started to change, however, by the late 19th century, the time of major scientific discoveries on the nature of matter and the onset of evolutionary theory. Both mitigated the gap between the human realm and the rest of the natural world if they revealed that we are made of the same stuff of the surrounding world and intimately akin to plants and animals. Impressionist painting is one of the artistic expressions of such a change if it attempted to capture and represent the energy embodied in the material world by means of effects of light and rough brushstrokes of paint reflecting the inner dynamism of objects and living things (Metcalf, 2004).

Frontline architecture of the time was not alien to these developments, as epitomized by the above-mentioned Antonio Gaudí (1852–1926). He went beyond the prevailing modernist tendencies of his generation to create a distinct style in which shapes of naturally-occurring living forms were incorporated into his buildings, not just as decorations, but as core architectural elements (Huerta, 2006). His approach resulted in a type of designs dominated not by straight lines and circles but by hyperbolic paraboloids, hyperboloids, helicoids, and conoids (Figure 3). Such type of nature-inspired organic architecture was largely based on the adoption of string-and-weight models (Figure 2) which enabled an easy solution to complex multi-objective optimization challenges (Makert & Alves, 2016) through an approach reminiscent of adaptive biological evolution (Porcar *et al.*, 2015). Such tendency–which tries to leave behind the conventional straight line-based architecture has a more recent example in the work of Friedensreich Hundertwasser (1928–2000) and his utilization of non-regulated irregularities in his curvy buildings to deliver structural diversity that is reminiscent of the natural, living world (Hundertwasser, 1997). Gaudí and Hundertwasser can be regarded as pioneers of diverse architectural concepts that draw inspiration from structures found in living organisms. They even go so far as to emulate some of the mechanisms that biological systems employ in response to environmental changes (see Figure 3). These styles have adopted various denominations such as *bionic* (Yuan *et al.*, 2017), *biomimetic* (Aldersey-Williams, 2004; Chayaamor-Heil, 2023), *bioinspired* (Ripley & Bhushan, 2016), *biophilic* (Soderlund & Newman, 2015) and others. Yet, note that the interplay of architecture-biology at this point is that of echoing living structures in buildings which are made in any case of standard, hard construction materials. But is such structural inspiration enough?

Figure 3. Non-geometrical architecture. Many of the works of Antonio Gaudí (A and B) and Friedensreich Hundertwasser (C and D) avoid straight lines and perfect geometrical forms as much as possible for the sake of bridging the technical and conceptual gaps between naturally occurring shapes and human-made buildings. Note in (c) even adoption of wavy floors for making inhabitants aware that they are stepping on Earth. Photo credits: Casa Pedrera (Barcelona) and Kunsthaus (Vienna)

5. Biologicals as active building components

The next step in the way to biologization of architecture involves the progressive incorporation of materials coming from the living world to building design. The traditional use of wood as the key component of many structures is now complemented by utilization of other biological goods endowed with useful properties. One low-hanging fruit in this respect is the use of fungal mycelia as insulation material (Attias *et al.*, 2020). These microorganisms incorporate vegetal particles into their hyphal network, producing composite materials useful to this end. The biomass of filamentous fungi often acts as nucleation sites for biomineralization of calcium carbonate, further expanding the usability of mycelium composites as structural materials. Furthermore, mushroom-forming fungi generate hyphae rich in cellulose and lignin together, conferring high rigidity to the overall interconnected structure and mechanically strong enough as structural components at the architectural scale. Mycelium-based blocks are already available as an alternative to plastic-based insulation materials and building assets, for instance, bricks. Note however that such items of fungal origin are typically inactivated with heat or other methods before use and, therefore, the qualities of interest are limited to their physical properties. Given that such properties are ultimately determined by DNA, perspectives are that fungi can be improved and leveraged beyond their material qualities for endowing biological functionalities to the architectural designs they join–alone or in combination with other microorganisms (Jo *et al.*, 2023). In particular, for generation of, for example, living architectural skins (National Academies of Sciences, Engineering, and Medicine, 2017; Armstrong, 2023; Persiani & Battisti, 2019) for bioremediation (Shavandi & Jalalvandi, 2019) of polluted urban sites (soil, air) and carbon capture (Singh *et al.*, 2022).

The notion of buildings with functionalized living skins is, in fact, one of the frontline research topics at the interface between architecture and synthetic biology (Armstrong & Spiller, 2010; Armstrong, 2015). Both outer and inner walls have been customarily used only for the separation of spaces in buildings, but their surfaces are basically limited to support, in case of decorative and/or low functional elements, such as paintings, portraits, mirrors, and so on. But, as proposed by the LIAR Project (https://livingarchitecture-h2020.eu/), such surfaces can, in fact, be converted into flat bioreactors to produce valuable substances *in situ* (in a sort of micro-agriculture) and remediate environmental toxicants. Early examples of this possibility include incorporation into buildings of exterior vertical gardens (https://newatlas.com/architecture/8-shenton-way-som/) and/or surfaces covered with moss for interior air purification (https://greencitysolutions.de).

A separate but related development is that of self-healing concrete (Vijay *et al.*, 2017). Despite its advantages, concrete tends to form cracks at various stages of its life cycle. Fortunately, some bacteria produce a range of minerals (in particular, carbonates) which can act as concrete fillers. This has originated formulations of bio-cements bearing specific microorganisms that once in place, can deposit solid minerals that plug potential micro-fissures in construction concrete. Again, given the ultimate dependence on DNA of these properties, such naturally occurring activities–whether fungal/bacterial remediation or functionalization of concrete—can be enhanced and adapted to specific needs through synthetic biology methods (https://neoplants.com/).

While the incorporation of living components into buildings is one significant stage in the interplay of architectural practice with biology, the underlying technological paradigm is still one in which the living world becomes submitted to human needs, and it just fills the gaps that are not yet amenable to sound engineering. But can we turn things around and develop a kind of architecture in which biology is not just an inspiration or one more asset along with others, but the principal driver of the building endeavor? This approach requires an attentive and caretaking attitude towards the natural world open to learning from it rather than sticking to our habitual, optimist belief that human technology can solve any problem, including conspicuous messes like climate change (Huesemann & Huesemann, 2011). How does this translate into the architectural realm? As Wil V. Srubar[1] put it "*… Nature has figured out how to do a lot of things in a clever and efficient way: we just need* to *pay more attention …*".

[1] https://sawdust.online/news/bacteria-in-this-building-material-keeps-it-alive/

6. A radical proposal: The Biosynthetic Towers Project and beyond

By looking at the way biological systems (in particular, woody plants) occupy the 3D space (Figure 1) and the possibilities of rewriting developmental programs opened by synthetic biology (Baltes & Voytas, 2015), we can entertain a future urban scenario where technology and nature team up for conforming an ecosystem able to provide an adequate habitat while being able to regenerate and evolve in a balanced and smart way. As an example of such picture, the *Biosynthetic Towers* (BTs) *Project* envisions a new system based on that conception as an alternative way of understanding urban planning, architecture, and construction, in which the biological component prevails over the earlier physical constraints and building technologies.

So far, there have been important contributions of synthetic biology in agriculture, energy, engineering, construction materials (de Lorenzo *et al.*, 2018), and even art (Ginsberg *et al.*, 2017), but it still has not reached a larger scale that could be used for developing a smart city planning. The BT Project puts forward a vision of how the future of our cities could be like if synthetic biology is radically applied to architecture and urban planning. The core of the BT project is the bioengineering of programmable trees (or tree-like biological structures) to develop into a building or a series of buildings that are living organisms that grow, change, evolve, regenerate, update, and transform over time. What could this look like?

First, as shown in Figure 4, no excavation would be required to lay the foundations of the intended building. There are not even construction works necessary because the system grows and evolves by itself. The initial planning is just based on a grid, where programmed seeds containing basic construction information have been planted on. Gradually, the seeds will start to transform into small cabins that could be used by people as living spaces or could be set for commercial or recreational purposes. This new embryonic organism contains additional growing information for the next evolution step of the BT. This way, the system expands following a slow and iterative process until it gets bigger and smartly merges with what is around it, naturally flowing with its context (Figure 5). Second, the whole system works with natural mechanical actions typical of living organisms, such as suction, condensation, inertia, uptake, or absorption, with little or no need of

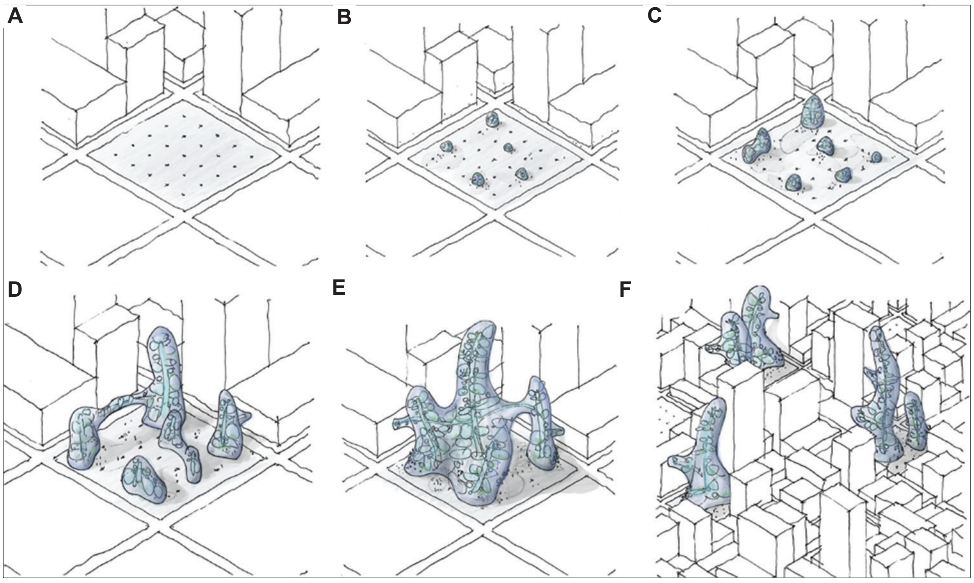

Figure 4. Stages in the development of a biosynthetic building. (A) The intelligent seed grid as the towers *foundations*. (B) Initial forms of small individual living spaces. (C) Formation of collective living spaces by adhesion. (D) The biosynthetic system develops as linked towers. (E) The Biosynthetic Tower matures. (F) The towers blend in with the existing town and promote urban transformation

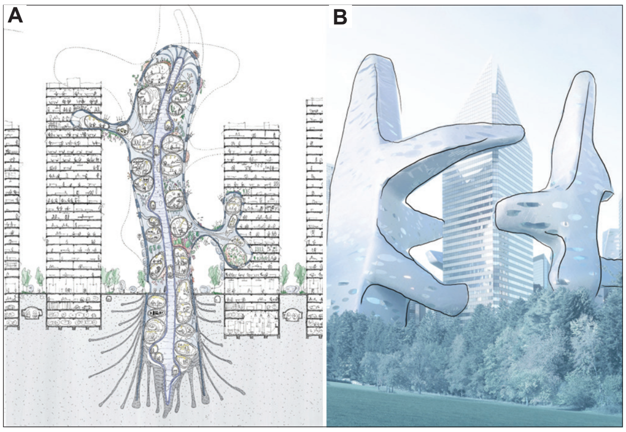

Figure 5. Inside and outside of the Biosynthetic Tower. (A) The overall structure of the building adopts the outline of a tree, where roots act as foundations and energy supply and where a central core branches out to support the different rooms and to serve as a guide in its extension and connection with other towers and buildings in its immediate surroundings. (B) Simulation of how the fully developed Biosynthetic Towers could become integrated in the pre-existing urban landscape

electricity input other than its inner natural power as a living organism. Energy supply is based on the chemical reactions of bacteria with natural agents (such as sunlight, water, air, and temperature) and the vegetal, animal, and human activity inside. The skin and stem of the tower configure one self-supporting structure. Besides, there are multiple elements such as flexible fabrics, microcavity membranes, filaments, fluids, and sticky matter that permit the BT to be sensitive towards exterior agents and to respond smartly to its user's requests. For example, if the inhabitant feels such as sitting or lying down, by just touching a pad on the wall, a chair or a bed can emerge from the inner skin of the living space. And third, the physical supports of the towers lack traditional systems of reinforced concrete or steel construction and rely altogether on woody materials. Some details of specific parts and functionalities of the building are outlined in Figure 6; note that all are based on known properties of the biological elements at stake.

For instance, the interior of the organism tries to ensure that all the spaces inside it receive an adequate amount of natural light (Figure 6A). In turn, the outer skin of the system is formed by light and solar energy collectors that can transport photons to illuminate, by means of ampoules as lamps, those deeper places where it is more difficult for direct sunlight to reach. The BTs are in continuous and slow growth and transformation (Figure 6B), so the circulation routes that run through its interior must absorb these movements. The inhabitants circulate by means of a mechanism consisting of capsules that advance by peristalsis (or progressive contractions) through tubular organs (Figure 6B), which run through the extensions of the organism connecting the different habitable spaces. As if they were parks or green areas of a city, certain sections of the skin of the BTs function as fertile surfaces where vegetation can grow. These spontaneous gardens (Figure 6C) not only serve as places for the enjoyment and relaxation of their inhabitants but also function as cultivation fields or greenhouses that complement the food supply of the towers' inhabitants. The part of the lowest façade of the BTs that is closest to the street functions as a storage and loading (Figure 6D) and unloading base for vehicles compatible with the system. A mucous membrane allows such vehicles to adhere to and slide over the skin of the towers. Now, the driver of these vehicles decides to access the tower, a hole is opened both in his vehicle and in the façade, allowing him to penetrate inside the tower. Inside the living cells, the floor, walls, and ceiling will form a single autonomous and intelligent unit (Figure 6E). From a tactile inner skin, privacy, and comfort parameters typical of a home can be controlled. There is no furniture since it emerges from the inner skin of the cell at the request of its inhabitants (Figure 7). The same happens with other domestic elements such as loudspeakers to listen to music or screens to watch a movie. The BT's system of installations is also integrated into the organism itself. Rainwater and solar energy are recycled and stored (Figure 6F), thus serving as sources of supply for the future. The management of organic waste, wastewater, and air extraction is carried out by means of a network of tubular vessels that run attached to the structure and membranes of the organism.

In sum, the BT Project is a futuristic anticipation of how the merging of architecture, urban planning, and advanced synthetic biology could converge for the sake of sustainable building-making in harmony with the rest of the living world. The project's ambition is to make humans think of an

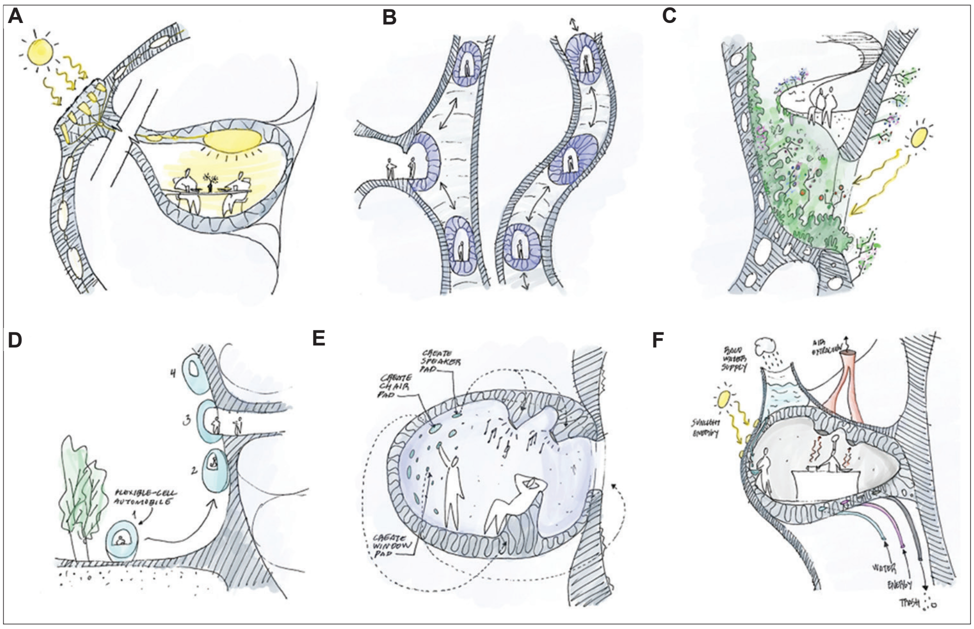

Figure 6. Key functionalities genetically programmed in the Biosynthetic Towers. (A) Sunlight capture and CO_2 fixation. (B) Transportation structure. (C) Spontaneous garden. (D) Storage membranes. (E) Smart skin. (F) Fluid and energy logistics (see text for explanation)

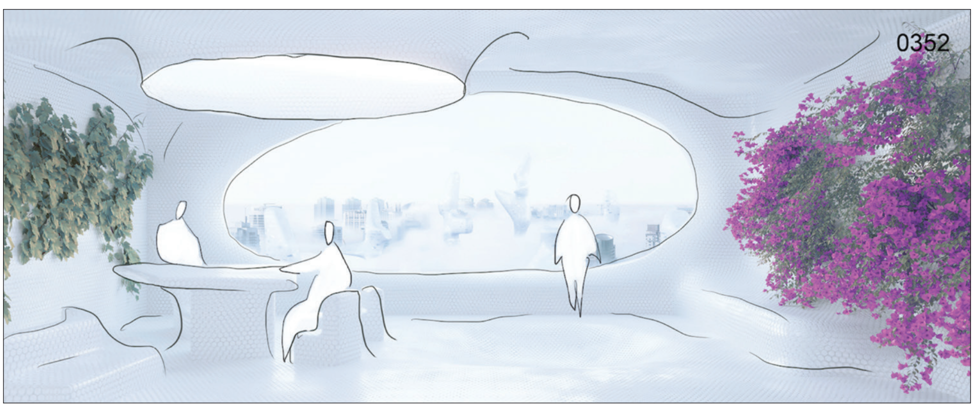

Figure 7. Towards all-organic human habitats. DNA-based programmability of multi-scale biological development empowers synthetic biology not only to engineer large living structures but also specific functionalities at the dimension optimized for human use. This involves, for example, emergence of shapes and objects usable as typical pieces of furniture

alternative way of understanding how we live in the cities, and how we move within them, especially during uncertain times like today. Obviously, the BT project is not the only one that has dealt with similar issues. The Supplementary File provides a list a non-exhaustive inventory of architectural initiatives and undertakings that align well with the philosophy of the BT project. They are about letting nature lead the solutions for healing the damage that unchecked technological development has inflicted on our common planetary habitat—and to which traditional construction methods have so significantly contributed (Habert *et al.*, 2020).

7. Conclusion

We live in a time characterized by what has been called a *polycrisis*[2] (environmental, societal, and migratory), along with unprecedented technical and scientific advances that enable us to revisit our interplay with the natural environment, both as an ethical mandate as well as a necessity for survival. The early 2000s witnessed the onset of synthetic biology, a veritable game changer in the way we leverage biological systems for human sake. In reality, synthetic biology opens an unprecedented two-way, win-win channel between engineering (which also encompasses technology-based architecture) and the living world. On the one hand, synthetic biology lays out a way to reprogram biology by accessing and rewriting DNA sequences following the logic of electric, mechanical, and computational engineering (Andrianantoandro *et al.*, 2006). On the other hand, the same channel makes available evolutionary mechanisms (a kind of *natural computation*) that living entities exploit for adapting and proliferating in a dynamic environment. By learning such a biological language, we can move from domination to partnership with the natural world for a sustainable, albeit quite different, future. Given that the construction sector has one of the major impacts on climate change and environmental deterioration, it is urgent to develop the conceptual and technical tools for making the above-discussed BTs projects (and others listed in Supplementary File) a reality.

While the proposal of all-organic, living buildings is indeed futuristic, the challenge is by no means fictional or a mere fantasy. One can make a list of gaps in our current knowledge of plant and animal developmental programs necessary to develop each of the biological components and focus on research efforts in filling them. While full morphologies of plants are still difficult to program, there has been considerable progress in recent years in reshaping root (Morris *et al.*, 2017) and branching (Nicolas *et al.*, 2022) architecture with rationally designed genetic circuits (Brophy *et al.*, 2022; Kocaoglan *et al.*, 2023). There is no reason why such studies cannot advance toward the determination of complex shapes in woody plants, including their aerial parts. The same applies to plant growth rates. As this quality is also genetically encoded, chances are that plants engineered with superior abilities of CO_2 fixation and biomass production (a super-active research field at this time; Tan *et al.*, 2022) can be also designed for the erection of organic buildings within a sensible period of time. The same for each of the functionalities are indicated in Figure 6. Obviously, we are not there yet in the scenario sketched in Figure 7. But the time is ripe for considering it seriously and giving it a chance, not just as a virtue but as a vital need.

[2] https://www.weforum.org/agenda/2023/03/polycrisis-adam-tooze-historian-explains/

Acknowledgments

The authors are indebted to architect Manuel Belso for his renders of Figures 5 and 7 and to Isabel Andrés for help with the English style.

Funding

Research in Víctor de Lorenzo's Laboratory is funded by SYNBIO4FLAV (H2020-NMBP-TR-IND/H2020-NMBP-BIO-2018-814650), the MIX-UP (MIX-UP H2020-BIO-CN-2019-870294), the NYMPHE (HORIZON-CL6-2021- UE 101060625), Contracts of the European Union, the BIOSINT-CM (Y2020/TCS- 6555), and the Project of the Comunidad de Madrid - European Structural and Investment Funds (FSE, FECER).

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Víctor de Lorenzo, Miguel de la Ossa
Writing - original draft: Víctor de Lorenzo, Miguel de la Ossa
Writing - review & editing: Víctor de Lorenzo, Miguel de la Ossa

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

Further disclosure

A preliminary version of the Biosynthetic Towers Project was submitted to the 2021 edition of the eVolo architectural contest (https://www.evolo.us/).

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ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Analysis of hot spots and paths of China's industrial heritage reuse mode based on CiteSpace

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Abstract

The development of industrial heritage reuse has followed a trajectory from disorder to order, displaying distinct characteristics across different periods. This study aims to examine the focal points and trajectory of industrial heritage recycling in China, with a focus on the Nizhny Tagil Charter as the starting point. Utilizing the China National Knowledge Infrastructure visualization tool and CiteSpace, this research analyzes the quantity of journal articles, authors, institutions, and the timeline of literature keywords. The analysis reveals four distinct periods: the initial period, the vigorous period, the mature period, and the innovative period. The findings indicate that topics related to industrial heritage reuse have expanded extensively and comprehensively over time, demonstrating interconnectedness and inseparability. Industrial heritage has evolved from a singular utilization mode to encompass multifaceted aspects, such as economy, society, ecology, environment, and other multidirectional considerations.

Keywords: Industrial heritage; Reuse; CiteSpace; Time evolution; Mode

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Citation: Zeng, Y., Jin, R., Tao, J., & Sun, L. (2023). Analysis of hot spots and paths of China's industrial heritage reuse mode based on CiteSpace. *Journal of Chinese Architecture and Urbanism*, 5(3):1034. https://doi.org/10.36922/jcau.1034

Received: June 1, 2023

Accepted: July 11, 2023

Published Online: August 2, 2023

1. Introduction

Industrial heritage serves as a testament to the development of industrial civilization, preserving the essence of industrial culture and contributing to the collective memory of urban history. In the context of urbanization and urban transformation, the conservation and utilization of industrial heritage hold significant importance in facilitating the diversified transformation of urban land. It is crucial to not only assess the intrinsic value of industrial heritage but also employ suitable activation approaches to ensure its effective preservation and utilization.

The conservation and utilization of industrial heritage originated in Britain, where the aftermath of the industrial revolution led to the abandonment of numerous industrial plants and equipment. Initially, these remnants faced the threat of being scrapped and destroyed. However, in 1955, scholars called for the preservation of machinery and monuments associated with the British Industrial Revolution. This event marked the beginning of public awareness regarding the significance of industrial heritage. Industrial heritage is not only valuable in terms of its scientific and technological contributions and social importance but also holds the potential for transformation and reuse as well-preserved industrial legacies (Shan, 2006).

Research on Chinese industrial heritage began in the 1990s, and since then, a substantial amount of knowledge and experience has been accumulated, ranging from theoretical studies to practical projects. Scholars have employed various scientific tools, such as knowledge graph analysis, to visualize and analyze tens of thousands of documents, summarizing the work of previous researchers and exploring the future development trends of industrial heritage. However, it is worth noting that few studies have specifically utilized the China National Knowledge Infrastructure (CNKI) as their literature database, with most scholars relying on the "Web of Science" platform (Huang & Liu, 2022). Furthermore, many researchers tend to categorize their studies under the broad umbrella of "industrial heritage," which results in a wide-ranging and less targeted scope of research. Consequently, a comprehensive research system for the "reuse model of industrial heritage" has yet to be fully developed (Su, 2020).

In this context, this paper aims to fill the gap by utilizing the literature database provided by the CNKI. Employing the scientific knowledge graph analysis tool, CiteSpace, we conducted a visual analysis of the literature on the reuse model of industrial heritage in China over the past 20 years. The 20-year duration was divided into four distinct periods, capturing the characteristics of each phase, and analyzing the emerging trends and patterns in recycling modes. The findings of this study aim to provide valuable experience and serve as a reference for future research on the reuse modes of Chinese industrial heritage.

2. Data and methods

The Nizhny Tagil Charter for the Industrial Heritage, issued in July 2003, is recognized as the first international consensus document on industrial heritage. This landmark charter provides a comprehensive framework for understanding industrial heritage, including its definition, value assessment, legal protection provisions, and other important aspects. It offers strong guiding principles for the field (Bai & Chen, 2022).

Based on the significance of this charter, we chose the year 2003 as the starting point for analyzing the evolution and trends of keywords related to the activated utilization patterns of industrial heritage. The literature selection criteria are as follows:

(i) Search topic: "industrial heritage * activation" OR "industrial heritage * reuse" (exact match)
(ii) Selection of Chinese literature database
(iii) Limiting the type of literature sources: Limited to "all journals," resulting in a total of 1488 retrieved journals. Journal catalogs, conference notices, solicitations, newsletters, and duplicate literature were excluded. To ensure the authority and reliability of the research, the database includes 369 papers from the Chinese Social Sciences Citation Index, Chinese Science Citation Database, and Peking University core journals, as well as 658 other research papers relevant to industrial heritage. In total, 1027 papers were included in the research sample to establish the literature database.

3. Analysis of literature statistical results

3.1. Number of publications analysis

Figure 1 illustrates the quantitative visualization analysis feature offered on the CNKI search page, which was employed to generate the annual trend analysis chart of literature publications. The analysis reveals that there was a scarcity of literature addressing the topic of activation and reuse of industrial heritage before 2005, with only one piece of literature published in 2003.

From 2005 to 2009, the State Administration of Cultural Heritage of China issued the "Wuxi Proposal - Pay Attention to the Protection of Industrial Heritage in the Period of Rapid Economic Development." This document emphasized the protection of valuable industrial heritage at different stages of development, including modern and contemporary industrialization (House, 2006). Consequently, the number of published papers and related research results gradually increased. After 2010, the international perspective on industrial heritage began to develop, with the adoption of the Dublin Principles in 2011, and the Taipei Declaration on Asian Industrial Heritage in 2012. These documents played a significant role in highlighting the importance of Asian industrial heritage (Ji, 2017). Subsequently, the number of relevant papers has consistently increased each year. In 2018 and 2021, the literature reached a 20-year peak, surpassing 90 publications. The research content expanded to include industrial transformation design in various domestic cities, such as Shanghai, Beijing, Yangzhou, Quanzhou, and Qingdao, among others (Ji, 2022).

3.2. The author and the institution

A total of 1,027 articles were included in the database, involving 486 authors. Figure 2A presents the number of articles published by the top 10 authors in the database. Notably, prolific authors such as Xu Subin (32 papers) from Tianjin University, Liu Boying (22 papers) from Tsinghua University, Shino Aoki (14 papers) from Tianjin University, Liu Fuying (13 papers) from Northeastern University, and

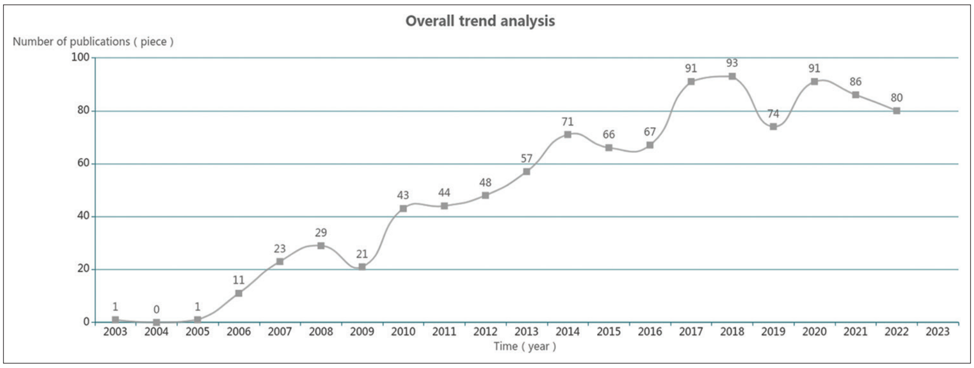

Figure 1. Annual trend analysis of publications on the activation and reuse of industrial heritage. Source: Literature visualization analysis of China National Knowledge Infrastructure

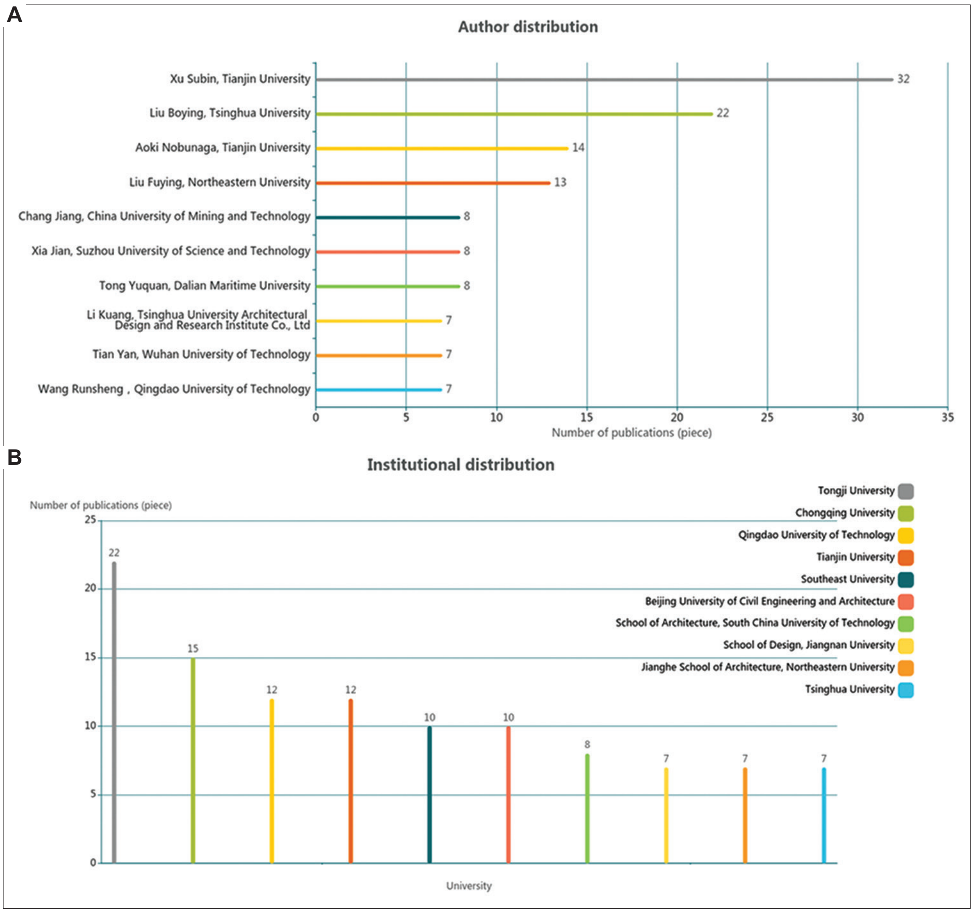

Figure 2. Distribution of data on the top 10 authors and affiliations. (A) The top 10 authors. (B) The top 10 institutions. Source: Literature visualization analysis of China National Knowledge Infrastructure

Chang Jiang (8 papers) from China University of Mining and Technology, have made significant contributions in the field of industrial heritage activation and reuse.

Furthermore, researchers such as Shan Jixiang from the Palace Museum, Wang Jianguo from Southeast University, Yu Kongjian from Peking University, and Zhang Yishan from Suzhou Landscape Design Institute Co. Ltd in Jiangsu Province, have received extensive attention from other scholars. Their work has played a pivotal role in promoting the activation and utilization of industrial heritage.

Figure 2B displays the research institutions involved in the study. Notably, Tongji University, Chongqing

University, Qingdao University of Technology, Tianjin University, Southeast University, Beijing University of Civil Engineering and Architecture, School of Architecture, South China University of Technology, School of Design, Jiangnan University, Jianghe School of Architecture, Northeastern University, and Tsinghua University, are among the prominent institutions. It is worth mentioning that Tianjin, Chongqing, Shanghai, and Qingdao have emerged as significant industrial development cities in modern times. These cities possess a rich foundation in terms of industrial development, making them important contributors to the field of industrial heritage research and reuse (Zhao, 2020).

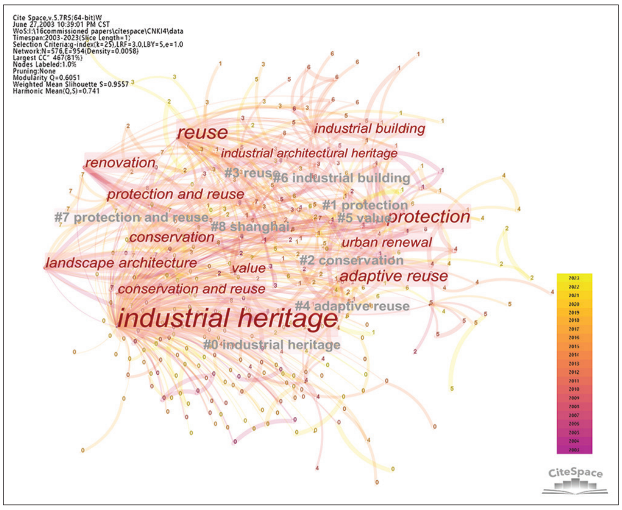

Figure 3. Industrial heritage activation utilization mode keyword co-occurrence map. Source: Drawing by the authors

It is evident that research scholars in the field of industrial heritage in China predominantly come from backgrounds in architecture and urban planning. In addition, scholars from fields such as human geography, art and design, and archaeology have also contributed to the research on the preservation and revitalization of industrial heritage.

4. Research hotspot and research path

4.1. Analysis of research hotspots

Keywords extracted from academic papers serve as an important tool for literature retrieval, as they reflect the core content and ideas of the articles (Su, 2020). By analyzing the co-occurrence frequency of keywords in the literature database, the relationship between different topics can be determined, and hot research topics can be identified through the analysis of keyword content and network density. In this study, CiteSpace was used to analyze the literature database, covering from 2003 to 2023 with a time slice of 1 year. The analysis focused on keywords, with the top 100 keywords in each time slice, using "Cosine" as the intensity of the connection. The "Find cluster" function was applied to cluster the keywords, with a maximum clustering value set to K = 9. The resulting keyword clustering graph is shown in Figure 3.

The keyword clustering view, represented by different clusters, provides insights into the structural features between clusters, highlighting key nodes and important connections (Chen *et al.*, 2015). In the graph, the size of the circles corresponds to the frequency of the keywords,

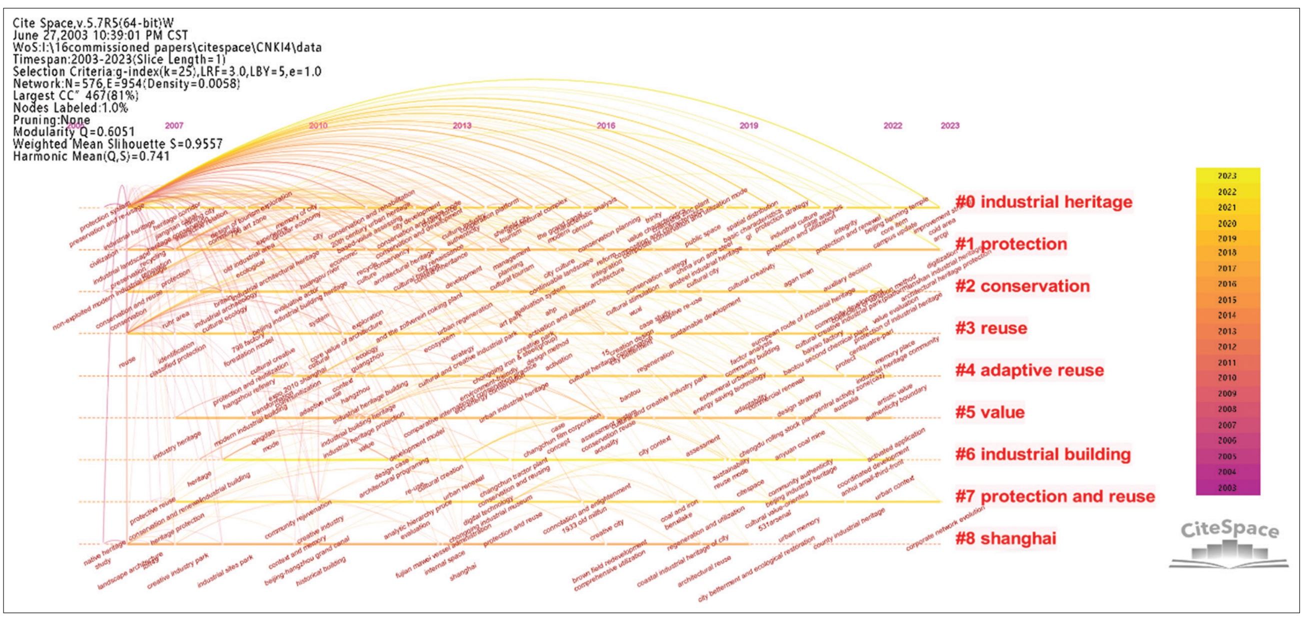

Figure 4. Keywords timeline graph depicting the industrial heritage activation utilization mode. Source: Drawing by the authors

Table 1. High-frequency keyword data statistics

No.	Keywords	Frequency	Year of the first appearance
1	Industrial heritage	446	2006
2	Reuse	68	2006
3	Protection	48	2007
4	Protection and reuse	24	2014
5	Adaptive reuse	21	2010
6	Urban renewal	20	2013
7	Conservation	19	2006
8	Conservation and reuse	18	2006
9	Industrial building	13	2008
10	Landscape architecture	13	2006
11	Transformation	12	2009
12	Value	11	2011
13	Industrial architectural heritage	9	2009
14	Renovation	9	2007
15	Cultural heritage	8	2012
16	Activation and utilization	8	2015
17	Reconstruction	8	2007
18	Heritage protection	8	2007
19	Industrial heritage protection	8	2011
20	Creative industry	8	2010

Note: This table only lists the top 20 most frequent keywords

while the color changes from dark to bright based on the historical year, with darker colors indicating earlier periods. The results indicate a significant community structure with Q (module value) = 0.6051 (Q > 0.3), and a convincing clustering efficiency with S (average contour value) = 0.9557 (S > 0.7) (Chen *et al.*, 2015).

To analyze the connections and changes in keyword topics more clearly and intuitively, a keyword timeline graph was utilized, resulting in the timeline view presented in Figure 4. The timeline graph focuses on illustrating the relationship between clusters and the historical span of literature within each cluster, allowing for a clear depiction of the chronological appearance of keywords (Chen *et al.*, 2015). In this analysis, the timeline graph was generated with a threshold set to 0, a font size of 8, and a node size of 2. The keyword "industrial heritage" was excluded from the analysis. The top 8 clustering tags of the keywords are as follows: "protection" (1#), "conservation" (2#), "reuse" (3#), "adaptive reuse" (4#), "value" (5#), "industrial building" (6#), "protection and reuse" (7#), and "Shanghai" (8#). As observed in Figure 4**,** research on the activation and reuse of industrial heritage encompasses a wide range of fields, with varying degrees of connection between cluster units.

According to the distribution of high-frequency keywords presented in Table 1, research on the activation and reuse of industrial heritage highlights several key areas. In terms of transformation methods, "adaptive reuse," "landscape architecture," "creative industry," and "reconstruction" have emerged as significant keywords. These keywords reflect the various approaches employed in the process of repurposing industrial heritage sites. When evaluating the value of industrial heritage, keywords such as "value" and "cultural heritage" have gained prominence. These keywords represent important evaluation methods used to assess the significance and worth of industrial heritage sites. Regarding the scale of heritage activation and reuse, multiple fields are involved, including "urban renewal," "industrial architecture," and "landscape architecture." These keywords indicate the broad scope of research and the interdisciplinary nature of endeavors related to the activation and reuse of industrial heritage.

The analysis of burstiness, which examines the emergence and prominence of keywords, provides insights into the evolution of the knowledge structure and research trends in the field of activation and reuse of industrial heritage (Chen *et al.*, 2015). Based on the analysis conducted using CiteSpace, Table 2 presents the keywords outburst map.

From the prominent keyword "Protection of industrial heritage," it is evident that since industrial heritage entered the research field, there has been a significant emphasis on recognizing the value of heritage and exploring ways to protect and utilize it. The research scope covers landscape sites, industrial parks, and buildings, highlighting the comprehensive preservation of various types of industrial heritage. "Industrial heritage tourism" has emerged as a prominent and enduring keyword during the period from 2010 to 2015, signifying its importance as a mode of transformation and utilization for industrial sites. The concept of industrial heritage tourism centers on repurposing and revitalizing former industrial factory zones into attractive destinations for tourists and businesses alike. This mode of transformation and utilization gained momentum due to its potential to drive economic growth in urban areas. Many practical design projects were undertaken, converting derelict industrial sites into vibrant business and tourism parks. "Adaptive reuse" and "visualization" are emerging keywords in industrial heritage reuse, reflecting the increasing influence of digital and intelligent approaches. In the information age, these keywords highlight the evolving patterns and trends in industrial heritage transformation. Digitalization, visualization, virtualization, and related technologies are becoming essential tools for studying and implementing adaptive strategies. They offer new

Table 2. Keywords outburst map of industrial heritage activation utilization mode.

Keywords	Strength	Begin	End	2003 – 2023
The Grand Canal	2.57	2006	2007	□□□■■□□□□□□□□□□□□□□□□
Old industrial buildings	2.46	2006	2007	□□□■■□□□□□□□□□□□□□□□□
Transform	4.27	2007	2010	□□□□■■■■□□□□□□□□□□□□□
Protective reuse	2.65	2007	2010	□□□□■■■■□□□□□□□□□□□□□
Shanghai World Expo	2.52	2007	2011	□□□□■■■■■□□□□□□□□□□□□
Protection of industrial heritage	6.37	2010	2011	□□□□□□□■■□□□□□□□□□□□□
Industrial heritage tourism	3.02	2010	2015	□□□□□□□■■■■■■□□□□□□□□
Cultural protection unit	2.6	2010	2010	□□□□□□□■□□□□□□□□□□□□□
City memory	2.46	2010	2010	□□□□□□□■□□□□□□□□□□□□□
Industrial architecture heritage	2.42	2011	2016	□□□□□□□□■■■■■■□□□□□□□
Urban renewal	2.98	2013	2013	□□□□□□□□□□■□□□□□□□□□□
Landscape architecture	2.74	2013	2013	□□□□□□□□□□■□□□□□□□□□□
Reuse	2.36	2013	2013	□□□□□□□□□□■□□□□□□□□□□
Evaluation system	2.74	2015	2016	□□□□□□□□□□□□■■□□□□□□□
Architectural heritage	2.29	2015	2016	□□□□□□□□□□□□■■□□□□□□□
Creative industries	3.74	2016	2018	□□□□□□□□□□□□□■■■□□□□□
Third-line construction	2.4	2017	2018	□□□□□□□□□□□□□□■■□□□□□
Sustainable development	1.93	2018	2021	□□□□□□□□□□□□□□□■■■■□□
Activation utilization	3.65	2018	2023	□□□□□□□□□□□□□□□■■■■■■
Renew	2.4	2018	2023	□□□□□□□□□□□□□□□■■■■■■
Industrial culture	2.97	2020	2023	□□□□□□□□□□□□□□□□□■■■■
Industrial relics	3.13	2020	2023	□□□□□□□□□□□□□□□□□■■■■
Heritage protection	2.75	2021	2023	□□□□□□□□□□□□□□□□□□■■■
Adaptive reuse	3.14	2021	2023	□□□□□□□□□□□□□□□□□□■■■
Visualization	2.07	2021	2023	□□□□□□□□□□□□□□□□□□■■■

Source: Drawing by the authors

possibilities for data analysis, immersive experiences, and public engagement, shaping the future of industrial heritage research and practice.

4.2. Research path analysis

Based on the keywords outburst map, this study examines the evolution of research hotspots in the activation and reuse of domestic industrial heritage. The period spanning from 2003 to 2023 is divided into four distinct phases, each characterized by shifts in development and significant time nodes marking keyword transformations. Table 3 presents an analysis of the distinct features, representative keywords, and emergent keywords for each period. Over time, scholars' investigations into the activation and reuse of industrial heritage will further advance, with research themes transitioning from the material space to the immaterial realm.

(i) The initial period: Protection comes first, exploring the mode (2003 – 2009)

This period marks a significant stage in urban planning and development in China, characterized by rapid urban expansion. Major industrial cities across the country faced challenges related to factory enterprise relocation and adjustment due to the "two in three" policy. As a result, "abandoned lands" emerged in cities as factories were relocated. Industrial heritage, recognized as a new form of cultural heritage, garnered widespread attention and was activated through pilot initiatives in various cities (Shan, 2006), including Beijing, Hangzhou, and Qingdao. Relevant keywords that reflect this stage include "unexploited modern industrial heritage," "old industrial areas," "mining cities," "Hangzhou Refinery," "Beijing's industrial building heritage," and "Qingdao."

During this period, research on the reuse models of industrial heritage primarily centered around theoretical investigations, with limited practical experience. Some researchers have proposed preservation and utilization strategies for industrial heritage based on its value.

Table 3. Statistics of attention to the research literature on "Activation and Reuse of Industrial Heritage"

The initial period	
Characteristics	Protection comes first, exploring the mode
Period	2003 – 2009
Representative keywords	preservation and reuse of protection systems; cultural civilization; industrial landscapes; unexploited modern industrial heritage; indigenous heritage research; conservation and reuse efforts; heritage corridors; Jiangnan Canal; mining cities; interactive relationships; identification; protective reuse strategies; conservation and revitalization; tourism exploration design; 798 Art Zone; old industrial areas; ecological approaches; British industrial archaeology; 798 Factory; afforestation models; protection and reutilization; Hangzhou Refinery; modern industrial buildings; Qingdao; urban memory; circular economy; evaluative actors; Beijing's industrial building heritage
Emergent keywords	The Grand Canal; Old industrial buildings; Transform; Protective reuse; Shanghai World Expo
The vigorous period	
Characteristics	Diversified transformation and all-round development
Period	2010 – 2015
Representative keywords	Expo 2010 Shanghai; community involvement; revitalization of communities; context and memory preservation; Beijing-Hangzhou Grand Canal; conservation and rehabilitation efforts; 20th-century urban heritage; economic considerations; core value of architecture; ecology; industrial building heritage; protection of industrial heritage; design case studies; architectural programming; city development; modes of conservation and reuse; recycling; preservation efforts; architectural heritage; urban renaissance; context preservation; ecosystem; strategic approaches; cultural creation; cultural industry; collaborative platform; architectural complex; management; planning; city culture; evaluation system; environmentally friendly; eco-energy conservation; Changchun Tractor Plant; digital technology; Chongqing Industrial Museum; the Grand Canal; characteristic analysis; census; AHP; creative park; design methodology; case study; Changchun Film Corporation
Emergent keywords	protection of industrial heritage; industrial heritage tourism; cultural protection unit; city memory; industrial architecture heritage; urban renewal; landscape architecture; reuse; evaluation system; architectural heritage
The mature period	
Characteristics	Overall planning and utility integration
Period	2016 – 2019
Representative keywords	information integration; cultural revitalization; Wuxi; creative design; urban improvement; evaluation system; conservation and reuse; redevelopment of brownfields; Trinity; value characteristics; integrated conservation and utilization model; China Iron and Steel Company; Ansteel industrial heritage; coastal industrial heritage of the city; spatial distribution; factor analysis; energy-saving technologies; sustainability; modes of reuse
Emergent keywords	creative industries; third-line construction; sustainable development; activation utilization; renew
The innovative period	
Characteristics	Innovation-driven development, sustainable development
Period	2020 – 2023
Representative keywords	fundamental characteristics; preservation strategies; industrial heritage; case studies; integrity; key element; enhancement strategies; digitization; Anshan industrial heritage; community development; coefficient of variation method; value assessment; memory place; central activity zone; artistic value; commercial revitalization; community authenticity; coordinated development; cultural value-oriented
Emergent keywords	industrial culture; industrial relics; heritage protection; adaptive reuse; visualization

Relevant keywords such as "preservation and reuse of protection systems," "protection and reutilization," and "evaluative factors" can provide valuable insights for reference. Shan (2006) acknowledged the historical, social, scientific, technological, economic, and esthetic values of industrial heritage and emphasized the need for industrial heritage to demonstrate its values through sustainable and adaptive rational utilization (Shan, 2006). Liu & Li (2006) developed an evaluation method for assessing the values of industrial heritage and put forward a protection system for industrial heritage in China (Liu & Li, 2006).

In addition, research scholars have provided summaries and analyses of protection and reuse methods for industrial heritage. Innovative approaches to the development of industrial heritage tourism have also been explored (Niu & Wu, 2007; Wang & Liu, 2009). Successful cases of industrial heritage reuse have been critically evaluated, and both "top-down" and "bottom-up" methods for the protection and reuse of urban industrial heritage have been proposed

(Zhang & Xia, 2008). Yu & Fang (2006) have identified four models for the protection and reuse of China's industrial heritage, including urban open spaces, tourist resorts, exhibition halls, convention centers, and creative industrial parks (Yu & Fang, 2006). Their research findings also indicate a limitation in the categorization of industrial heritage, as it lacks differentiation based on different scales and tends to be overly generalized. This means that the existing classification systems may not adequately capture the nuances and specific characteristics of industrial heritage at various scales, such as regional factories, factory areas, industrial factories, and single structures.

Due to the ambiguous definition of "industrial heritage," scholars have used terms like "abandoned land" and "brown land" to describe the vacant spaces left behind after industrial heritage relocation, which possess distinctive landscape characteristics (Xu, 2021). Consequently, some practical projects have explored the protection and reuse of post-industrial heritage through landscape transformation and design. The landscape design of industrial heritage during this period exhibits esthetic features, and there is a growing trend toward the "parkization" of industrial heritage sites.

Theoretical research during the initial stage laid the groundwork for exploring the value of industrial heritage reuse. However, the research content was scattered, and a comprehensive theoretical framework had not yet been established. The concept, meaning, classification, and scope of industrial heritage had not been clearly defined. Moreover, scholars analyzed practical projects aimed at revitalizing large-scale industrial heritage in cities to explore the fundamental direction of industrial heritage reuse. Nevertheless, there is a lack of research data specific to industrial heritage sites in China, leading to reliance on international perspectives, particularly from the UK, Germany, France, and other countries (Liu *et al.*, 2007; Shao *et al.*, 2008). In addition, scholars have primarily focused on three areas: industrial tourism, the renovation of industrial buildings, and the design of industrial heritage landscapes.

(ii) The vigorous period: Diversified transformation and all-round development (2010 – 2015)

In 2010, the Academic Committee on Industrial Architectural Heritage of the Architectural Society of China was established. It endorsed the policy document "Beijing Initiative" for the rescue of industrial heritage. In the same year, the Shanghai World Expo opened, the transformation of industrial buildings into the World Expo exhibition hall showcased innovative modes of industrial heritage utilization, characterized by diversity, fashion, and ecological consideration (Huang & Liu, 2022; Zuo, 2010). This development led to a shift in national research on industrial heritage reuse toward a more comprehensive perspective. Notable engineering practices emerged during this period (Huang & Liu, 2022), including the transformation of Xinyi Guild Hall led by developers, the conversion of Xi'an Dahua Yarn Factory into an industrial museum, the redevelopment of Fujian Mawei Shipyard under active preservation measures, the repurposing of Guangzhou Red Brick Factory for creative industries, and the transformation of Tianjin Glass Factory into modern residential quarters.

Industrial tourism gradually gained attention as a prominent aspect of activation and utilization. The keyword "industrial heritage tourism" highlights the focus in this regard. Industrial heritage also began to embrace a more public and citizen-oriented approach, as indicated by the keywords "community involvement" and "rehabilitation of community." Researchers recognized the adverse impact of old industrial production on the urban environment. While emphasizing economic growth, they proposed various concepts emphasizing ecological restoration and conservation. The keywords "ecology," "environmentally friendly," and "eco-energy conservation" reflect these concerns.

The model of activating and reusing industrial heritage is proposed based on an analysis of different resource endowments and values in cities, along with the identification of suitable renewal methods within each site. Researchers have moved beyond a single transformation approach and explored multiple ways, leading to a proliferation of related research papers during this period. For instance, Bao & Xu (2012) proposed a comprehensive activation model for large-scale industrial heritage sites, considering the reuse of site corridors, site parks, and site museums. Chen & Hu (2013) analyzed the evolution of Shanghai's industrial heritage, observing a progression from the frozen protection in museums to artist-led preservation of individual industrial buildings, the establishment of creative industrial parks, and the emergence of more diverse forms of industrial heritage protection and utilization with commercial or cultural functions, and argued that industrial heritage protection and utilization are characterized by a diversified pattern. Specific measures for the reuse of docks in urban riverside industrial relics have been explored (Tian & Li, 2013). Regarding the ecotype transformation of industrial heritage, Tian & Dong (2013) discussed methods and approaches for the sustainable utilization of industrial heritage within the context of urban revitalization, and conducted design research on the overall protection and reuse of the Hanyang Steel Plant under the theme of "Steel Green Boat".

Table 4. Mode of activation and utilization of industrial heritage

Mode of industrial heritage protection and utilization		
Model name	**Meaning**	**Case**
Thematic museum model	The theme museum model is based on the premise of preserving significant industrial heritage. It involves transforming the internal space of the industrial heritage site into an industrial museum, complemented by other supporting facilities and landscape elements, thereby creating an urban cultural and leisure destination	Xi'an Dahua Museum, Chicago Museum of Science and Industry
Creative industry park model	The industrial factory buildings will be transformed into creative industry blocks or art parks, which will be used as places for exhibition, communication, leisure, and activities	798 Art Zone in Beijing, No. 8 Bridge Creative Industry Park in Shanghai
Landscape park model	To inherit the industrial history and culture as the goal, to protect and reuse the facilities and site environment on the abandoned industrial ground, the main method is to recreate the landscape elements	Zhongshan Qijiang Park, North Duisburg Landscape Park
Comprehensive development mode of business tourism	The industrial plant area will be developed and constructed into a park, integrating shopping, recreation, catering, exhibition, and other functions	Shanghai World Expo, Xi'an Banpo International Art Zone

The interior of industrial heritage buildings has also undergone a more nuanced transformation, which emphasizes the creation of a compelling "sense of experience" within the space. Ding (2013) puts forward strategies for internal functional replacement and classification positioning of industrial heritage based on social needs and value evaluation (Ding, 2013). Through an analysis of several industrial architectural heritage sites in Shanghai, Zhang & Liu (2013) have summarized and proposed models and suggestions for reshaping and expanding the internal space of industrial buildings.

During this stage, the main reuse modes of industrial heritage in China, including the museum mode, creative industrial park mode, post-industrial landscape park mode, and commercial tourism comprehensive development mode, have been established. Scholars have conducted in-depth analyses of these four modes, examining various aspects such as outdoor environment, indoor layout, spatial planning, functional distribution, macro positioning, and micro-texture. They have summarized a comprehensive set of refined reuse methods for each mode.

Furthermore, scholars have developed a classification system for industrial heritage based on scale and type (Liu, 2015). This system encompasses regional factories, factory areas, industrial factories, and single structures, and provides detailed activation methods suitable for different scales (refer to Table 4). This classification system serves as a standard framework for practical engineering projects, and numerous industrial heritage reuse patterns based on this system have emerged.

However, this standardized classification system also imposes limitations on the innovation of diverse reuse models. As a result, practical engineering projects in industrial heritage reuse exhibit a significant homogenization phenomenon, wherein similar patterns are often replicated without much variation.

(iii) The mature stage: Overall planning and utility integration (2016 – 2019)

In the context of urban transformation and development, the construction of ecological civilization, and the societal demand for urban revitalization, the research on the reuse modes of industrial heritage has expanded horizontally in this stage. The research not only focuses on the protection and renewal of individual industrial heritage sites but also takes a broader perspective by examining regional and urban scales. The aim is to study the activation modes of industrial heritage from policy, economic, ecological, and cultural perspectives (Zhong *et al.*, 2021). The sustainable development of the protection and reuse models for industrial heritage is emphasized, as it is closely linked to the activation of industrial heritage protection and urban renewal. Relevant literature can be found with keywords such as "information integration," "integrated conservation and utilization mode," "trinity," and "sustainability."

To achieve integrated development, industrial heritage should be compatible with urban industry, urban function, urban culture, and urban environment (Guo *et al.*, 2016). Scholars, such as Gao Changzheng, have proposed a model for the comprehensive protection and utilization of the Luoyang Bearing Factory, which involves the construction of an industrial heritage symbiosis model that promotes cultural symbiosis, pattern symbiosis, and environmental symbiosis (Gao *et al.*, 2017).

Furthermore, the cultural and regional characteristics of industrial heritage are increasingly prominent. Scholars have examined these aspects using keywords such as "cultural revitalization" and "spatial distribution." Tong

(2017) analyzed the ethnic and cultural characteristics of industrial heritage, considering its material, institutional, and spiritual dimensions (Tong, 2017). Zhang & Gao (2017) have explored industrial heritage as a carrier of urban memory and culture, emphasizing its role in the preservation of urban memory and community culture, as well as contribution to the development of new urban cultures. Xu & Chang (2017) emphasized the importance of historical context in reuse, highlighting the significance of place spirit, place memory, and public participation in revitalizing industrial sites.

A significant portion of industrial heritage transformations is now based on community-based approaches, through which the daily activities of residents are utilized to establish connections between people and heritage. This approach enables residents to develop a deeper understanding of their heritage, while also providing visitors from other regions with a means to recognize and appreciate it. The aim is to foster micro-circular interactions within the region and promote diverse interactions between people and industrial spaces. Wang *et al.* (2016) explored a novel approach to residential development at the Nanjing Zhongchuan Oasis Factory, utilizing public and open spaces to create residential communities with distinct characteristics (Wang *et al.*, 2016). On the other hand, Hao & Xu (2018) critiqued the challenges arising from the consumer culture associated with industrial heritage and proposed suggestions for transforming industrial heritage from symbols of consumption to community culture.

During this period, the activation of industrial heritage focused on the effectiveness of various utilization modes, both domestically and internationally. The emphasis shifted from a single recycling approach to the integrated utilization of multiple resources. A recycling strategy with a consistent theme emerged, leading to the enhancement of the multifunctionality of industrial heritage, attracting diverse users, and enriching the values of heritage. The goal was to maximize the potential of industrial heritage and optimize its contribution to society.

(iv) The innovative period: Innovation-driven development, sustainable development (2020 – 2023)

During this stage, research on the reuse of industrial heritage expanded beyond the physical space to include the intangible aspects. It encompassed various industrial remains, such as mining areas and railways, broadening the scope of the investigation. The literature on industrial heritage reuse also expanded in terms of breadth and depth, with scholars delving into more comprehensive and specialized areas (Huang & Liu, 2022). By combining the reuse planning strategies from the previous three periods with the policy concepts of "National Spatial Planning," "Integration of Multiple Planning," and "Rural Revitalization" in China, a localized approach for reuse can be proposed, incorporating distinctive local characteristics (Jin & Chen, 2021). This integration led to the proposal of reuse approaches that exhibited localized characteristics, considering the specific context and needs of different regions. By considering these localized factors, researchers aimed to optimize the effectiveness and sustainability of industrial heritage reuse in their respective areas.

During this stage, the research on the reuse of industrial heritage from a cultural perspective is moving toward a more comprehensive and systematic approach. Scholars are exploring the cultural values embedded in industrial heritage and its significance in shaping collective memory and identity. The keywords "industrial culture," "memory place," and "cultural value-oriented" reflect this shift in research focus. Ding (2021) research focuses on regenerating the spirit of the third-line construction site through narrative-driven spatial experiences that integrate natural and artificial elements and incorporate industrial heritage fragments as memory anchors (Ding, 2021). Liu's (2022) study explores the activation of heritage communities based on shared collective memory of industrial workers, utilizing local industrial culture and emotional memory orientation to create a distinct sense of community and cultural identity (Liu, 2022).

Overall, the research in this period highlights the importance of industrial heritage in preserving cultural values and fostering a sense of place and identity within communities. The focus is on creating meaningful and immersive experiences that allow individuals to engage with the cultural significance of industrial heritage.

During this period, the transformation and utilization of industrial heritage have witnessed the incorporation of advancements in scientific and technological methods, as indicated by keywords such as "digitalization" and "visualization." The emergence and application of new technologies have played a significant role in revitalizing industrial heritage sites. In 2013 and 2014, virtual reality technology was introduced as a potential tool for industrial heritage research (Zhang & Liu, 2013; Zhu *et al.*, 2014). However, it was not fully developed into a comprehensive system at that time. In recent years, with the advancement of big data and visualization technology, there has been a shift toward quantitative empirical analysis. For example, Xie *et al.* (2021) conducted research on the business forms surrounding industrial heritage sites by analyzing interest points and integrating qualitative research to identify suitable business forms for upgrading within the industrial network (Xie *et al.*, 2021). Furthermore, researchers have utilized simulations to assess population vision, microclimate, wind environment, and thermal environment, visualizing the ecological challenges faced by industrial heritage and proposing ecological design strategies (Xiao *et al.*, 2022).

5. Summary of Chinese industrial heritage reuse pattern trend

The characteristics of the keywords and representative literature can be summarized as follows:

(i) Cultural values: Industrial heritage is recognized for its cultural significance, and establishing a value evaluation system is considered crucial.
(ii) Diversified and compound reuse: The methods of reusing industrial heritage have evolved from simple approaches to more diverse and complex strategies.
(iii) Impact on population and environment: Researchers emphasize the importance of considering the effects of industrial heritage reuse on the surrounding population and environment. They advocate for sustainable development and ecological construction.
(iv) Case analysis: Literature research primarily focuses on analyzing and summarizing existing practical projects. Case studies are commonly employed as the main research method.

In general, the analysis of domestic industrial heritage recycling patterns in China has been influenced by Western approaches. The development of a distinct native and national character is still in progress. However, over time, domestic research on this topic is gradually becoming more comprehensive. Specifically, the reuse modes of industrial heritage in different stages exhibit their own characteristics, and the specific content of these modes is continuously evolving and innovating. The theories and practices from previous periods serve as foundations for further deepening and improvement in subsequent periods, leading to the emergence of specific strategic points and approaches.

At the cultural level, earlier studies primarily emphasized the commercial values derived from urban culture, leading to the proliferation of museum models and cultural and creative industrial park models. However, these approaches often failed to foster a sense of belonging among people in the subsequent use of industrial heritage sites. In the middle period, there was a correct recognition of urban culture, and the national and regional characteristics of industrial heritage were acknowledged. In recent years, there has been an even greater emphasis on the spirit of place and the memory associated with specific locations. These aspects have emerged as dynamic sources of reuse and revitalization within industrial communities.

At the technical level, earlier studies relied heavily on qualitative research and case analysis as the primary method for summarizing reuse models. However, this approach may introduce subjective biases into the analysis. In contrast, with the advent of the digital era and the availability of big data, digitalization and visualization techniques have gained prominence in contemporary industrial heritage research. These advanced technologies provide quantitative and scientific support, offering a more objective and data-driven approach to studying and understanding industrial heritage. In the early stages, the focus of industrial heritage was primarily on landscape design to restore the ecological environment of brownfield sites. However, these approaches often prioritized esthetic characteristics, overshadowing the requirements for urban ecological construction.

At the level of urban concept, the idea of "two mountains" has emerged, emphasizing the importance of sustainable development and adaptability, which has led to a shift in the perception of industrial landscapes, and which now strives to balance the development requirements of both "beauty" and "ecology." In addition, the concepts of "double urban repair" and "double carbon vision" have gained prominence, indicating a growing theoretical research system with distinct Chinese characteristics (Han, 2021; Liu *et al.*, 2021).

These evolving concepts are expected to influence future research on the activation, reconstruction, and reuse modes of industrial heritage, shaping the focus and content of studies in the coming years.

Acknowledgments

None.

Funding

This work was supported by Guangdong Basic and Applied Basic Research Foundation (Project Number: 2021B1515020013), and Guangdong Provincial Philosophy and Social Science Planning Project (Project Number: GD21CYS05).

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Yuxin Zeng, Rui Jin
Formal analysis: Yuxin Zeng
Methodology: All authors
Writing – original draft: Yuxin Zeng
Writing – review & editing: Yuxin Zeng, Rui Jin

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

In the case of reasonable requests, the method of obtaining the original data can be consulted through the email of the corresponding author of this article.

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ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Study on the walkability of old city streets in Beijing from the perspective of application of Central Axis for World Heritage List

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Abstract

The year 2023 is a key year for Beijing's Central Axis to apply for World Heritage List. As the social space of urban culture, the streets are the communication space between modern-day residents and living heritage. In the blocks applying for World Heritage status, the walkability of the streets has an important impact on the presentation of the scene, cultural exchange, and tourist guidance. Based on the perspective of Central Axis application for World Heritage List, this study attempted to provide updated planning suggestions for the improvement of street walkability quality. Focusing on the human scale, first, 13 objective indicators and three subjective indicators of the streets in the buffer zone were evaluated by semantic segmentation, virtual audit, Likert scale, and other methods, as well as by acquiring the latest street view. Pearson's correlation analysis was used to explore the main factors affecting the walkability of the streets. The results show that 13 objective indicators such as street interface, street facilities and street style in space show a trend of gradual decline from the central axis to both sides. Buildings on the north side of Chang'an Avenue in Beijing's Old Town better preserve the architectural style of the traditional hutong. The factors that were strongly related to the sense of security were the proportion of fences and the width of the street. The strongest correlation factor concerning comfort is the street aspect ratio, whereas the most important factor related to aesthetic perception is the degree of preservation of traditional features. Finally, the paper puts forward some new strategies, such as clearly distinguishing street pedestrian and vehicular functions, controlling green visual ratio to adjust street visual aspect ratio, and protecting traditional street pattern.

Keywords: Central Axis; Buffer zone; Walkability; Street view; Index analysis

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Citation: Zhang, X., Yu, C., & Gong, Y. (2023). Study on the walkability of old city streets in Beijing from the perspective of application of Central Axis for World Heritage List. *Journal of Chinese Architecture and Urbanism*, 5(3):1033.
https://doi.org/10.36922/jcau.1033

Received: June 1, 2023

Accepted: July 28, 2023

Published Online: August 21, 2023

1. Introduction

In his praise about the Central Axis of Beijing, Liang Sicheng acclaimed the unique magnificent order of Beijing created by the construction of this Central Axis. To date, there are seven world heritage sites in Beijing, and the heritage elements of the Central Axis include three world heritage sites, which are the Forbidden City, the Temple of Heaven, and the Grand Canal Wanning Bridge. Beijing has attached great importance to the protection and inheritance of the Central Axis since it was included in the preliminary list of China's World Heritage Sites in 2012. In 2023, the application of the Central Axis for World Heritage List will enter the crucial stage (Song, 2022).

The inscription of the Central Axis on the World Heritage List will accelerate the cultural revitalization and heritage protection of Beijing Old City. In addition to focusing on the heritage itself, more attention needs to be paid to the street as a space for urban life and cultural functions, especially in terms of dialog and communication between modern residents and historical heritage (Zhang & Huo, 2002). The increasing people congregation will put more pressure on the existing conservation of heritage, but excessive control and unwalkable streets will also turn the huge resources invested in heritage protection into a silent cost. Therefore, how to improve the walkability of streets and effectively connect the heritage tourist paths under the condition of ensuring the promotion of the Central Axis as a World Heritage Site is an important issue to further promote the application of the Central Axis as a World Heritage Site and improve the quality of urban space.

Domestic and foreign scholars have mainly focused on two aspects in previous studies of urban street walkability (Dong & Long, 2015; Fang *et al.*, 2018), namely, the evaluation of objective factors of street walkability, and the analysis of influencing factors. The content of the research is mainly about constructing a system for indexing the walkability of streets (Liu, 2020; Song, 2021). With the updated assessment techniques and methods (Wang *et al.*, 2021), attempts have been made to assess indicators of street walkability back in the 1980s, with Gehl (2011) being the first one describing the quality of outdoor space required for walking. Many researchers have followed his work, developing a vocabulary of walkability and a systematic index system for assessing walkability (Ewing & Handy, 2009; Blečić *et al.*, 2018). To meet the different guidance requirements of measuring unmeasurable factors, different evaluation indices have been established (Maghelal & Capp, 2011).

However, most of the methods can easily obtain urban physical space walking environment indicators (Frank *et al.*, 2010; Manaugh & El-Geneidy, 2011; Hall & Ram, 2019). This index evaluation method not only ignores complex physical indicators, such as microclimate conditions, but also ignores pedestrians' subjective perception. As a supplement, some scholars use subjective perceptions and observations based on perception data to assess walkability (Cerin *et al.*, 2007). However, it is time-consuming and labor-intensive to carry out fieldworks, such as observing walking activity. New techniques and algorithms have revealed the possibility of automated quantitative measurement of walkability and overcome previous limitations. For example, Wang *et al.* (2021) used SVM algorithm, deep neural network algorithm, and random forest algorithm to carry out machine learning and build a scoring model to achieve automatic perception and scoring of street view pictures.

The studies on walkability were narrowed down to neighborhoods, commercial district (Xie, 2017; Carson *et al.*, 2023), track station exit (Liu & Pan, 2018) and other urban spaces, with lesser focus on historic districts with rich world heritage. Liu & Zheng (2023) used multi-source big data to measure the walkability of streets in Beijing's Second Ring Road from the perspective of landscape architecture. Liu (2020) used space syntax and index score to measure the street walkability of Dashilan Historical District in Beijing. Shartova *et al.* (2023) evaluated the walkability of the old city of Moscow from the perspective of healthy city. Thus, for the evaluation methods of street walkability, the walking environment scale and walking index are widely used abroad (Cunningham *et al.*, 2005), while the questionnaire survey and multi-source data evaluation are mainly applied in China (Yu & Wu, 2018).

With the advancement of science and technology, big data extraction and machine learning are increasingly applied to the evaluation of street walkability. However, focusing on historic districts with rich heritage requires local modification of evaluation indicators. Based on the above studies, this paper focuses on Beijing's old city streets within the Second Ring Road from the perspective of the World Heritage application. First, 13 objective evaluation indicators and three subjective evaluation indicators were used to comprehensively evaluate the walkability of the old city streets from two levels. Correlation analysis was used to identify factors that influence the walkability of the streets, and strategies were proposed to improve the walkability of the street for the purpose of heritage conservation and revitalization.

2. Research design

2.1. Research scope

The old city of Beijing, which was the ancient capital of five dynasties, has undergone big transformation, and the city streets, which were initially used for walking, had become amenable to motor traffic and then changed back to walking. The Central Axis Heritage embodies the essence of Chinese civilization and the history and culture of Beijing. The street is an important space for dialog between people and heritage. However, the current road traffic situation in the Second Ring Road is becoming worse, rather than better, posing safety risks to the pedestrians and affecting the walkability and walking comfort of the street.

In a macro sense, Beijing Old City generally refers to the central area within the Second Ring Road. However, from the perspective of the application of the Central Axis for World Heritage List, the volume of modern residential buildings and commercial buildings in the Southern district of the city and the Eastern and Western districts of the city within the Second Ring Road is very different from that of the historic district, thus it is not included in this study. As shown in Figure 1, the eastern and western boundaries refer to the heritage area and buffer zone of the Beijing Central Axis Protection and Management Plan (2022-2035), and the western boundary reaches the center line of *Xinjiekou* North Street, *Xinjiekou* South Street, *Xisi* South Street, *Xidan* North Street, *Xuanwumen* Inner Street, *Xuanwumen Wai* Street, and *Caishikou* Street; in the east, it reaches the center line of *Yonghegong* Street, *Dongsi* North Street, *Dongsi* South Street, *Dongdan* North Street, *Chongwenwai* Street, and *Tiantan* East Road; in the north, it reaches the foot line of the north moat; in the south, it reaches the center line of the Second Ring Road. It covers an area of 32.19 sqkm, of which 5.9 sqkm is the heritage area. The residential population density is about 20,500 inhabitants per square kilometer.

2.2. Image acquisition and screening

Building and road network data within the area were obtained using the OpenStreetMap platform, and then unified into GCS_WGS_1984 geographic coordinates in the ArcGis platform. First, the road network was processed, eliminating urban expressways with high road grade and far more traffic function than pedestrian leisure function. On this basis, the road network with street view was selected as the basis for street analysis. As shown in Figure 2, on the open platform of Baidu Map, the function of "obtaining panoramic data" was used to capture and select street scenes in the four directions of the road every 200 m, and the view data of vehicles in February 2022 were extracted, to obtain a total of 800 street attractions and 3200 Baidu Street Views. The actual data used in this study are 1600 street view images of 0° and 180°. Since the road surface and road facilities are generally similar and even highly consistent in the street scene at 200 m intervals, this study used the image recognition tool provided by the CUG.HPSCIL laboratory to perform a preliminary semantic segmentation. According to the length of the street, a number of typical street scenes were selected, giving 254 representative street scenes. Part of the street view is shown in Figure 3.

2.3. Evaluation index

2.3.1. Evaluation index construction

To evaluate walkability from the perspective of human walking, Ewing & Rundle (2009) and Purciel *et al.* (2009) objectively measured spatial walkability from a three-dimensional perspective, using street wall continuity,

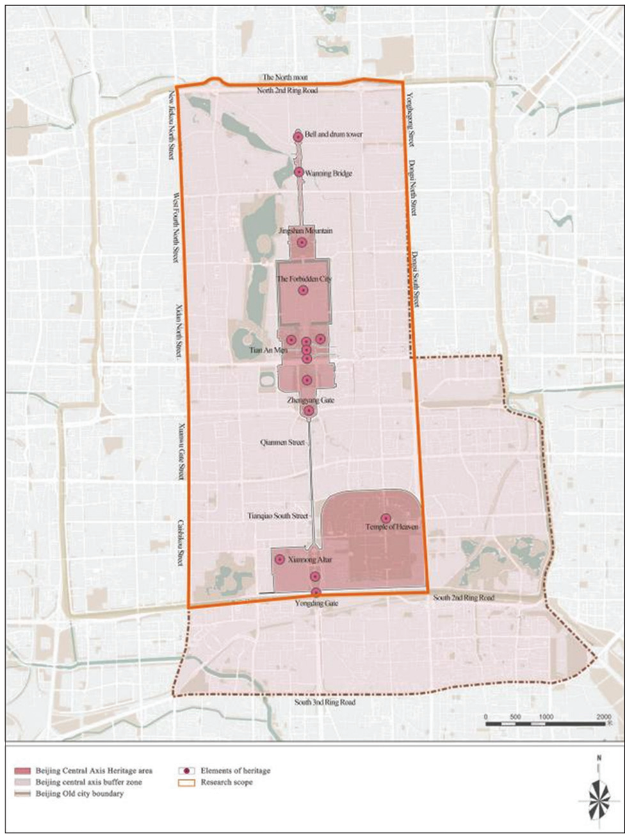

Figure 1. Study area map. Source: Beijing Central Axis Protection Management Plan (2022 – 2035)

Figure 2. Access to street attractions. Source: Drawing by the authors

aspect ratio, sky ratio, and other variables. Harvey *et al.* (2014) proposed the concept of street skeleton to measure the geometric features of streets. Therefore, different from the evaluation indexes of walkability by Liu & Zheng (2023) and Xu *et al.* (2018), this study describes the street skeleton

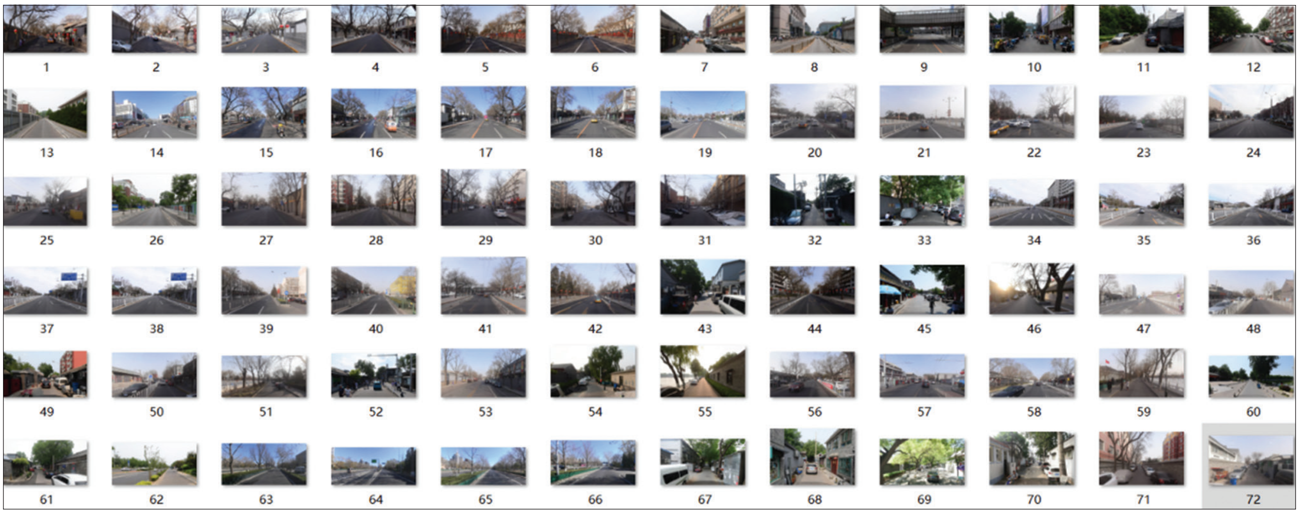

Figure 3. Part of the street scenes. Source: Baidu Map open platform

in more detail and measures the continuity and aspect ratio on both sides of the street from different walking directions. At the street-style level, the protection index of traditional style is supplemented to represent the street characteristics of the old city. To evaluate the walkability of old city streets, we chose street interface, street facilities, and street style as the three primary indexes to evaluate Beijing streets. Based on human walking and usage scale, 13 secondary evaluation indicators were constructed. The specific concept and acquisition methods of indicators are shown in Table 1.

2.3.2. Street skeleton evaluation model

The degree of street wall continuity and the street aspect ratio are calculated according to both sides of the street, respectively, as shown in Figure 4. Since walking can only be done on one side of the street, one could experience the different sensations after having walked on both sides of the street due to the different interfaces from a walking perspective. The data on both sides of the street were obtained and calculated using the street skeleton rating model developed by Chester Wallag Harvey in New York and Boston (Harvey, 2014).

2.3.3. Pixel recognition

First, the image semantic recognition software provided by the CUG.HPSCIL laboratory was used to identify the initial elements of the image, and then Adobe Photoshop CC was used to manually identify and revise the indicators of street furniture, and then the elements of street furniture were calculated according to the proportion of index pixels in the fixed-point street view. As shown in Figure 5, the ratio of indicator pixels to image pixels was used as the final data of this indicator.

2.3.4. Evaluation of virtual audit method

Index calculation of street skeleton and image pixel recognition of street facilities cannot fully reflect the street style. Therefore, to better study the relationship between the quality and walkability of streetscape elements, the virtual audit method was used to evaluate the street-style level, building quality, the degree of street maintenance management, and the degree of traditional style protection. Audit is a measurement method that combines expert knowledge and common sense around the theoretical framework (Clifton *et al.*, 2007). Due to the professional evaluation of relevant indicators, 20 undergraduates with urban and rural planning and landscape architecture background scored 254 street scene pictures in the experiment, and the average scoring result was the last data of this index.

2.4. Walkability evaluation experiment

Based on the Hierarchical Needs Theory, street walkability is divided into three aspects: sense of security, comfort, and aesthetic perception. The sense of security is the most basic guarantee of the street, while the comfort emphasizes the use function and walking experience of the street, and the aesthetic perception emphasizes the visual self-satisfaction of pedestrians. After interviews and surveys with more than 100 participants, 45 effective and complete subjective evaluations of walkability were obtained, of which two-thirds were evaluated by students with a major in this field, and the rest were by urban residents aged 18 – 45.

A total of 254 street-scene pictures were divided into three groups according to numbering. Each group included 85 pictures, which were distributed to the students and city

Table 1. Concept and data source of street walkability index

First-order index	Number	Secondary index	Index concept	Data source
Street interface	01	Street width	Road red line width	Road source data property sheet downloaded OpenStreetMap
	02	Average building height	Average height of buildings on both sides of street	Street view picture
		Street aspect ratio	Ratio of one side building to road width	Single side building height/ street width
	03	Higher side street aspect ratio		
	04	Lower side street aspect ratio		
		Street continuity	The ratio of the length of the building interface to the length of the street within 200 m on one side of the street	Continuous length of unilateral building /200 m
	05	Street wall continuity, more continuity side		
	06	Street wall continuity, less continuity side		
Street furniture	07	Motorway	Bike lanes are one of the street components in pedestrian-friendly scale	Street view image semantic segmentation, elements of the street view map area
	08	Fence	Iron fence between motorway and non-motorway	
	09	Green barrier	Isolation green belt between two-way traffic lanes and between motor vehicles and non-motor vehicles	
	10	Street sign	The sign facility appears in the street view image	
Street style	11	Architectural quality and design aesthetics	Evaluation is carried out on the standards such as the unity of architectural color, construction age and building height in street view pictures	Virtual audit method
	12	The extent of street maintenance management	The number of garbage cans in the street view, the level of cleanliness of the street, and whether the motor vehicle parking is orderly were evaluated	
	13	The degree of preservation of traditional features	How many traditional elements of street view, attractiveness, and other standards for evaluation	

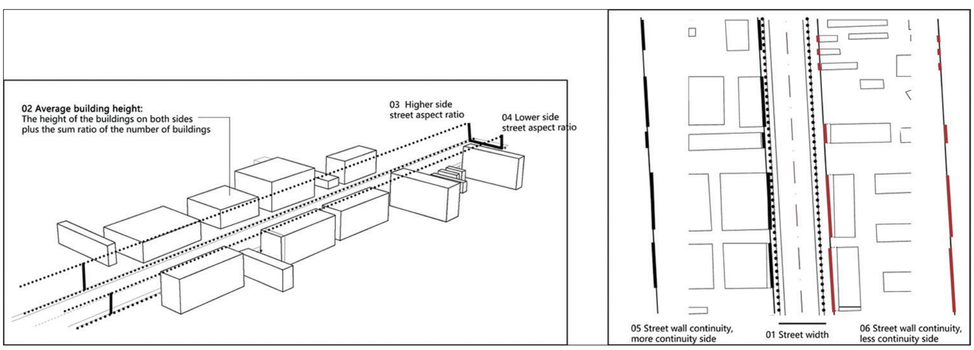

Figure 4. Street interface indicator calculation diagram. Source: Redrawing by the authors in reference to Harvey (2014)

residents who participated in the evaluation. The visual perception of street-scene pictures was rated according to the seven-level Likert scale. Through the analysis of the absolute value and the trend of the evaluation results, it can be seen that the rating trend of students and residents is overall consistent and the difference is small. It is specifically reflected by the scoring trend of professional students which is higher than that of residents, with the absolute value ranging from 0 to 1.2. Therefore, the following data analysis combines the scoring results of the two groups of participants.

3. Research results

3.1. Analysis of objective indicators of walkability

3.1.1. Street interface

The results of the road interface analysis show that the six indicators have different spatial distribution characteristics, and the distribution characteristics are generally different along both sides of Chang'an Avenue. As shown in Figure 6, the road interface is characterized by road width, road aspect ratio, and road continuity. As can be seen from the following analysis results, the streets north of Chang'an Avenue are relatively narrow and most of the branch streets have a width within 10 m, which is related to the fact that there are many hutongs (alleys) in the heritage area north of Chang'an Avenue and within the buffer zone. The average height of buildings is higher on both sides of the main road and lower on both sides of the branch streets. The buildings to the south of Chang'an Avenue are taller than those to the north, owing to the earlier development of the south of the old city of Beijing and the preservation of historical buildings in the north.

From the high side and the low side, the aspect ratio mainly represents the pedestrian's perception in different walking directions of the same street. Thus, the road network with street view was selected as the basis for street analysis. The spatial distribution characteristics of the overall index are north of Chang'an Avenue and east of the Central Axis. The higher side of the street aspect ratio is mainly distributed in the branch roads, such as Ganyu Alley. The width of the road is only 5 m, while the height of the buildings on the higher side reaches 18 – 24 m, giving people a feeling of narrow space and strong sense of constraint (Yu, 2013). The height to width ratio of the lower side is between 0 and 3.3 m, and the height to width ratio of zero indicates that the street side is the non-physical building space, such as green space or square. Street continuity represents the continuity of the physical interface formed by buildings on both sides of the street (Jiang *et al.*, 2016). The academic community advocates creating a unified, orderly, and vibrant urban street through complete and continuous building façades along the street (Jin, 1991; Jiang & Chen, 2014). The spatial distribution of continuity is characterized by higher continuity to the north of Chang'an Avenue and lower continuity to the south of it, with the lowest continuity being zero. For example, in the north of Xihai and Houhai, one side of the street is an architectural space, whereas the other side is an ecological space.

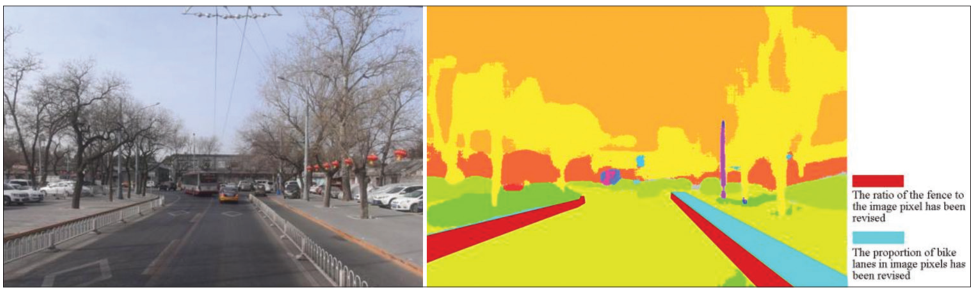

Figure 5. Extraction results of fence pixels. Source: Street scene repainting

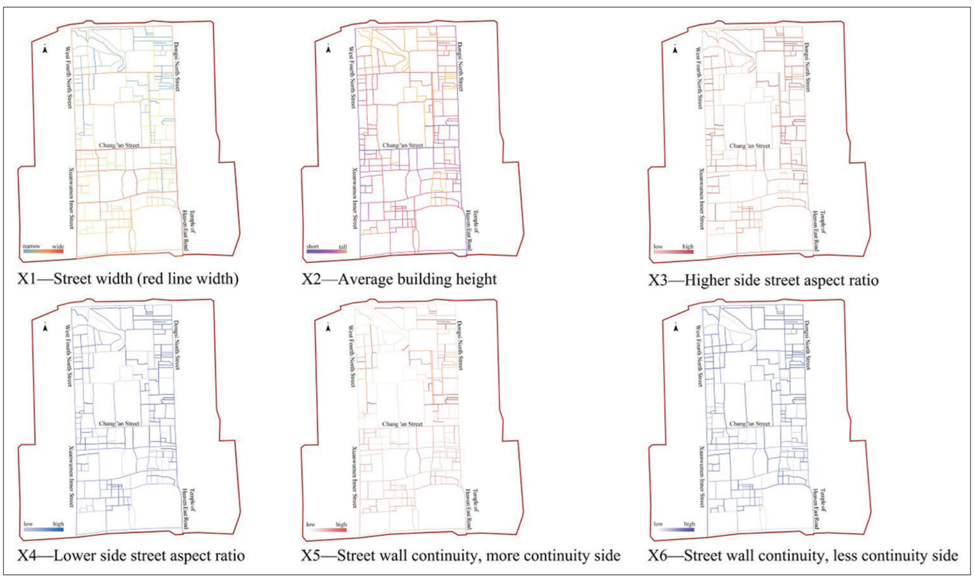

Figure 6. Analysis results of street interface indicators. Source: Drawings by the authors

3.1.2. Street facilities

The results of street facilities analysis showed that the overall facility coverage rate was high, but pedestrian signs were missing at some spots, and there is a tendency that the wider the road, the more street signs there are. As shown in Figure 7, according to the results of index analysis, there is a relatively high proportion of cycle lanes, mainly on trunk roads. Most of the branch roads are single carriageways, and there is no clear distinction between motor vehicle lanes or bicycle lanes. Fences and green barriers are mainly distributed on roads with higher grades and where there are conflicts between pedestrians and vehicles, such as Chang'an Avenue and other high-grade roads. East of the Imperial City Root South Street between the motor road and the walkway has more fences without green barriers. The fence of Qianmen Street is relatively high, which is caused by the contradiction between tourist attractions and car demand. Street signs are used to guide pedestrians along the street. More street signs can facilitate smooth traffic flow and ensure pedestrian safety, while consistent use of sign with attractive appeal can improve street view. From the perspective of current street sign facilities, the spatial distribution law is that high-grade road signs occupy a high proportion in the street-scene pictures, while low-grade road signs occupy a low proportion, indicating that low-grade road signs are gradually removed as they cannot guide the walking function.

3.1.3. Street style

The traditional style of the street gradually decreases from the central axis to the east and west sides (Figure 8). Specifically, the streets with high architectural quality are mainly located in Meishi Street, Qianmen East Street, Houhai Beiyan, and other adjacent historical heritage areas. The streets with low architectural quality are mainly located in the historical districts with narrow space, such as Yuqun Alley and other buildings that have not been repaired for a long time. It was shown that the extent of street maintenance is high, and the style control of the buffer zone of the Central Axis has a good effect. However, management of some low-grade roads is not in place, and the street management by residents to improve the living atmosphere is less than satisfactory. The degree of preservation of traditional features is related to the

Figure 7. Analysis results of street facilities index. Source: Drawings by the authors

Figure 8. Analysis results of street style index. Source: Drawings by the authors

historical buildings on both sides of the street. The overall trend is higher in the north and lower in the south, and higher in the middle and lower on both sides. The areas with lower degree of protection are mainly distributed around the Temple (or Altar) of Agriculture, and the Temple of Heaven. The road accessibility around these two historical areas is low, and the visibility of the Temple of Agriculture and the Temple of Heaven is insufficient. The sites surrounding the historic buildings are occupied by modern buildings, for instance, the Temple of Agriculture and the Temple of Heaven are occupied by schools and hospitals, respectively (Han, 2005), and the protection of these historic buildings from the street is low.

3.2. Analysis of subjective index of walkability

Specifically, according to the seven-level Likert scale, as shown in Figure 9, the streets with a high sense of security perception are Tian'anmen Square East Side Road (5.8 points) and West People's Hall Road (Rendahuitang West Road) (5.65 points), which are in the vicinity of Chang'an Avenue. In terms of comfort evaluation results, the longitudinal streets tended to be higher than the horizontal streets. Specifically, the streets with higher scores were Tian'anmen Square East and West Roads (5.95 points) and *Dashan* Alley (5.45 points). The evaluation results of esthetic perception are generally similar to those of the previous two. Specifically, *Dashan* Alley (5.75 points) has a higher score, which is related to the fact that the road is located near *Wangfujing* and has Beijing characteristic shopping malls. *Houhai beiyan and Xihai beiyan* (5.5 points) also have a higher score, which is related to the road's proximity to water. The correlation between objective and subjective indicators of walkability was analyzed based on detailed data.

3.3. Correlation analysis of walkability

First, the subjective and objective data were imported into IBM SPSS Statistics version 25 for Z-score standardized processing, and then Pearson's correlation test was used to analyze the relationship between subjective feelings of walkability and specific objective data, such as street interface, street furniture, and street style. The results of correlation analysis are shown in Table 2.

The above are the results of correlation analysis of 13 independent variables and three dependent variables. In general, the degree of correlation between the three subjective indexes and the 13 objective indicators are relatively high, indicating the rationality of the selected indicators. The sense of security has the strongest correlation with the degree of street maintenance management, and the feeling of comfort has a strong correlation with the architectural quality, design aesthetics, and the street aspect ratio. The main factor affecting the esthetics perception is the degree of preservation of traditional features.

The following will specify the influencing factors of street safety perception. At the level of street interface, the sense of security has the strongest correlation with road width, that is, the wider the road, the stronger the sense of security. This is similar to what Su (2017) has found in his assessment of feelings of road safety. Figure 10 shows the wider road width and walking path contributes to the larger walking field of vision and the increased sense of security for pedestrians. On the contrary, there are narrower hutong branch roads with fewer people at the site, most of which are unable to be distinguished from motor roads, non-motor lanes and walking lanes, and the sense of security for pedestrians is reduced. At the level of street facilities, there is a significant correlation between the proportion of fence and the sense of security, which also indicates that the walking safety not only depends on the width of the walking lane, but also depends on the degree of green barrier between the walking lane and motor road. At the street-style level, architectural quality, design esthetics, and the degree of street maintenance management are significantly correlated with the sense of security, and the correlation coefficient with the degree of

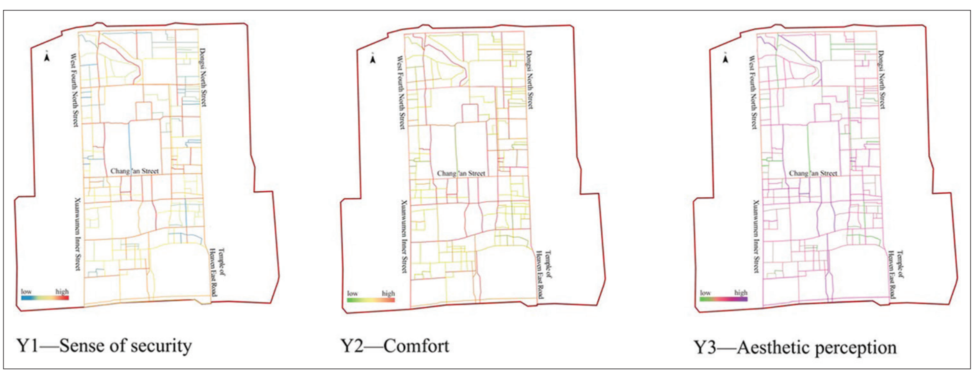

Figure 9. Analysis results of subjective index of street walkability. Source: Drawings by the authors

Table 2. Walkability correlation analysis results

Objective index			Subjective index		
			y1	y2	y3
			Sense of security	Comfort	Aesthetic perception
x1	Street interface	Street width (red line width)	0.428**	0.314**	0.291**
x2		Average building height	0.265**	0.150*	0.076
x3		Higher side street aspect ratio	−0.383*	−0.550**	−0.348**
x4		Lower side street aspect ratio	−0.304	−0.470**	−0.301**
x5		Street wall continuity, more continuity side	−0.241*	−0.253**	−0.197**
x6		Street wall continuity, less continuity side	−0.286	−0.241**	−0.337**
x7	Street furniture	Motorway	0.386**	0.295**	0.243**
x8		Fence	0.418**	0.244**	0.183**
x9		Green barrier	0.148*	0.184**	0.128*
x10		Street sign	0.161*	0.113	0.056
x11	Street style	Architectural quality and design aesthetics	0.674**	0.732**	0.417**
x12		The extent of street maintenance management	0.872**	0.539**	0.752**
x13		The degree of preservation of traditional features	0.135*	0.299**	0.801**

Note: **Indicates significant correlation at level 0.01 (two-tailed); *Indicates significant correlation at level 0.05 (two-tailed). Source: Calculation results by the authors

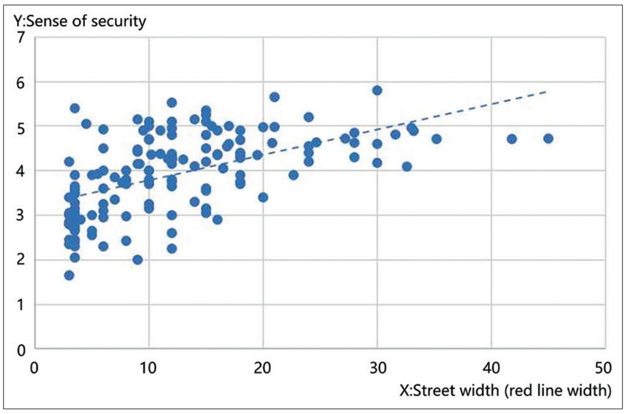

Figure 10. Normalized scatter plot of the degree of protection of traditional style and street security. Source: Plot by the authors

street maintenance management is the strongest among the 13 independent variables, indicating that improving the degree of street maintenance management can effectively improve the sense of walking security.

The index of influencing factors of street comfort has strong correlation mainly at the level of street interface. The correlation coefficient between the street aspect ratio and street comfort is the highest and negatively correlated, that is, the higher the aspect ratio, the lower the comfort. This is in line with Fang *et al.* (2021) analysis of the factors influencing street facilities in Shanghai. Most scholars, such as Sitte (1965) and Ashihara (2006), believe that the ideal aspect ratio of streets is 1 – 2. According to Figure 11, within the aspect ratio of 3, comfort is mostly above 3 points, which is also related to the height limit in the study area within the site and the widening of streets forced by traffic functions. The overhanging of the first floor and the façade decoration of the buildings along the street also weaken the feeling of comfort of unilateral walking on the street with excessively high aspect ratio to some extent.

The street studied is located in the buffer zone of the Central Axis of the old city of Beijing. The street beauty perception is mainly correlated with the degree of protection of traditional features, and the correlation coefficient is the largest. In the aspect of street interface, there is a significant negative correlation with street aspect ratio and street continuity. At the street level, there is no correlation with street sign; the degree of protection of traditional features is the main factor influencing the esthetic perception of the street, that is, improving the protection of traditional features on both sides of the street can improve the aesthetic perception of the street more efficiently. The index of the degree of protection of traditional features is a preliminary screening of street types. Streets with lower traditional style have no or fewer historic buildings. Therefore, as shown in Figure 12, the level of protection of traditional features starts at around 2, and the esthetic perception of the street is mostly above 2.

4. Discussion

In this study, by extracting the latest central axis of Beijing and the street scene within the buffer zone, using the

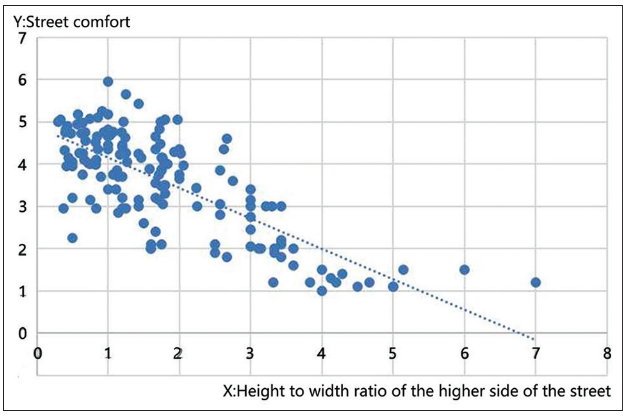

Figure 11. Normalized scatter plot of the height to width ratio of the higher side of the street and the street comfort. Source: Plot by the authors

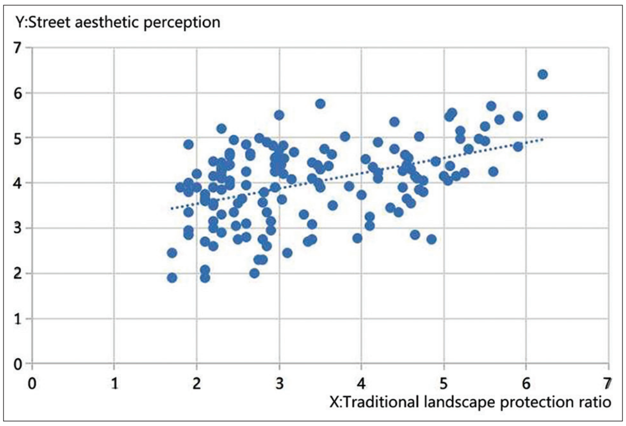

Figure 12. Scatter plot of traditional landscape protection ratio and street aesthetic perception. Source: Plot by the authors

correlation analysis of subjective and objective indicators, the results showed that 13 objective indicators, such as street interface, street furniture, and street style; and three subjective indicators, such as the sense of security, comfort, and aesthetic perception, are significantly correlated, indicating that the evaluation method of the index system is feasible and reasonable. The results of spatial analysis of objective indicators showed that walkability gradually decreased from the central axis to the east and west sides.

Thirteen objective indicators have different degrees of influence on subjective indicators. In terms of the sense of security, it is necessary to make a clear distinction between pedestrian space and vehicle space, and to reduce the vehicle function in the Central Axis area as much as possible. Paying attention to the diversity of pedestrian functions can further maximize the use of pedestrian space and increase the effective width of traffic, which will effectively improve the feeling of pedestrian safety. In terms of road comfort, reasonable design of road aspect ratio is an effective measure to improve walking comfort. In this study, winter streetscape research was used as much as possible to accurately express the effect of street physical framework on walking experience, and walking comfort can be improved by street green vision rate. In terms of the esthetic perception of the street, within the buffer zone of the Central Axis under World Heritage Site application, the historic traditional style is an important feature that shows the quality of the street. However, in addition to the complete protection of the Central Axis Heritage Area and the Historic District for tourism development, there are still many historic buildings with inadequate protection. Therefore, the Beijing Central Axis Protection and Management Plan (2022-2035) should be regarded as a guide to protect the street texture of the old city and shape the stylistic characteristics.

Different from the goal of funds used to improve ordinary streets in the city, a large amount of construction funds have been invested in shaping the appearance of streets under investigation in this study and hiring more service groups to tend to tourists on the streets, all of which are crucial for shaping the impression of the ancient capital of Beijing. From the research results, it can be concluded that the spatial heterogeneity of street walkability in the old city is largely related to historical factors and urban construction, that is, the degree of heritage protection, the shape of the old city, and the habits of citizens. To improve the walkability of the street, the heritage areas on both sides of the street should first be protected orderly, the street style should be coordinated, the continuity of the street interface should be improved, and the height ratio of the street should be controlled between 1 and 2 as far as possible. However, due to the management of the height control on both sides of the street, street trees and street facilities can be used to create a comfortable street interface. Then, at the street level, we need to supplement and improve the signage facilities for walking guidance, in addition to inclusive construction standards, improved barrier-free facilities, multi-language signs in Chinese and foreign languages, and Braille signs. Finally, at the level of street style, it is necessary to accelerate the withdrawal of the buildings that occupy the heritage area and strengthen the stylistic design of street façades, especially on pedestrian lanes, such as *Qianmen East Street* and *Houhai North Street*.

At the same time, there are still some limitations in the study. First, there is a lack of dynamic research on street pedestrians. Different time periods, characterized by stark difference between the bustling and empty streets, will also affect how people feel about walking. Secondly, with the enrichment of the GIS database, it is expected that the red line boundary of the street can be extracted more accurately, and the aspect ratio and continuity of the street can be calculated by machine learning. Streets are the soul of the culture of a Central Axis. It is hoped that this study can provide insights to the application of Central Axis for the World Heritage status, and offer updated suggestions for improving the walkability of the streets around the Central Axis.

Acknowledgments

None.

Funding

This project was funded by the National Natural Science Foundation of China "Research on Urban Green Space Renovation Based on Walkability" (No: 51708030).

Conflict of interest

The authors declare that this paper has no conflict of interest with other institutions or organizations.

Author contributions

Conceptualization: Xiaoyong Zhang, Changming Yu
Data curation: Xiaoyong Zhang, Yue Gong
Investigation: Xiaoyong Zhang, Yue Gong
Methodology: Xiaoyong Zhang, Yue Gong
Writing – original draft: Xiaoyong Zhang, Changming Yu
Writing – review & editing: Xiaoyong Zhang, Changming Yu, Yue Gong

Ethics approval and consent to participate

The interview content of this study does not involve the privacy of the interviewees, and the interviews were not recorded. Only the interviewees' responses regarding the evaluation of street walkability were obtained.

Consent for publication

Not applicable.

Availability of data

Building and road network data within the area were obtained using the OpenStreetMap platform, and then unified into GCS_WGS_1984 geographic coordinates in the ArcGis platform. Then, on the open platform of Baidu Map, the function of "obtaining panoramic data" was used to capture and select street scenes in the four directions of the road every 200 m, and the view data of vehicles in February 2022 were obtained, to obtain a total of 800 street attractions and 3200 Baidu Street Views.

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ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Envisioning rural futures: Lishui and the *Future Shan-Shui City* competition

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(This article belongs to the *Special Issue: Reshaping Rural China*)

Abstract

This paper presents an international competition called *Future Shan-Shui City: Dwellings in the Lishui Mountains*, promoted by Lishui Municipality (Zhejiang Province) in 2020, and examines the three award-winning projects: *Future Super Shan-Shui Park* by the China Academy of Urban Planning and Design, *A Symbiotic Urban Change* by Olivier Greder Architects, and *Prosperous Lishui* by South China University of Technology and Politecnico di Torino. By investigating how policies are changing current planning activities, and how the themes raised and then addressed in urban projects, this contribution sheds light on the salient features of today's development in Chinese marginal areas and provides the opportunity to discuss new visions for rural futures that transcend the Chinese context.

Keywords: Urban-rural relationship; Future Shan-Shui City; Urban planning; Urban design; Agricultural modernization; Lishui

1. Introduction

After three decades of strong economic growth, today's rural China is still characterized by economic and social inequities, environmental problems, and demographic imbalances. To address these issues, numerous policies and projects have been developed in recent years. Particularly, the Zhejiang Province has been a site of great experimentation: new facilities and accommodation for rural dwellers have been realized, villages have been restored, and new economic activities have been promoted thanks to programs such as the Building a New Socialist Countryside (BNSC), the Beautiful Countryside, and the Rural Revitalization Strategy. As part of this development strategy, the *Future Shan-Shui City: Dwellings in the Lishui Mountains* competition was launched by Lishui Municipality in 2020. The aim was to turn a 152 sqkm site south of Lishui city into a laboratory to experiment with new relationships between urban and rural while enhancing the environmental features of the area. This article presents the competition, its genesis, and its links with planning policies and then discusses the three award-winning projects. These materials invite us to reflect on three points: the efforts to slow down urban entrepreneurialism; the attempts to promote new plans and projects to redefine urban-rural relations; and the promotion of high-quality urban spaces and environmental wellbeing.

This research is the result of studies conducted from 2020 to the present, in which the author has been directly involved in the design activities, interacted with academics

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Citation: Ramondetti, L. (2023). Envisioning rural futures: Lishui and the Future Shan-Shui City competition. *Journal of Chinese Architecture and Urbanism*, 5(3):0957.
https://doi.org/10.36922/jcau.0957

Received: May 17, 2023

Accepted: July 17, 2023

Published Online: August 22, 2023

and practitioners investigating the transformations in Chinese rural areas, and corresponded with the teams involved in the competition. These first-hand data have been combined with secondary sources, such as planning and policy documents, consultancy reports, and statistical information from official yearbooks. For a more detailed account of the methodology adopted and the activity undertaken, see the paper by Ramondetti *et al.* (2023).

The purpose of this paper is to investigate urban projects envisioning new ways of inhabiting rural and marginal areas, which are facing great upheaval. The displacement of the rural population and changes in patterns has provoked what Araghi (1995) and Ghosh and Meer (2021) termed global depeasantization. This problem goes side by side with the phenomenon of amenity migration (Abrams *et al.*, 2012; Matarrita-Cascante & Stocks, 2013), entailing the exploitation of the natural and cultural resources of the countryside, or other areas of significant environmental value. This issue has also been driving an expansion in suburbanization (Keil, 2017; Wu & Keil, 2020), with increasing land consumption and a redefinition of the relationships between core cities and hinterland areas. All these phenomena have profoundly characterized the development of rural China over the past three decades, raising issues that have been addressed mainly in terms of socioeconomic policies and governance programs (see for instance Zhang *et al.*, 2023). While these measures play an important role, planners and architects need to reflect on these issues from a design perspective (Koolhaas & AMO, 2020), that is, to engage critically with alternative spatial configurations that promote novel ways of inhabiting and practicing rural spaces. Since urban design plays a key role in contemporary China, this is a privileged realm to observe the most innovative trends and experimental projects. Urban competitions, such as *Future Shan-Shui City*, thus offer precious insights into methods and strategies for rural-urban development.

The paper is structured as follows: Section 2 briefly presents the main policies and initiatives undertaken to improve the living conditions in rural areas over the past few decades. Section 3 examines the planning activities in Lishui, Zhejiang Province, highlighting the shift from large-scale initiatives to boost urbanization, to new environmentally friendly and site-specific development strategies. Section 4 presents the competition *Future Shan-Shui City* instituted by Lishui Municipality in 2020 and describes the three awarded projects: *Future Super Shan-Shui Park* by the China Academy of Urban Planning and Design (CAUPD), *A Symbiotic Urban Change* by Olivier Greder Architects, and *Prosperous Lishui* by South China University of Technology (SCUT) and Politecnico di Torino. Finally, the concluding part summarizes the current trends in Lishui urban development, discusses the issues arising from the competition, and the strategies proposed by the projects examined.

2. Reshaping rural China

Over the past two decade, most of Chinese urban policies and projects have progressively shifted their focus from large urban centers toward what Rozelle & Hell (2020) defined as the "invisible China:" rural, internal areas impacted only slightly by the development that came after the economic reform. Addressing the challenges of this part of the Chinese territory, it means to deal with what President Hu Jintao and Prime Minister Wen Jiabao already defined in 2006 as the "three rural issues:" the fall in agricultural production, the widening income gap between urban and rural populations, and the lack of infrastructures and services (Hsing, 2010; Chen *et al.*, 2021). Agricultural production as a percentage of total GDP has declined by 30% over the last 20 years, mainly due to the gradual disappearance of arable land, which has diminished by about 60,000 sqkm (National Bureau of Statistics of China, 2022). Not only has this triggered a problem of food security (Hong, 2016) but it has also sparked a wave of migration toward the large urban centers at a rate of about 16 million people per year (Miller, 2012). Even though there has been improvement in rural standards of living, data from the National Bureau of Statistics (2022) showed that the average income in rural areas was nearly three times lower than that of urban areas; 7% of the rural population had no access to running water, while 2.6% had no access to hospital facilities, and the infant mortality rate in rural areas was 10%.

To address these problems, various initiatives were put in place to improve rural living conditions since the 2000s. At first, fiscal measures were employed: price floors for agricultural products, the abolition of most agrarian taxes, and the introduction of subsidies for farmers (Ye, 2009). In parallel, about 400 billion CNY was invested by the national government in agriculture, and the fiscal expenditure of local administrations in the primary sector rose by 20% (Su, 2009). This policy led to farmers' incomes growing from 45 to 126 billion CNY (Ye, 2009). Alongside these economic measures, urbanization programs were also implemented. The most important one was the BNSC program, introduced in 2006 and is still ongoing (Ahlers, 2014). The program's main objectives are to improve services and standards of living in rural and suburban areas and to preserve farmland and boost agricultural production in response to the growing demand for food. This program, like many others, has been implemented through major infrastructural investments that have led to a radical reorganization of constructed spaces and productive sites in rural areas (Bray, 2013). In continuity with these initiatives, the National New Type of Urbanization Plan and the Rural Revitalization Strategy Plan have been launched in 2014 and 2018, respectively, with massive resources for improving agricultural production, new policies to address governance difficulties, and novel programs for improving the standards of living in rural areas (Wang & Zhuo, 2018; Chu, 2020; Liu *et al.*, 2020a). Furthermore, since 2019, the State Council has established an inter-ministerial joint conference system with the National Development and Reform Commission (NDRC) to foster the coordination between these many initiatives and better integrating urban-rural development (Han, 2019).

While these many initiatives have been promoted by the national government, forms of grassroots urbanization involving local administrations and private players have led to a rise in independent projects to improve rural areas. In particular, the Zhejiang Province has been a place of exceptional experimentation (see Commerell & Feireiss, 2020; Sun *et al.*, 2022; Lin & Jia, 2023). Already in 2002, the Provincial Government launched the Green Rural Revival program to supply services in rural areas and to improve agricultural production. Following this strategy, local cadres implemented specific projects, which have resulted in important achievements. Particularly, the government of Anji County enacted policies for the preservation and renewal of villages and traditional crops, strongly promoting slow tourism centered on well-being and health in 2008. This initiative known as Beautiful Countryside had a great success, which prompted the regional government to adopt it in other parts of its territory. Five years later, the national government launched the Beautiful China Initiative (BCI), extending this strategy for the recovery of rural areas nationally (Weller & Hands, 2021). In parallel, the Zhejiang Province also hosted one of Alibaba's pilot projects, the Qingyanliu Taobao Village in Yiwu Municipality, where 10% of the families and over 100 stores are active in e-commerce through the Taobao Marketplace platform (Li, 2017; Wang *et al.*, 2021). The success of this experiment, which generated strong growth, has led this model to be adopted in the less developed areas of the Coastal and Central Regions, with a boom in the number of Taobao Villages, from 212 in 2014 to 7,023 in 2021 (Ali Research Institute, 2022).

These initiatives are summarized in Figure 1, together with the projects undertaken by Lishui Municipality to promote development.

3. The development of Lishui Valley

Initiatives for promoting novel patterns of development in rural spaces have sprung up since 2015 as a result of both administrative cadres and private corporations. While these projects have improved the living conditions of rural citizens, they also emphasize the tension between the goals of environmental conservation of land on one hand and the modernization and improvement of productive activities on the other. This tension is reflected in today's urban and architectural competitions, which require the protection of the environment, the reduction of land consumption, the increase in agricultural production, and the preservation of traditional rural characters. In Zhejiang Province, the attempt to reconcile these demands is evident in the initiatives recently implemented by administrative bodies such as Lishui Municipality. These evidence a shift from urban and industrial development to a more environmentally friendly approach.

The Lishui Municipality extends over 17,298 sqkm and has a population of about 2.7 million people (Lishui Bureau of Statistics, 2020). Due to its marginal status and the difficult orography of the area, it is one of the poorest in the Zhejiang Province: It has the lowest per-capita GDP, less than half of that of the more developed areas, and the lowest annual per-capita income, an average of 30,000 CNY (Yue *et al.*, 2014). Furthermore, access to education and healthcare is poor, and the migration rate toward the Coastal Regions is the highest in the province (Zhejiang Province Bureau of Statistics, 2022). To address these issues, the local government has promoted many initiatives to develop this area over the past 30 years. These schemes have centered on Liandu District: A mountainous territory that extends over 150,000 hectares, with 417,200 inhabitants, of whom 180,000 live in Lishui city (Lishui Bureau of Statistics, 2020).

In 1993, the provincial government of Zhejiang instituted the Lishui Economic Technology Development Zone (Lishui ETDZ), and in 2002, work began on the Lishui Shuige Industrial Park: a 14,534-hectare development located 4 km southwest of Lishui city. Since the initial 2-year phase of construction, the site has been under the supervision of the NDRC, which has funded its realization. Thereafter, in 2007, Lishui Municipality promoted Nancheng District: The eastward expansion of the above industrial park with the addition of a new town for 170,000 inhabitants. To turn this project into a reality, a hilly territory of 3528 hectares was leveled and equipped with roads parceling out plots of 500 × 500 m. Within this development, 30% of the area was designated for industry, 25% for environmental facilities and public spaces, and the remainder for residential use (Administration of Lishui ETDZ, 2011). Work began in the following year, and Nancheng District was included in the *Urban Masterplan of Lishui City* (*2013 – 2030*). In

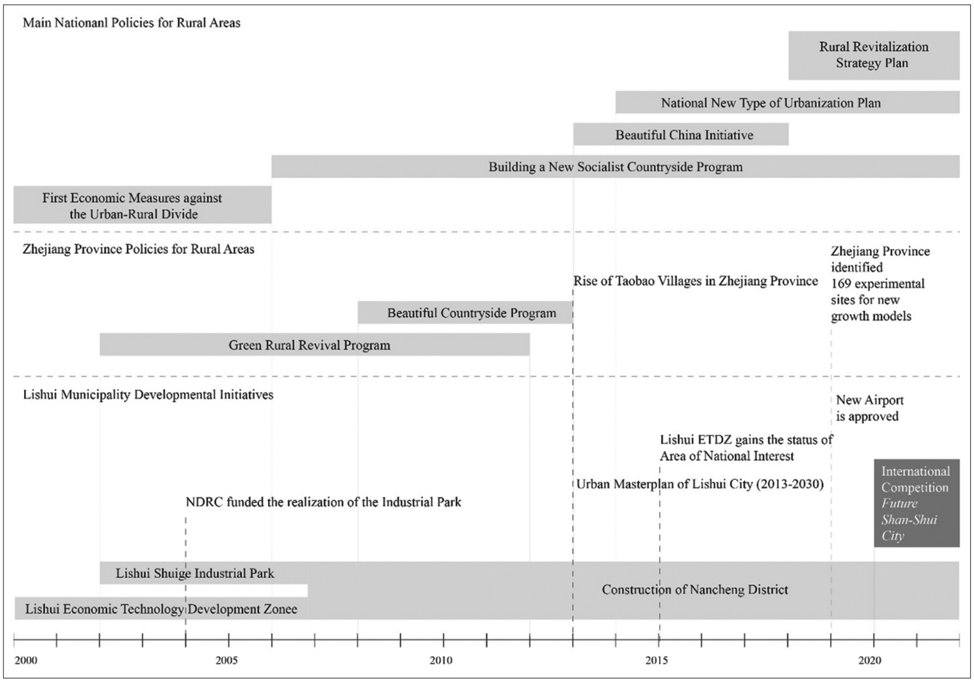

Figure 1. Timeline showing the main national and provincial policies for rural areas, and the initiatives undertaken by Lishui Municipality. Source: Illustration by the author; reprinted (adapted) with permission from Leonardo Ramondetti; Copyright © 2023 Leonardo Ramondetti

parallel, the local administration established the Liandu-Yiwu Shanghai Cooperation Industrial Park, a low-carbon district on two sites. The first site covers 250 hectares close to Bihu Town, 18 km southwest of Lishui city. Since 2008, this development has been gradually equipped with infrastructures, and inhabited. The second site covers 250 hectares along the mountainous western edge of the valley plain, 17 km southwest of Lishui city. Between 2013 and 2015, it was leveled and divided into plots. Thanks to this set of initiatives, the State Council raised Lishui ETDZ to the status of "area of national interest," and in 2019, approval was given for the construction of an airport to the south of the new district (Government of Zhejiang Province, 2019). Today, most mobility infrastructures have been completed; about half of the area for industrial use has been leased, while housing, services, and parks are under construction. As a result, Lishui ETDZ has 40,000 inhabitants, and 1100 companies and accounts for 20% of the GDP of Liandu District (Lishui Bureau of Statistics, 2020).

However, this development model, centered on heavy industry and urbanization, has impacted the environment (Wang & Lu, 2011), and failed to stem migration and depopulation in rural mountainous areas (Shen & Li, 1996; Zhang & Song, 2003). At the same time, many doubts have been voiced regarding the ability of minor municipalities like Lishui to effectively fulfill their ambitious plans for urban growth (Shepard, 2015; Wu, 2015). In this regard, national and provincial administrations are now pressing for alternative developmental strategies to boost the primary sector. This is especially relevant for the municipality of Lishui, where agriculture represents 7% of its GDP and employs 475,000 people (one in five residents), with revenues that have more than tripled to 15.5 billion CNY over the past two decades. Here, land reclamation has been at the heart of this new strategy. In Liandu District, which accounts for 20% of the agricultural production of Lishui Municipality, the agricultural land area has more than doubled, with an increase of 5700 hectares (Li *et al.*, 2016; Lishui Bureau of Statistics, 2020).

Furthermore, new policies to develop environmental and cultural resources and to promote tourism have been enacted (Government of Zhejiang Province, 2018; Zhejiang Provincial Department of Culture and Tourism, 2018). In January 2020, the Zhejiang Province identified 169 experimental sites for new growth models (Government of Zhejiang Province, 2020). Among these, two strategic areas have been designated in Liandu District: Bihu Town, as an experimental site for urban-rural integration; and Dagangtou Town, as a place of great cultural and tourism value.

4. *Future Shan-Shui City*: Three projects

In line with the change in Lishui urbanization strategy, the municipality launched the international competition

Future Shan-Shui City in May 2020.[1] The competition took place in two phases. The first phase attracted 93 applications from individual firms or groups of experts, design institutes, and universities. Each participant was required to submit a portfolio and a preliminary draft of the strategy for the overall site. Based on these documents, ten contestants were shortlisted for the second phase.[2] They were asked to develop a territorial project for the overall area, in-depth urban plans for five different sites, and an architectural prototype for each (Lishui Municipal People's Government, 2019). The competition set four main objectives: (i) the development of new typologies of settlement to curb land consumption and repopulate the mountainous areas; (ii) the promotion of new economic activities based on agriculture, tourism, and well-being; (iii) the re-organization of services and facilities throughout the site; and (iv) the preservation and enhancement of the local landscape. Within this brief, the theme of *shan-shui*, that is, the landscape in its pictorial and contemplative meaning, underscores the focus on the environment, while the adjective *future* encourages experimental and innovative approaches.

The site for the planning activities is a 152 sqkm area centered on a valley 20 km southwest of Lishui. The main industry on the valley floor is agriculture with 5000 hectares of farmland (Figure 2). This is surrounded by mountains featuring forests, small waterways, and terraces for rice cultivation (Figure 3). This environment is prone to hydrogeological events, such as flooding and landslides, during the rainy season from April to June (Liu *et al.*, 2020b). The Ou River flows from the southwest to the northeast of this valley (Figure 4). The riverbed ranges from 120 to 350 m in width, but in places, it is more than 1 km wide. Apart from the new developments close to Bihu and Dagangtou Towns, most of the settlements are agricultural villages with a population from 500 to 2000 people. The typical dwellings are two- or three-story, single-family houses, in concrete and brick (Figure 5). This site has a total population of about 85,000 people; more than 85% of residents are classified as rural citizens (*hukou*) (Lishui Bureau of Statistics, 2020).

Within this area, four sites were assigned to all the participants to develop site-specific projects, plus a fifth one specific to each competitor (Figure 6). These sites varied from mountainous terrains with traditional villages,

Figure 2. Cultivations in Lishui Valley, 2021. Source: Photo by Raul Ariano; reprinted (adapted) with permission from Raul Ariano; Copyright © 2021 Raul Ariano

Figure 3. Lishui mountains and the agricultural villages, 2021. Source: Photo by Raul Ariano; reprinted (adapted) with permission from Raul Ariano; Copyright © 2021 Raul Ariano

[1] The competition was organized by the Lishui Municipal People's Government with Lishui Municipal Development and Reform Commission, and Dwellings in Lishui Mountains Project Planning and Construction Leading Group Office; and the planning executive was the Shanghai One-Tenth Art Space Co., Ltd. The jury was composed by Jiaming Cao (Architectural Society of China), Kai Cui (Chinese Academy of Engineering), Yansong Ma (MAD Architects), Weidong Ma (Architecture and Urbanism), Nishizawa Ryue (SANAA Architects), Alan J. Plattus (Center for Urban Design Research), Zhiqiang Wu (Chinese Academy of Engineering and Tongji University), Shiling Zheng (Chinese Academy of Science and French Academy of Architecture and Science), and Jian Zhuo (Shanghai Tongji Urban Planning and Design Institute and Urban Planning Society of China).

[2] The ten finalist are: Boeri Architecture Design Consulting + Tongji Architectural Design + WWSZ; UNStudio + Gross Max + Systematica; SCUT + Politecnico di Torino; Eco Systems Design Studio + Cai Yongjie; Canada GA City Planning and Landscape Design + Zhejiang Province Institute of Architectural Design and Research + ZIAD; CAUPD, Architectural Design and Research Institute of Tsinghua University; Olivier Greder Architects; China Architecture Design and Research Group; DE-SO Asia Design Consultant Joint Stock Company + DDON Planning and Design.

Figure 4. The Ou River, 2021. Source: Photo by Raul Ariano; reprinted (adapted) with permission from Raul Ariano; Copyright © 2021 Raul Ariano

Figure 5. Traditional houses in Lishui Valley, 2021. Source: Photo by Raul Ariano; reprinted (adapted) with permission from Raul Ariano; Copyright © 2021 Raul Ariano

to agrarian landscapes and natural reserves along the Ou River. Such a heterogeneity offers a unique opportunity to develop an overall strategy incorporating the themes of the competition, but sensitive to the specificity of each area. This was achieved by the top three entries in the competition: *Future Super Shan-Shui Park* by the CAUPD, *A Symbiotic Urban Change* by Olivier Greder Architects, and *Prosperous Lishui* by SCUT and Politecnico di Torino. As summarized in Table 1, these projects adopt different approaches and prioritize diverse features. The result is a collection of different visions for the *Future Shan-Shui City*, which interpret Chinese rural areas in radically different ways. These schemes are discussed in greater detail in the next sub-paragraphs.

4.1. *Future Super Shan-Shui Park* by the CAUPD

The project *Future Super Shan-Shui Park* by the CAUPD (China) focuses on the environmental features of the

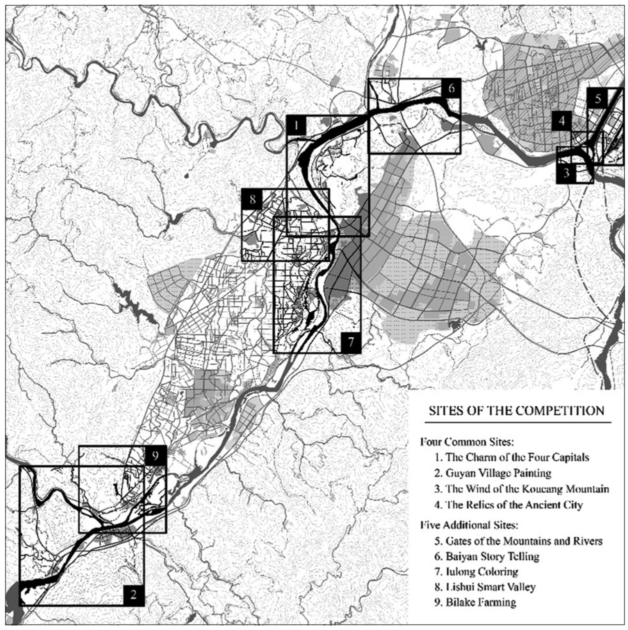

Figure 6. Map of the sites for the competitors. Source: Map by the author; reprinted (adapted) with permission from Leonardo Ramondetti; Copyright © 2023 Leonardo Ramondetti

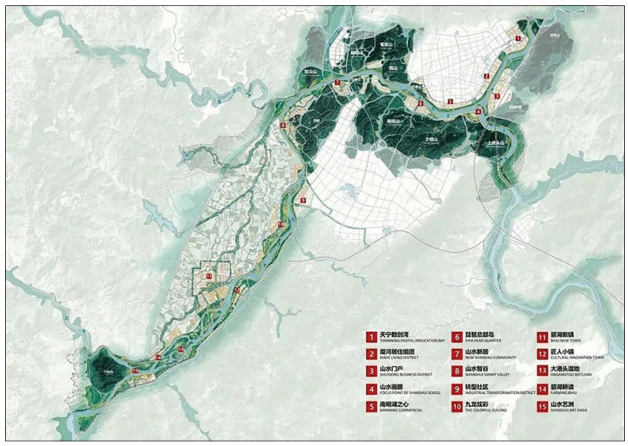

Figure 7. *Future Super Shan-Shui Park* overall plan. Source: One Tenth Culture & Art Company; reprinted (adapted) with permission from One Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Company

local ecosystem to promote a new type of urbanization in harmony with nature. The plan allocates 63% of the area to ecological preservation, 17% to agriculture, and 14% to new urban developments while the remaining 6% is existing villages. The overall strategy is based on three points: the improvement of the environment, particularly the water system, its flora and fauna; the development of a new urban system along the Ou River; and the promotion of a new economy based on cultural activities and innovative industries (Figure 7).

The plan fosters the renaturing, preservation, and enhancement of the local environment. Within this framework, the areas along the river are designated as protected zones, which form a single nature reserve for animals and native vegetation, with a small number of pavilions for responsible interaction between people and nature. These wetlands are also helpful in water management, reducing the risk of floods while phytodepurating the water (Figure 8). In parallel with the renaturing process, the agricultural villages in these zones are to be renovated to harmonize with the surrounding countryside. Finally, the sites for new facilities and businesses also feature rain gardens to blend the new developments into their natural surroundings, and to promote a healthy environment for the new inhabitants.

Indeed, within this new landscape, the main urban layout is a linear system that runs along the Ou River from Lishui to Dagangtou Town, which is composed of eight “shan-shui units” interspersed with wooded mountains

Table 1. Key strategies adopted by the three awarded projects in the *Future Shan-Shui City* competition

Project	Author	Approach	Design strategies
Future Super Shan-Shui Park	CAUPD	Environmental approach	• Preservation and valorization of the riverfront with attention to the environment • Urbanization harmonized with the mountainous scenery • Cultural activities, high-tech industries, and research as core businesses
A Symbiotic Urban Change	Olivier Greder Architects	Morphological approach	• Incremental addition to the existing villages to create a mixed-use development • Preservation of the traditional lifestyle • Tourism and recreational activities as core businesses for the area
Prosperous Lishui	SCUT Politecnico di Torino	Landscape approach	• Modernization of the agricultural system • Preservation of the scenic spots • High-tech agriculture and cultural activities as core businesses for the area

CAUPD: China Academy of Urban Planning and Design; SCUT: South China University of Technology

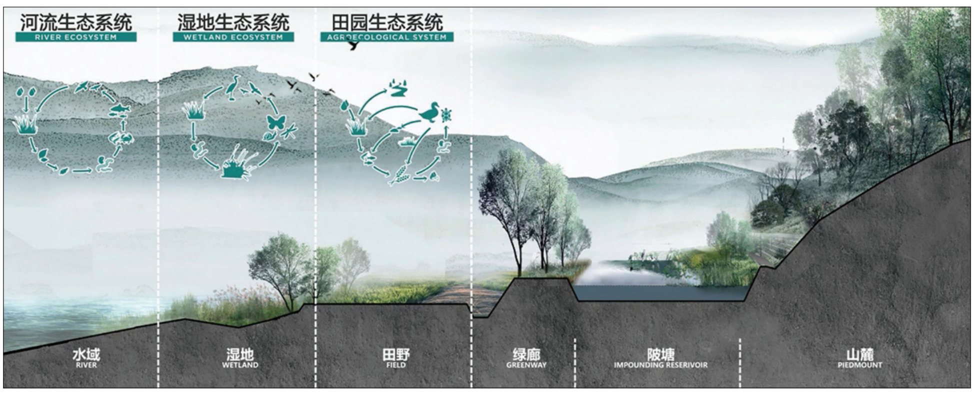

Figure 8. The new ecosystem along the Ou River. Source: One Tenth Culture & Art Company; reprinted (adapted) with permission from One Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Company

Figure 9. View of the “shan-shui units.” Source: One Tenth Culture & Art Company; reprinted (adapted) with permission from One Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Company

and agricultural fields. This urban structure takes greater account of the visual impact of the built-up areas on the landscape. Hence, a continuum is created along the river between construction and nature thanks to the pace and density of the shan-shui units, each limited to a 1 km river frontage (Figure 9). Similarly, the height of the buildings is in proportion to the altitude of the mountains in the background. These shan-shui units differ from real estate compounds, in that they are low-density housing developments themed on their settings: living inside the gardens, living inside the fields, living inside the valley, and living near the river.

Finally, the proposal envisages a new economy for the area based on three sectors: tourism, high-tech, and R&D (Figure 10). *The Wind of the Koucang Mountain*, *The Relics of the Historic City,* and *the Guyan Village Painting* are scenic spots for leisure and cultural activities. Conversely, the *Gates of the Mountains and Rivers* and the *Baiyan Story Telling*, the newly urbanized areas close to Lishui city, are for digital industries, high-tech services, and business. Finally, the new shan-shui units located in proximity to the agricultural plain in *The Charm of the Four Capitals* and *Bilake Farming* are for research centers and educational facilities. This mix of spaces and functions promotes a landscape rich in aesthetics, where traditional architecture meets new trends, and the rural and the urban combine harmoniously.

4.2. *A Symbiotic Urban Change* by Olivier Greder Architects

The project *A Symbiotic Urban Change* by Olivier Greder Architects (China) aims at reconnecting humankind and nature in a unique interdependent environment, where both coexist harmoniously. With respect to the other proposals, this one focuses on the development of multiple settlements promoting various ways of inhabiting the valley. According to the specificities of each site, these new built-up areas define relations with the environment based on their diverse morphologies (Figure 11).

Figure 10. New economic activity within the Lishui Valley. Source: Courtesy of One-Tenth Culture & Art Company; reprinted (adapted) with permission from One-Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Compan

Figure 11. The different living experiences along the Lishui Valley. Source: One Tenth Culture & Art Company; reprinted (adapted) with permission from One Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Company

Figure 12. View of Bihu Town as "15-min city." Source: One Tenth Culture & Art Company; reprinted (adapted) with permission from One Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Company

Figure 13. New settlements along the Ou River. Source: One Tenth Culture & Art Company; reprinted (adapted) with permission from One Tenth Culture & Art Company; Copyright © 2020 One Tenth Culture & Art Company

In Bihu Town, the project plans to reclaim 2 sqkm of industrial land for agriculture and to adapt the road grid for new housing for rural villagers. These new developments form a membrane of high-density courtyard buildings, with recreational and business activities on the first floor. The resulting open spaces do not have strictly defined functions but can be used and adapted freely by the inhabitants for drying crops, temporary markets, and recreational activities. In this way, the new housing provides an experience of urbanity while preventing a complete detachment from farmers' traditional habits. Furthermore, thanks to the wide variety of functions and the new system of connections, Bihu Town is laid out as a "15-min city," that is, a new mixed-use settlement where inhabitant may access all the major facilities in less than a 15-min walk (Figure 12).

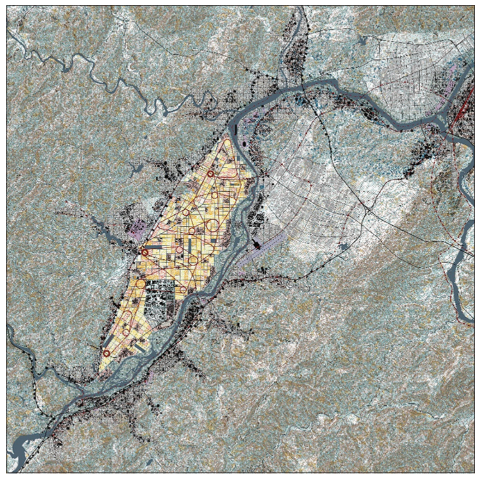

Figure 14. *Prosperous Lishui* overall plan. Source: Courtesy of SCUT and Politecnico di Torino; reprinted (adapted) with permission from SCUT and Politecnico di Torino; Copyright © 2020 SCUT and Politecnico di Torino

Figure 15. *Prosperous Lishui* overall view. Source: Courtesy of SCUT and Politecnico di Torino; reprinted (adapted) with permission from SCUT and Politecnico di Torino; Copyright © 2020 SCUT and Politecnico di Torino

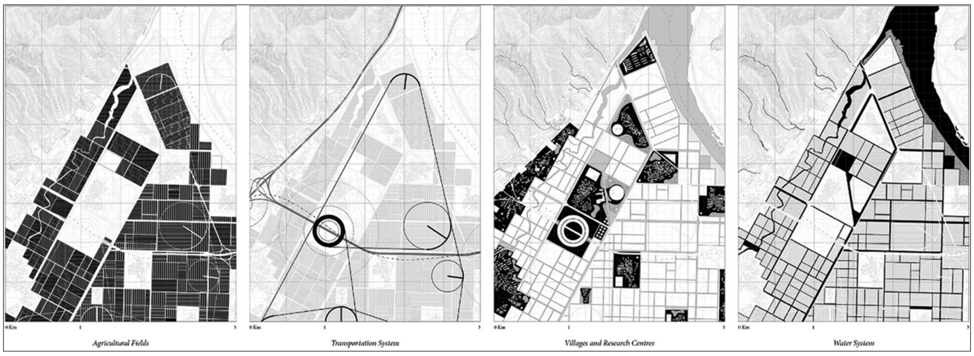

Figure 16. Plan of *Lishui Smart Valley*. Source: Courtesy of SCUT and Politecnico di Torino; reprinted (adapted) with permission from SCUT and Politecnico di Torino; Copyright © 2020 SCUT and Politecnico di Torino

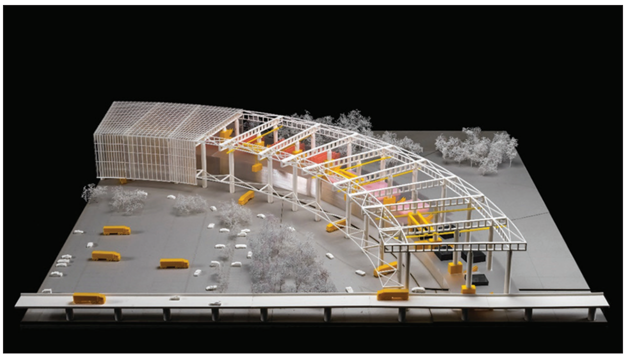

Figure 17. Model of the logistics hub. Source: Courtesy of SCUT and Politecnico di Torino; reprinted (adapted) with permission from SCUT and Politecnico di Torino; Copyright © 2020 SCUT and Politecnico di Torino

In *Baiyan Story Telling*, the project envisages the preservation of seven existing villages, so the high-rise compound under construction to relocate the villagers will instead be turned into a mixed-use neighborhood, with housing, offices, retail market, and vertical farms. This new form of composite development, rich in functions and uses, is then to be expanded to the whole area. Here, small mixed-use towns are to be built on the summits of each of the three hills facing the river. Siyao Wellness Town is dedicated to sport facilities, health centers, and nursing homes; Qian Wu Recreative Town is home to tourism services, hotels, agritourism, and a panoramic monumental tower; finally, Xiao Bayan Mother Town will be the core of the area, where the main markets, education facilities, and amenities for the inhabitants are located. The three towns are planned for 5500, 4000, and 9500 inhabitants, respectively; however, since these centers are mostly for tourism and recreational uses, the population is expected to double during the peak season and national holidays. Within this strategy, <25 hectares are for construction, while the remainder is reserved for forests and agricultural fields. A similar development is also proposed for the Charm of the Four Capitals, where new mixed-use settlements are planned to accommodate research activities centered on agribusiness and high-tech industries.

Two other types of dwellings are proposed for the *Gates of the Mountains and Rivers* and *Guyan Village Painting*. Since the former is close to Lishui city, the project envisages a high-density settlement with buildings in symbiosis with the river (Figure 13). A system of stilt houses is to be built along the banks of the Haoxi Brook to accommodate the new inhabitants, offering an unconventional way of living with water. Conversely, the *Guyan Village Painting* site is home to traditional wood houses, which establish close relations with the surrounding forests. These houses are to accommodate local and international artists, offering the unique experience of Lishui picturesque scenery.

Finally, two sites are entirely devoted to educational and recreational activities: *The Wind of the Koucang Mountain* and the *Relics of the Historic City*. The first is a 32-hectare site on the southern bank of the Ou River, where the Zhongan Expo-Park Town is proposed. With only 27% of the area for construction, this space is designed to accommodate eight major pavilions to host the most important exhibitions and cultural activities in the metropolitan area. It is surrounded by minor buildings for sport activities and hospitality. This group of buildings has a park at the center, while the riverbank is turned into a wet area to protect the site from flooding. The Zhongan Expo-Park Town is also connected to the *Guyan Village Painting*, which is to become the Gucheng Shan-Shui Recreational Island. This is home to a restored traditional village with small agricultural fields for educational activities.

4.3. *Prosperous Lishui* by SCUT and Politecnico di Torino

Unlike the other proposals, *Prosperous Lishui* by SCUT (China) and Politecnico di Torino (Italy) focus on

Figure 18. Plan of *The Charm of the Four Capitals*. Source: Courtesy of SCUT and Politecnico di Torino; reprinted (adapted) with permission from SCUT and Politecnico di Torino; Copyright © 2020 SCUT and Politecnico di Torino

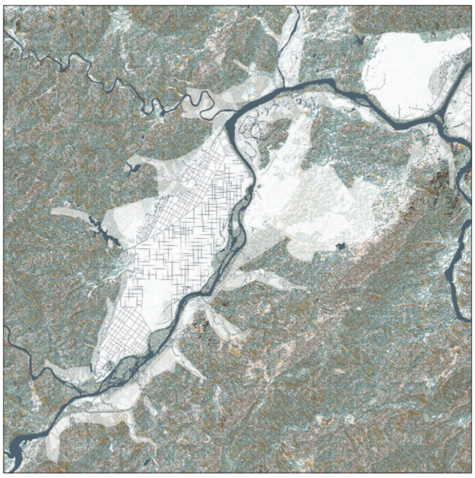

Figure 19. *Prosperous Lishui* environmental system. Source: Courtesy of SCUT and Politecnico di Torino; reprinted (adapted) with permission from SCUT and Politecnico di Torino; Copyright © 2020 SCUT and Politecnico di Torino

agriculture as the core activity, and envisions the agrarian valley south of Lishui as the new green center of the emerging metropolitan development. Hence, the project combines the best features of city and countryside to produce an urbanized agricultural landscape where new settlements and facilities coexist with high-tech farms and traditional villages. In this regard, most of the flatland is reserved for agriculture, while new developments are situated either along the existing mobility infrastructures at the foot of the mountains, or on the slopes (Figures 14 and 15). Based on this layout, the project focuses on three goals: the reorganization of farmland to increase agricultural production, the development of new settlements and housing to populate the mountain slopes, and the preservation of the environment.

The restructuring of the farmland aims to consolidate smallholdings to increase output. At present, fields range from 0.1 to 0.5 hectares in size, and much of the land is rented to large agribusinesses. The project envisages lots from 5 to 12 hectares, for a total 3500 hectares of arable land. While encouraging crop diversity and the preservation of native varieties, this restructuring also promotes the use of new agricultural technology. The plan proposes 180 greenhouses over 860 hectares, 150 vertical farms, and a system of educational facilities, such as schools, research centers, and laboratories. Furthermore, as visible from *Lishui Smart Valley*, an innovative infrastructure for the movement of goods and the production of green energy connects the agricultural fields to three major logistics hubs (Figures 16 and 17).

To save as much flatland as possible for cultivation, the proposal locates the major constructions at the side of the agricultural valley, close to the existing main mobility systems. These are upgraded with a new system of sustainable mobility made up of trains and subway lines to reduce air pollution. Along this new transport system, in sites such as *The Wind of the Koucang Mountain*, new high-density residential areas are planned, together with metropolitan facilities such as stadiums, museums, and large hospitals. The result is an "urban ring" that encircles the plain, and enriches the entire valley with services, recreational areas, and activities. As visible from the urban layout proposed for *The Charm of the Four Capitals*, this urban system also connects the side-valleys, integrating into the metropolitan area small settlements, forests, water basins, and terraces for rice cultivation (Figure 18). This traditional landscape is preserved and enhanced with small, high-quality architectures, to promote cultural activities, and tourism industries.

The side valleys and the mountain slopes are also home to a complex and fragile ecology based on water (Figure 19). In this respect, in areas such as *Guyan Village Painting* and *The Relics of the Historic City*, the project promotes the construction of small dams to optimize water management through the year, and the reinforcement of the existing basins to produce hydroelectric energy. Similar initiatives are proposed for the agricultural plain. Based on the new farmland layout, the number of waterways is reduced, and, while the historical canals are restored, the new ones are enlarged for navigation. Together with this, the proposal entails the construction of new locks, water basins, and fishponds. Finally, the project promotes the consolidation and renaturing of the banks of the Ou River in two ways: where the riverbed narrows, "hard banks" are planned by reinforcing the existing borders; vice versa, "soft banks" are envisioned where the riverbed widens: wetlands to absorb the excessive water of the rainy season, which are also avifaunal oases accessible to visitors thanks to bridges and floodable walkways.

5. Conclusion

This article has examined the greater attention of today's planning activities to the cohesive development of urban and rural areas. Particularly, the priority has shifted from keeping the city expanding to preserving the land for agriculture and protecting the environment. Initially driven by national policies, this shift is now generating a plethora of practical initiatives at a local level. The new urbanization model of Lishui Municipality, including the *Future Shan-Shui City* competition, is just one example of this trend. Since 2020, the One-Tenth Culture & Art Company alone has promoted six other competitions to envision new ways of living rural and marginal areas of Zhejiang Province (One-Tenth Culture & Art Company, 2018). Similar initiatives have sprung up everywhere in China: the Xiong'an Smart City close to Beijing has been targeted as a pilot project for testing new urban-rural relations under the aegis of the national government (Veglianti *et al.*, 2021); in the Central Plains, the construction of numerous agricultural parks and the flourishing e-commerce businesses are raising living standards in rural areas (Ramondetti, 2022); finally, even in arid Lanzhou, new developments are building water-conservation facilities, high-tech greenhouses for cultivation, and transport systems for moving produce (Safina *et al.*, 2023). These many projects show the efforts to envision new economies, and ways of inhabiting the rural and marginal areas of China while moving away from the logic of urban entrepreneurialism (Ramondetti, 2023).

This break from the past is clear in the projects for the *Future Shan-Shui City* competition: they all share a vision of the countryside as a composite landscape to be enriched in ecology, public services, and high-tech production. These projects hybridize new technologies and traditional culture, contemporary dwellings and ancestral settings, urban lifestyle, and environmental comfort. Not only does this urbanization differ from the previous urban-centric models for Lishui expansion but also from the more general trends in urbanization that characterized China over the last few decades: they are as far from the expressive urban planning of the 2000s (e.g., the nine new towns around Shanghai), as from the eco-development of the 2010s (e.g., Zhengbian New District in Zhengzhou, Henan; and Sino-German Ecopark in Tsingtao, Shandong). By eschewing the morphological approach that characterized the urban design of that first period, and the vague configurations of the projects of the last decade, these new proposals provide a clear urban organization through forms and quantity, while preserving a certain degree of flexibility. Furthermore, by adopting diverse approaches, they highlight several issues that contemporary planning must address, thus opening to a reflection on themes that transcend the Chinese context.

The projects presented in this paper are exemplary. In overcoming the traditional distinction between urban and rural spaces, *Future Super Shan-Shui Park* by the CAUPD engages with the environment as the primary resource of the new city. This approach recalls the recent debate in design theory on the need to abandon a human-centric vision to take care of all life forms equally (see Rawes, 2013). Conversely, by focusing on the inhabitants' well-being, *A Symbiotic Urban Change* by Olivier Greder Architects proposes mixed-use morphologies to reconnect the urban fabric to the natural landscape. This search for the right measures, densities, and mix of uses is not new to urban planning (see Schenk, 2022). However, in engaging with both new technologies and traditional local characteristics, the project contributes to the current debate on preservation and renovation. Finally, *Prosperous Lishui* by SCUT and Politecnico di Torino, focused on the spaces for labor, envisions a new urban system in the form of a territorial agricultural park where high-tech services and facilities blend into nature reserves and croplands. This strategy addresses the need to increase food production while integrating new specialized landscapes within local ecologies and existing urban realms. The result is a domestication of the so-called "operational landscapes" (Brenner & Katsikis, 2020), which, instead of being mere technical sites for resource extraction, become fully fledged parts of the city.

The engagement with such topics, which transcend the specificity of a single place, makes the visions developed in today's China significant to the wider debate on innovative urban-rural relations. Indeed, the themes raised by this competition, and the strategies to address them, have also been at the core of many international contests and public programs all over the world in recent years.[3] These

3 Consider, for instance, the consultation for Gran Paris in 2007, the Bruxelles-Métropole 2040 in 2010, and the more recent consultation for Grand Genève in 2018.

include the transformation of the countryside brought about by changes in the economy and advances in farming techniques, the preservation of land and environment, and access to high-quality services. With respect to these topics, the projects currently underway in China seem to be at the forefront of urban and architectural experimentation (Petermann, 2020; Ramondetti, 2022; Semprebon, 2022; Wang, 2020). While divergences from the vision of these scenarios could still lead to the same problems which have characterized previous urbanization (Shepard, 2015; Williams, 2017; Bonino *et al.*, 2019), today's development appears radically different: administrations demand high-quality projects, expertise from all over the world is available, and construction techniques and materials have improved enormously. Consequently, urban planners and architects working in China are at the vanguard of this process, and their projects are relevant not solely for their local outcomes but also for their impact on the contemporary culture of urban planning and design.

Acknowledgments

The author would like to thank Angelo Sampieri and Michele Bonino for the opportunity to take part in the competition *Future Shan-Shui City: Dwellings in Lishui Mountains*; and Mauro Berta, Edoardo Bruno, Gong Dong (Vector Architects), and other people involved in the research project *Envisioning Rural Futures: Agricultural Areas and Suburban Developments in Zhejiang, China* (2020 – 2023).

Funding

This research benefited from the support of the Co-Run Dual Master's Degree program in Urban Design at SCUT and Politecnico di Torino, and the research project *Rescaling the Belt and Road Initiative: Innovation patterns and urbanization processes in urban China* (2020-2023) carried out by Politecnico di Torino and Università di Macerata, and financed by Italian Minister of Research and University.

Conflict of interest

The author declares that he has no competing interests.

Author contributions

This is a single-authored paper.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Ecosystem service value evaluation method for local-oriented rural water ecological governance: A case study on Shuiku Village in Shanghai

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(This article belongs to the *Special Issue: Reshaping Rural China*)

Abstract

Ecosystem service assessments play a crucial role in highlighting the importance of ecosystems in human life and guiding regional planning processes. This study examines the significance of rural ecosystems and their diverse ecological services, ranging from agricultural productivity to water purification and esthetic value. At present, the ecological restoration of rural riparian zones in China mainly relies on engineering standards as reference guidelines, lacking responses to surrounding land use patterns (including diverse ecological functional requirements) at the planning and design level. This paper proposes 17 assessment indicators for ecosystem services based on a case analysis of Shuiku Village in Shanghai. Through the evaluation of the supply-demand relationship of ecosystem services in the water network rural riparian zone, the paper suggests feasible restoration approaches based on a comprehensive evaluation of the ecological status to address the diverse needs of rural water ecosystems. The result indicated that using an ecosystem services evaluation framework can provide more precise analysis at a small scale.

Keywords: Rural landscape; Water; Ecological restoration

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Citation: Dong, N., Fabris, L. M. F., Wang, Y., & Chen, X. (2023). Ecosystem service value evaluation method for local-oriented rural water ecological governance: A case study on Shuiku Village in Shanghai. *Journal of Chinese Architecture and Urbanism*, 5(3):1055. https://doi.org/10.36922/jcau.1055

Received: June 7, 2023

Accepted: August 2, 2023

Published Online: August 22, 2023

1. Introduction

Ecosystem service evaluation is used to highlight the significance of ecosystems in human life, allowing people to demonstrate their importance to society. Regional planners consider these assessments valuable tools in their planning processes. Various assessment methods, including biophysical, social, and economic approaches (Ervin *et al.*, 2014), can be employed, which form the foundation for mapping ecosystem services, enabling their incorporation into decision-making processes related to spatial planning, nature conservation, land management, and utilization of natural resources. The rural ecosystem holds a distinctive significance as an integral part of the overall ecosystem. It offers a wide array of essential ecological services to both urban and rural residents. These services encompass the provision of agricultural products, conservation of biodiversity, facilitation of nutrient cycling, regulation of climate and gas levels, safeguarding and purification of water sources, and control of pollutants, as well as esthetic value and recreational opportunities (Ge *et al.*, 2023). In addition, water is the foundation of ecosystem services and a fundamental factor affecting ecosystem evolution (Martin-Ortega, *et al.*, 2015). However, rural areas are vulnerable to the impact of climate change and other environmental threats, for example, declining soil and water quality, and decreasing biodiversity (European Environment Agency, 2020). According to the research, one of the main threats in rural areas is industrial livestock production, which leads to severe water pollution (Kupiec *et al.*, 2022). A study investigated the chemical properties of Orla River in Poland and found a positive correlation between livestock building areas and chemical parameters in the river (Kupiec *et al.*, 2022). A study conducted in Córrego da Olaria Basin in Brazil similarly indicated that the water quality of the river was correlated with land use (Simedo *et al.*, 2018). Therefore, it is important to pay attention to the fragile river ecosystem and to provide local-based ecological restoration approaches. In recent years, several studies have employed the ecosystem services approach to assess restoration in riparian areas (Castellano *et al.*, 2022). Furthermore, a pilot study on Shanghai's Baoshan District specifically analyzed the provision of ES in the area. The findings indicated that the implementation of an ecological network plan led to an overall increase in the supply of ecosystem services (Zepp *et al.*, 2021).

Domestic research on rural characteristics in China primarily focuses on the evaluation and development of rurality, utilizing both social and managerial perspectives (Cui *et al.*, 2021). The rural revitalization effort that began in the 1980s, is still the largest-scale endeavor to promote rural governance and restore rural socio-economic vitality. An important task in these efforts is the governance of the ecological environment. While efforts have been made to enhance rural infrastructure and strive toward the goal of creating a beautiful countryside, the ecological protection of rural areas has often been overlooked in the implementation process. In the southern part of China, the water environment in rural areas is currently facing several problems. The increasing population and economic activities have resulted in water pollution, habitat loss, and deterioration of water quality. Industrial discharges, agricultural runoff, and inadequate sewage treatment systems have contributed to high levels of pollutants in the water, affecting both aquatic ecosystems and public health (Qian, 2022). More than 80% of underground water is unsafe for drinking or bathing in China (Buckley & Paio, 2016). In addition, excessive extraction of water resources and improper water management practices has led to water scarcity issues, particularly during the dry seasons. Eutrophication and algae bloom are the main problems facing the rivers in rural areas (Qian, 2022). At present, the existing approach used to ecologically restore water network in the rural riverbank areas in China mainly relies on a single water body or land cover type, as the basis. In the process from planning to design, there is less emphasis on the relationship between the riverbank boundary and the adjacent land uses, making it difficult to carry out tailored ecological restoration work based on the diverse needs of different land uses (Fu & Liu, 2019).

By presenting a case study, this paper proposes relevant assessment indicators for ecosystem services through the evaluation of the land use types and the supply-demand relationship of ES. A holistic and detailed understanding of the restoration needs can be obtained through a comprehensive evaluation of the ecological status and functions of rural water ecosystems.

2. Data and methods

The river network in Shanghai is well-developed and performs various functions, with different types of rivers providing different ecosystem services. This study focuses on Shanghai city in the Jiangnan region of China, where the water environment holds immense significance for the rural landscapes. The ecological service capacity of rural rivers is important, not only for the green infrastructure of the countryside, but also for the ecological space of the metropolitan area. In the rural landscape planning of Shuiku Village in Shanghai, we started with a supply and demand trade-offs model of ecosystem services and provided a reference for decision-making based on the wide extent of participation. Through innovative mapping techniques, we precisely formulated resilient landscape tasks under the goals of water environment improvement, biodiversity enhancement, and sociocultural reconstruction, providing a spatial and temporal interface for an integrated and collaborative ecological restoration workflow.

2.1. Shuiku village

Shuiku Village, located in Caojing Town, Jinshan District, Shanghai, is one of the typical representatives of Shanghai's water villages, as shown in Figure 1. The village was formed by sediment carried by the Yangtze River, which was later reclaimed by hand to create an island-like landscape. The village boasts 39 rivers, covering a total length of 28.91 km, with a water area ratio of about 40%. However, the density of the river network is high, mostly in the form of cutoff hills, which hampers water system circulation and leads to insufficient hydrodynamic power. Until 2019, Shuiku Village's primary industry was agriculture and farming. However, farmland surface source pollution and uncontrolled fish and shrimp farming resulted in water pollution and weak biodiversity as the processed water

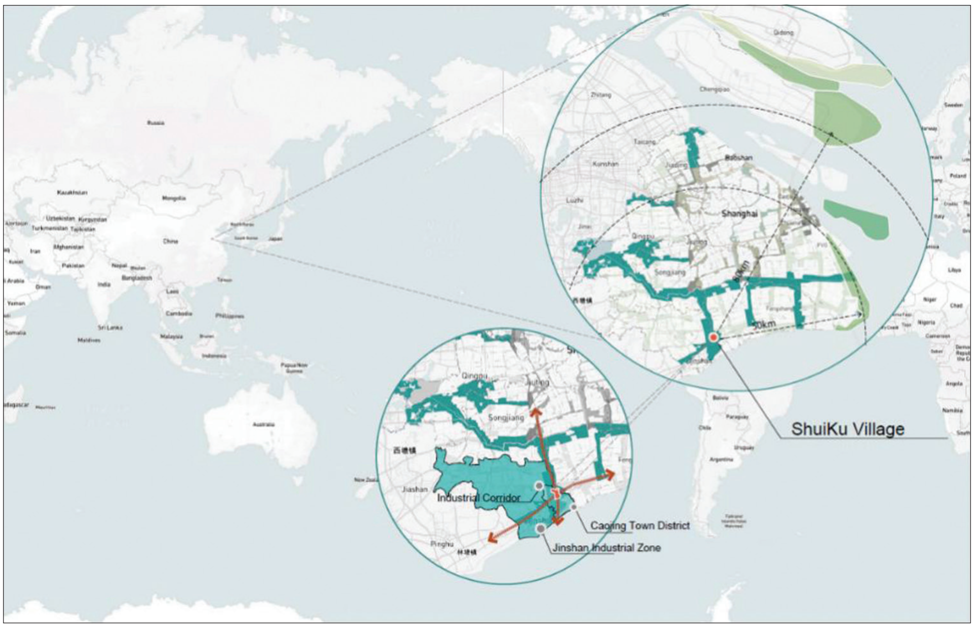

Figure 1. The geolocation of Shuiku Village. Source: Map by the authors

was discharged directly into the river. Based on the survey, the average nitrogen concentration is 1.41 mg/L and the average phosphorus concentration is 0.17 mg/L, which exceeded the water quality standards.

2.2. Evaluation indicators of river channels

The study took Shuiku Village in Shanghai as an example and surveyed 114 sample plots of seven types of riparian zones within the village. Based on the statistical results of the current land use types in rural areas in Shanghai, the study divided the land use types adjacent to rural riparian zones into seven categories (Figure 2): Residential area boundary riparian zone (R1), industrial land boundary riparian zone (R2), agricultural land boundary riparian zone (R3), pond boundary riparian zone (R4), commercial land boundary riparian zone (R5), ecological land boundary riparian zone (R6), and green space boundary riparian zone (R7).

In this study, the spatial composition elements of riparian zones were divided into three parts: vegetation structure, vegetation community hierarchy, and artificial facilities. Based on the results of field investigations, the basic parameter range of spatial characteristics of current rural riparian zones was summarized, providing a local reference for discussing the ecological performance of rural riparian zones in Shanghai (Table 1).

Based on the equivalent factor evaluation method, the study reviewed the literature and summarized the evaluation indicators (Table 2) for assessing the supply and demand of ecosystem services in riparian zones. On the support services level, the focus is primarily on the vegetation diversity of riparian zones in the water network rural areas (Graf *et al.*, 2019), which reflects the richness and stability of habitat provided by the vegetation community. In terms of regulatory services, existing studies have explored the purification and regulation functions of riparian zones in tackling agricultural non-point source pollution. This includes the deposition and purification of surface runoff particulate matter (Zhang *et al.*, 2007; Yu *et al.*, 2021; Zhao *et al.*, 2022) and the purification of water in the soil (Yang *et al.*, 2019; Liang *et al.*, 2022; Wang, 2022). In addition, the regulation of microclimates in riparian zones as a typical scene in rural areas has been investigated (Garner *et al.*, 2015). On the level of cultural services, existing research mainly focuses on the cultural services provided by rural rivers, including discussions on the cultural services of riparian zones in the water network rural areas (Liu *et al.*, 2021). This encompasses showcasing the characteristic features of the water network in rural areas, supporting water-related recreational activities, and exhibiting the historical and cultural significance of rural areas through scientific and educational services (Wang *et al.*, 2021). Table 2 summarizes the spatial indicators for evaluating the eight dimensions of the ecosystem services method above.

To evaluate the supply efficiency of different types of riparian zones, the study adopted the indicator of ecosystem service supply-demand ratio (ESDR) to reflect the degree of supply-demand match. ESDR is used to reflect the balance between the actual supply of ecosystem services in a specific area and human demand, which can be either

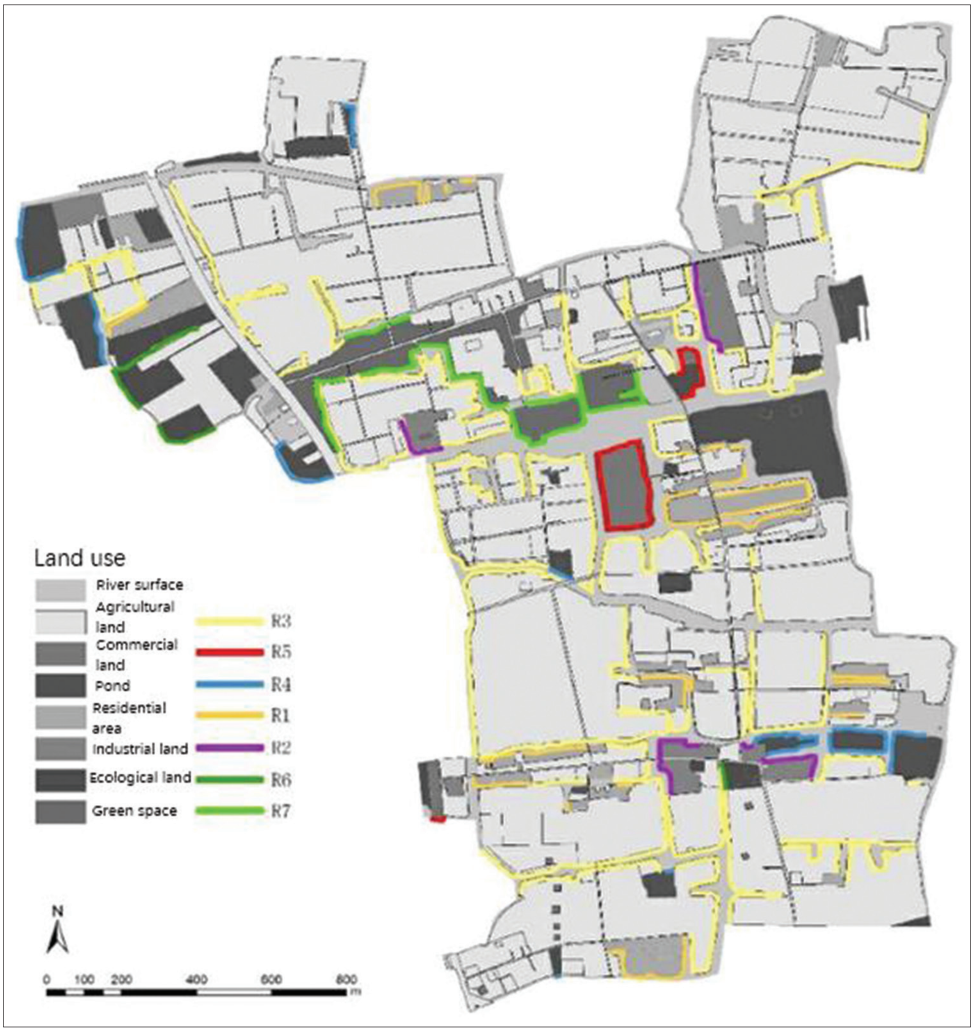

Figure 2. Riparian zone types in reservoir villages based on land use patterns. Source: Drawing by the authors

complete match, surplus, or deficit, and these states are collectively referred to as the matching characteristics of the ecosystem (Bai *et al.*, 2017).

Based on the results of the supply-demand match, a supply-demand match-supply level distribution model was introduced to evaluate the supply efficiency of riparian ecosystem services, by calculating the degree of supply-demand match and the supply level of the riparian zone (Jiang & Liang, 2022). The supply-demand match-supply level distribution model uses the absolute value of the supply-demand ratio |ESDR| as the horizontal coordinate and the supply level of the riparian zone as the vertical coordinate, using the critical values of the degree of supply-demand match and the supply level of the riparian zone to divide the four quadrants (Figure 3). Quadrant I represents the area of efficient supply-demand match, where the supply level of ecosystem services is high and the match degree is high, resulting in high supply efficiency. Quadrant II represents the area of supply surplus, where the supply level of ecosystem services is high, but the supply-demand difference is significant, resulting in supply surplus. Quadrant III represents the area of inefficient supply-demand match, where both the supply and demand levels of ecosystem services are low, resulting in a high degree of supply-demand match but an overall inefficient state. Quadrant IV represents the area of weak supply, where the supply level of ecosystem services is low, but the demand level is high, resulting in a significant supply-demand difference and insufficient supply.

3. Results

According to the evaluation results in Figure 4, the ranking of ecosystem service supply levels in the residential area boundary riverbank zone (LU1) from high to low is as follows: Provision of village landscape value service (5.00)

Table 1. Summary of revetment characteristics in riparian zones adjacent to different types of land use boundaries

Land use type	Revetment type	Characteristics of riparian zone	Typical scenarios
R1 – Residential area boundary riparian zone	Soft revetment	The slope length is 2 – 3 m, with natural slope bank and a gradient of 10° – 45°. The vegetation is dominated by trees and ground cover, with some areas used for vegetable cultivation	 (Shuiku Village)
	Hard revetment	Width is 1 – 2 m; there is a waterfront platform or a stepped entrance to the water forming a dock; there are planting ponds with trees	 (Shuiku Village)
R2 – Industrial land boundary riparian zone	Soft revetment	Slope length of 3 – 5 m; in the form of natural sloping banks with a gradient between 30° and 45°; dominated by a combination of trees and ground cover vegetation	 (Shuiku Village)
R3 – Agricultural land boundary riparian zone	Soft revetment	The slope length ranges from 2 - 4 m, with a regular shape of human-made reinforced slope. The slope degree ranges from 30° - 45°, and the vegetation is mainly ground cover plants with sign of vegetable planting	 (Shuiku Village)
R4 – Pond boundary riparian zone	Soft revetment	Slope length is mainly 2 – 3 m; the slope surface is artificially modified and has a regular form; the vegetation on the revetment surface is relatively scarce, mainly consisting of bare soil or incomplete coverage by ground cover plants	 (Lianhu Village)
R5 – Commercial land boundary riparian zone	Soft revetment	The slope length is 3 – 5 m; the slope surface is regular with a slope of 30° – 45°; the vegetation is dominated by lawns with decorative shrubs planted	 (Shuiku Village)

(Contd...)

Table 1. ***(Continued)***

Land use type	Revetment type	Characteristics of riparian zone	Typical scenarios
	Hard revetment	Width of 2 – 5 m; a waterfront platform or stepped entrance to the water forms a dock; some have planting pools with shrubs or trees	 (Shantang Village)
R6 – Ecological land boundary riparian zone	Soft revetment	The slope length is about 3 – 5 m, and some exceed 5 m. The slope surface is natural with a slope of 30° – 45°, dominated by a combination of trees and ground cover plants	 (Beiguan Village)
R7 – Green space boundary riparian zone	Soft revetment	Slope length ranges from 3 - 5 m, with a natural slope surface and a gradient between 30° and 45°. The vegetation consists mainly of trees and understory plants	 (Shantang Village)

Source: Tabulation by the authors

Table 2. Hierarchical table of ecological service evaluation indicators for water network-type rural riverbanks

Service type level	Service dimension	Primary indicator	Secondary indicator	Value
Crop production	Crop/Agricultural product output (AP)	Nursery economic output (A_i)	Fruit and vegetable output	5
			By-product output	3
			No output	1
Supporting service	Biodiversity enhancement (BD)	Tree species (T_S)	>5 species	5
			3 – 5 species	3
			1 – 3 species	1
		Shrub species (S_S)	>5 species	5
			3 – 5 species	3
			1 – 3 species	1
		Herb species (G_S)	>5 species	5
			3 – 5 species	3
			1 – 3 species	1

(Contd...)

Table 2. ***(Continued)***

Service type level	Service dimension	Primary indicator	Secondary indicator	Value
Regulating service	Runoff regulation (FM)	Revetment slope (R_S)	10° - 30°	5
			30° – 45°	3
			>45°	1
		Revetment width (R_W)	>5 m	5
			2 – 5 m	3
			1 – 2 m	1
		Plant buffer width (P_W)	>5 m	5
			2 – 5 m	3
			1 – 2 m	1
	Microclimate regulation (EM)	Tree coverage (T_C)	≥ree	5
			30%≤T_C<80%	3
			<30%	1
		Plant spatial structure (P_S)	Tree-shrub-grass	5
			Tree-grass	4
			Shrub-grass	3
			Herb	2
			Bare soil	1
	Water purification (WU)	Plant cover width (P_W)	>5 m	5
			2 – 5 m	3
			1 – 2 m	1
		Revetment foundation structure (I_S)	Ecological zone/natural revetment	5
			Stone/pile revetment	3
			Concrete or other rigid revetment	1
		Wet plant width (W_P)	>5 m	5
			2 – 5 m	3
			1 – 2 m	1
Cultural service	Village landscape value (VL)	Shoreline length (R_N)	Natural vegetation revetment	5
			Vegetation planted on hard slope	3
			Hard, vegetation-free revetment	1
		Water visibility (W_V)	All visible	5
			Part visible	3
			invisible	1
	Village recreational value (VR)	Types of recreational activities (A_S)	>5 species	5
			3 – 5 species	3
			1 – 3 species	1
		Distribution of recreational facilities (F_S)	Set up stop platform	5
			Set up walkways	3
			No recreational facilities	1
	Scientific, educational and cultural value (VT)	Historical monuments and reservations (H_R)	Fully save	5
			Partial save	3
			No save	1

Source: Based on ecosystem services classification systems provided by Costanza (2008)

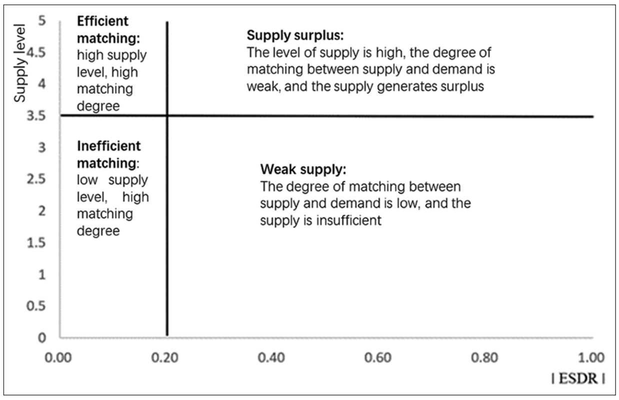

Figure 3. Supply-demand match-supply-level model of ecosystem services in riparian zones. Source: Figure modified by authors based on Jiang & Liang (2022)

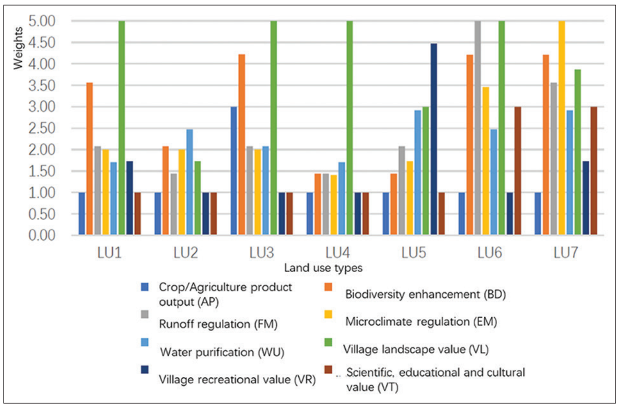

Figure 4. Evaluation results of ecosystem service supply of seven types of riparian zones in reservoir villages. Source: Bar chart by the authors

> vegetation diversity level (3.56) > runoff regulation service (2.08) > microclimate regulation service (2.00) > provision of recreational value service (1.73) > water purification service (1.71) > agricultural product output service (1.00) = provision of scientific, educational, and cultural value service (1.00). Among them, the provision of village landscape value service (VL) shows a strong supply level, while vegetation diversity (BD) is at a moderate level. The supply levels of other services are all below 3.00, indicating a relatively low supply capacity.

As shown in Figure 5, in the demand evaluation results for the residential area boundary riverbank zone (LU1), the demand evaluation for recreational value services (VR) and scientific, educational, and cultural value services (VT) is below 2.50, indicating a lower demand level. The demand for other types of services exceeds 3.00, indicating a moderate to high level of demand for improving village landscape value services among production services, supporting services, regulating services, and cultural services.

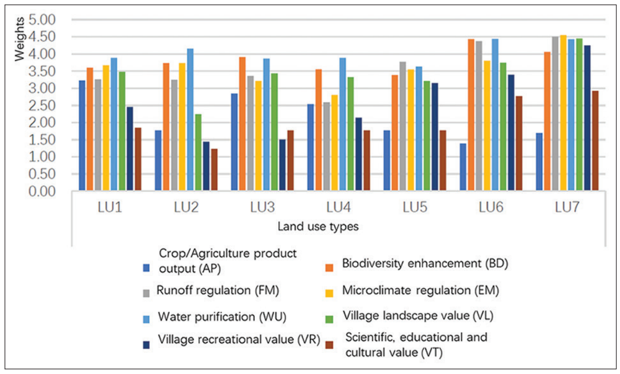

Figure 5. Evaluation results of ecosystem service demand of seven types of riparian zones in reservoir villages. Source: Bar chart by the authors

The results showed that in terms of village landscape value (VL), the seven types of riparian zones exhibited higher supply efficiency. R1–R5 riparian zones showed weak supply in regulating services. In addition, the supply efficiency of the seven types of riparian zones exhibited differentiated results, where the riparian zone at the boundary of residential areas (R1) exhibited weak supply in agricultural product output, the riparian zone at the boundary of industrial land (R2) showed weak supply in biodiversity, the riparian zone at the boundary of agricultural land (R3) showed weak supply in all three types of regulating services, the riparian zone at the boundary of ponds (R4) exhibited weak supply in agricultural product output (AP), biodiversity (BD), runoff regulation service (FM), microclimate regulation service (EM), and water purification service (WU), the riparian zone at the boundary of commercial and service land (R5) exhibited weak supply in biodiversity level (BD), and the riparian zones at the ecological land boundary (R6) and the green space boundary (R7) showed similar supply efficiency evaluation results, with village recreational value services (VR) being in a weak supply state.

The ecologically sensitive areas of the reservoir village, including the ecological land boundary riparian zone (R6) and green land boundary riparian zone (R7), exhibited higher levels of ecosystem service supply in supporting and regulating services than other types of riparian zones. Meanwhile, the ecological land boundary riparian zone (R6), commercial land boundary riparian zone (R5), and green space boundary riparian zone (R7) – three types of riparian zones closely related to human activities – exhibited higher levels of cultural services than other types of riparian zones. These findings confirm a strong correlation between the supply of ecosystem services in rural riparian zones and the land use types in their vicinity. When assessing the ecosystem services of rural riverbanks, local land use types can be taken into account and relevant ecological restoration recommendations can be proposed based on the local land use types.

4. Discussion

Based on field investigations and literature reviews, the study establishes a framework for evaluating the supply and demand of ecosystem services in the riparian zone of water network-type rural areas. The framework includes four major services: Provisioning, regulating, supporting, and cultural services, as well as eight sub-service dimensions: Agricultural production, biodiversity, runoff regulation, microclimate regulation, water purification, rural landscape value, recreational value, and rural cultural services. Other studies have employed the ecosystem services supply and demand in urban planning. For example, in Wuhan (Chen *et al.*, 2019), Zhengzhou (Xue *et al.*, 2022), and New York cities (Herreros-Cantis & McPhearson, 2021), ecosystem service supply and demand were used to assess the urban ecological management and environmental justice. In addition, the analyzed indicators can be utilized to evaluate the water ecosystem functions in various rural landscapes. Water network-type rural riverbank areas serve as transitional spaces that connect rural river ecosystems and terrestrial ecosystems, making them important linear ecological elements. Due to their dense network of water bodies, these areas are narrow and elongated and embedded between different land uses. As a result, they possess complex functions related to production, ecology, and livelihoods. They are closely intertwined with surrounding land patterns and human activities, exhibiting a high degree of heterogeneity. Therefore, they require more refined management approaches.

In this study, we divided the riparian zone types into seven types based on land use types. Land use is the most direct interaction between human activity and natural systems. According to the research, the use of land use data to assess ecosystem service value (ESV) and explore the relationship between land use change and ESV has emerged in the scientific literature over the last decades (Li *et al.*, 2010; Scolozzi *et al.*, 2012; Fu *et al.*, 2016). These studies have collectively demonstrated that analyzing land use data is an effective method for estimating ESV.

The application of ecosystem services supply and demand matching theory and methods is widely prevalent in the field of urban riverbank ecological restoration research, both domestically and internationally. Internationally, the United States have also adopted the ecosystem services approach in urban riverbank restoration projects. In Los Angeles, the Los Angeles River Revitalization Master Plan aims to restore the river's natural hydrological and ecological functions, while also providing recreational and cultural amenities to the local community. By understanding that the ecosystem services is required and valued by the community, restoration efforts are focused on enhancing water quality and flood regulation and providing opportunities for outdoor recreation (Hagekhalil *et al.*, 2014). Therefore, using an ecosystem-services evaluation framework at a small scale allows for more precise analysis, which provides delicate restoration approaches. However, the study has some limitations. Due to the force majeure that restricted field surveys, the empirical research in the study was conducted in October 2022 and January 2023 for the water reservoir village. As a result, the response of vegetation communities in the riparian zone to interannual climate change was insufficient, and the sample data were not comprehensive. There is still a certain gap in the accurate measurement of the actual supply level of ecosystem services in the riparian zone.

5. Conclusion

In this study, we divided the rural riparian zone into research units based on land use types and evaluated the supply-demand characteristics of ecosystem services in the riparian zone using value assessment methods. Thus, it helps gain an understanding of the ecological restoration needs of the riparian zone at the granularity of land use units. In terms of the rural landscape restoration, stakeholder engagement and collaboration with local communities, researchers, and policymakers are crucial for incorporating local knowledge and understanding the socioeconomic factors that impact water ecosystem functions. The vast and diverse water network areas in China far exceed the scope of water network rural areas in Shanghai, serving as the ecological foundation for various rural types. Due to regional differences in socio-economic development, the demand for riparian zones may vary. Future research should include field measurements. Incorporating the site-specific ES evaluation system can increase the comprehensiveness and effectiveness of the evaluation process, which contributes tailored restoration strategies that are better suited for the specific characteristics and goals of each rural area.

Acknowledgments

We would like to express our sincere gratitude to all those who have contributed to the successful completion of this research paper. We would also like to thank the members of our research team for their dedicated efforts and cooperation. Their contributions, either in data collection, analysis, or discussions, have greatly enriched the findings and conclusions of the paper.

Funding

Key Laboratory of Ecology and Energy-saving Study of Dense Habitat, Ministry of Education, in collaboration with Shanghai Tongji Urban Planning and Design institute Co. Ltd, has launched a joint open research project in 2022. The project, titled "Key Technologies for Precise Planning of Rural Ecological Restoration Supported by Digital Tools," is identified as KY-2022-LH-A05.

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Writing – original draft: Xinyue Chen
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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The raw data were jointly owned and subject to shared rights and responsibilities with our collaborating partners. We are unable to provide the raw data to readers. If readers are interested, they can contact us to explore possibilities for research collaboration.

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Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Spatial scale plasticity of urban residential areas: Lessons from Shanghai's model in response to COVID-19

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Abstract

Shanghai's measures to address the COVID-19 pandemic since March 2022 have attracted world-wide attention. The response to public emergency and pandemic in built environment has prompted a profound reflection in residential planning. This case study investigated an under-developed site located in Shanghai's Huangpu River waterfront. Based on a site survey, interviews, the phased lockdown policies of different urban areas, and published data on the spatial distribution of infection cases, this paper analyzes the effectiveness of strategies for coping with different stages of epidemic spread at different spatial scales. In addition to ensuring the privacy of living quarters, our residential planning ensures the flow and social communication of people in different neighborhoods, achieving the resilience of local lockdown and flow. This study redefines the openness and reasonable scale of residential areas based on analysis of the advantages and disadvantages of gated and block residential areas facing pandemic. This paper analyzes the feasibility of a residential site plan based on the above conception, which has spatial scale composable features for the basic residential building groups. This study emphasizes that design should be considered to achieve the flexibility of spatial scale through the different assembling pattern of basic-living-space-unit.

Keywords: Spatial scale plasticity; COVID-19; Residential building groups; Space responding model; Shanghai

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Citation: Yang, F., Wei, Z., & Wang, J. (2023). Spatial scale plasticity of urban residential areas: Lessons from Shanghai's model in response to COVID-19. *Journal of Chinese Architecture and Urbanism*, 5(3):1242.
https://doi.org/10.36922/jcau.1242

Received: July 4, 2023

Accepted: August 4, 2023

Published Online: August 25, 2023

1. Introduction

Pandemics are responsible for the greatest risk of mortality worldwide for most of the human history (Farquhar *et al.*, 2017). The COVID-19 pandemic, which broke out in the early 2020s, caused more than 567 million confirmed cases and 6.3 million deaths by July 2022[1]. Urban built environments tend to be more vulnerable to pandemic due to their high population clustering and mobility. Although the correlation between urban density and infection or fatality rates is inconclusive (Boterman 2020; Hamidi *et al.*, 2020; Sharifi & Khavarian-Garmsir 2020), outbreaks in urban informal settlements or slums, workers' dormitories in Singapore, and prisons in the United States are reminders of the impact of living environment on the transmission of COVID-19 (von Seidlein

[1] https://www.who.int/publications/m/item/weekly-epidemiological-update-on-Covid-19 [Last accessed 2022-07-27].

et al., 2021). Historically, public health events have been an important driver of transformation in urban planning and design. Existing research on non-pharmacological interventions for the COVID-19 pandemic has focused more on urban governance and management models, with less research on spatial responses at the residential quarter scale.

Reforms and opening up along with the commercialization of housing have gradually led to an increased awareness of private property rights among citizens, which has resulted in the prevalence of large gated residential quarters. Existing studies point out that this produces the isolation of urban space, the exclusivity of public service facilities, the pressure of urban traffic, and the separation of social classes (Sharifi & Khavarian-Garmsir, 2020; von Seidlein *et al.*, 2021)[2]. However, developers' pursuits of profit along with strict sunlight and fire regulations make it more reasonable to choose a layout pattern that combines point-type high-rises and row houses, which ultimately leads to the homogenization and monotony of urban space. The Chinese government proposed in 2016 that "no more enclosed residential quarters will be built in principle" in a bid to reverse space monotony. However, the new outbreak of the epidemic in Shanghai in 2022 has shown that with the layout of existing residential quarters, it is difficult to implement the policies to stop the spread of epidemics while respecting the rights of individual residents, and to reconcile the conflicts between the two.

2. Research concepts

In 2015, the United Nations introduced 17 Sustainable Development Goals (SDGs) to guide global development for 2015–2030. However, influenced by the uneven development between regions and the impact of the COVID-19 pandemic, many studies have concluded that the timing and plans for achieving the SDGs need to be reassessed (Achdut & Refaeli, 2020; Barbier & Burgess, 2020; "Time to revise," 2020; Fenner & Cernev, 2021). In the current highly connected and globalized world, pandemic across regions poses a huge risk. Thus, some studies have suggested that pandemic preparedness should be integrated into SDGs (Di Marco *et al.*, 2020). Dos Santos *et al.* (2021) proposed that COVID-19 pandemics should be integrated into SDGs 11 and 3 (11.5, 11.b, 3.d), and that smart city technologies should be used to increase planning resilience. Hamidi *et al.* (2020) proposed the role of community governance and increased communication (SDG 11.3) in pandemic prevention and control. In addition, it is also important to achieve public health goals while minimizing disruptions to daily life through precision management, which also needs to be incorporated into the SDGs (SDG 11.7).

In summary, this research reorders the subgoals of SDG 11 to highlight the sustainable ways with which cities and residential quarters can respond to COVID-19 outbreaks, while also ensuring the achievement of SDGs. The 11 subgoals are divided into three levels according to the degree of relationship of the subgoals with the response to the epidemic, corresponding to the concentric circles displayed in Figure 1. The outermost circle is for the basic objectives that support the functioning of urban communities, such as transportation systems and water management. The middle circle is for the residential goals related to community responses to disasters. The core circle is for the improvement of the planning and management capacity of a city, including the collaboration of management and planning (Figure 1).

Because SDGs are not isolated from each other, the spillover effects for other goals, including trade-offs and synergies, have to be considered when advancing one or more of the goals (Weitz *et al.*, 2018; Valencia *et al.*, 2019). First, the negative impact on personal freedom (SDG 16.10) is the most obvious in Shanghai while non-pharmaceutical interventions, such as social isolation (SDG 3.d), were used to control health risks. Second, the economy was also negatively impacted when the residents were quarantined. Third, in addition to the outbreak itself, secondary disasters arose as a result of the response to the outbreak. This includes mental health issues for those in quarantine, the lack of a timely supply of necessities, the occupation of medical resources, and the disruption of

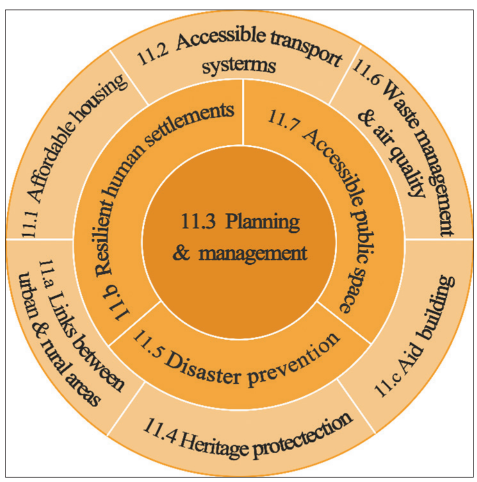


Figure 1. Three levels of COVID-19 responses according to SDG 11. Source: Diagram by the authors

2 http://www.gov.cn/zhengce/2016-02/21/content_5044367.htm [Last accessed 2022-07-27].

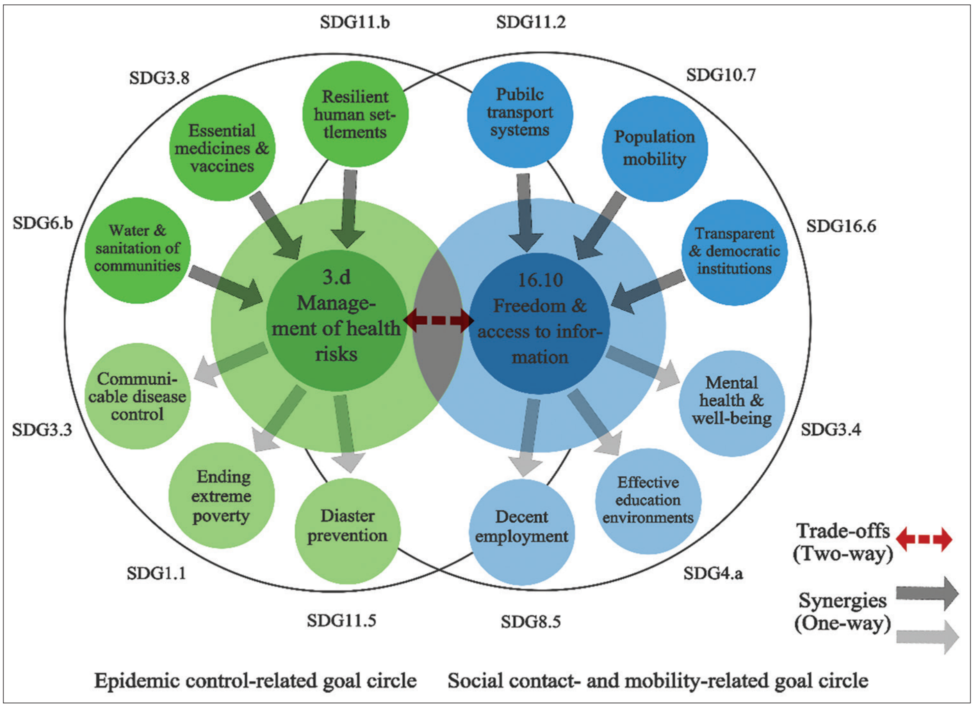


Figure 2. Synergies and trade-offs of COVID-19-related goals. Source: Diagram by the authors

the drug supply chain, leading to a disruption of normal medical treatment.

Therefore, researchers are aware of the issue of synergies and trade-offs between the relevant goals established in response to COVID-19 and the SDGs. Regarding the policy goal related to epidemics, its core goal is the health risk control and the avoidance of mass spread (SDG 3.d). Regarding the policy goal related to increased social contact and population mobility, its core goal is basic freedom and the right to information for residents (SDG 16.10). The two core goals are supported and achieved with different policy strategies in urban and community spaces. In addition, there are conflicts between the two aspects, including policy goals and means of achievement, which are transmitted to the other sub-goals of the two circles (Figure 2).

The study is conducted in four steps. In the fourth step, the model is applied to specific residential planning and design projects in Shanghai (Figure 3).

3. Materials and methods

3.1. Shanghai's main strategy in response to COVID-19

According to official reports, Shanghai experienced a wave of reported case growth in March 2022 and the 1.5 months that followed. Official statistics show that the total cases of new infections in 3 months exceeded 600,000. During the citywide static management, the Shanghai municipal government adopted a three-zone phased lockdown policy. Taking residential quarters as the unit, residents with positive infections within 7 days were asked to self-quarantine in the lockdown zone, where door-to-door service was provided. In the control zone, those without positive infections within 7 days could leave their homes but not their residential quarters. Those without positive infection within 14 days could move within their subdistricts, turning into a precaution zone. According to the data released by the Shanghai Health Commission, after the static management on April 1, there were more than 70,000 residential quarters, natural villages, units, or sites in Shanghai forming tiny "management units" that operated almost independently[3].

3.2. Spatial distribution and residential characteristics

3.2.1. Data acquisition

First, we captured the addresses with cases from March 6 to May 16[4] and counted the number of days with reported cases at each address point. Second, we captured the data for the residential quarters from Gaode Map[5] and classified them into six categories based on the year of completion and the characteristics of texture into workers' new village, commercial housing, apartments, villas, lilong, and garden

[3] https://www.thepaper.cn/newsDetail_forward_18356659 [Last accessed 2022-08-27]

[4] https://zt.changjing.com.cn/map/viewer?mid=d3vYDHfujJIkll_WdQ9Hcw [Last accessed 2022-08-27]

[5] https://www.amap.com/ [Last accessed 2022-06-23]

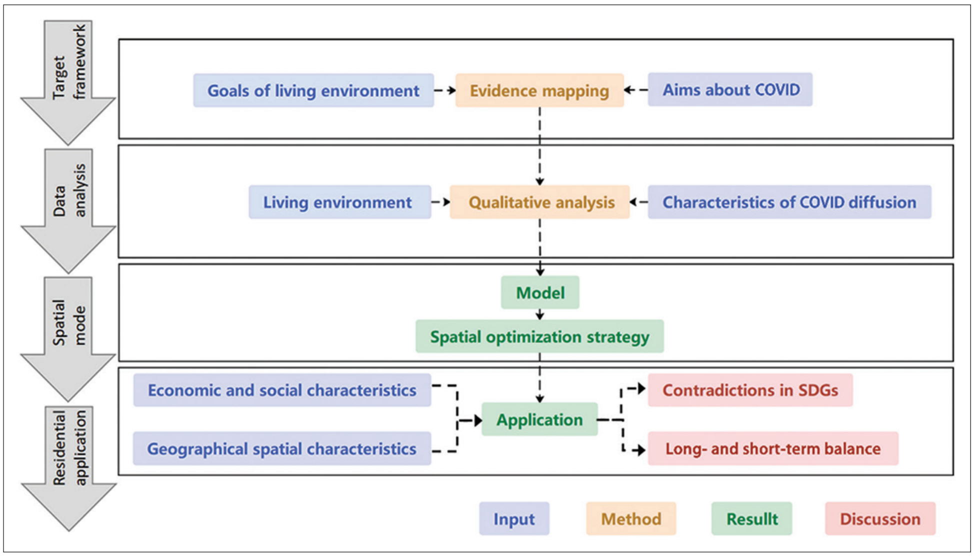
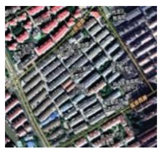
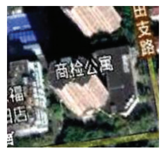
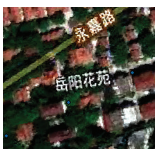
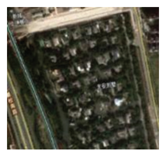


Figure 3. Path of analysis. Source: Diagram by the authors

Table 1. Classification of residential quarters in Shanghai

Image feature	Type	Image feature	Type	Image feature	Type
	1. Commercial housing		2. Workers' village		3. Apartment
	4. Garden Lilong		5. Lilong		6. Villa

lilong (Liao *et al*., 2008), and we calculated the area of each residential quarter. Third, the data for Baidu architecture[6] were used to calculate the average number of building floors and the floor area ratio of each residential quarter. In addition, the population of each residential quarter was counted using the 100-meter raster population of night lighting data[7]. The address points where the cases appeared, and the area of interests (AOI) data are correlated to analyze the characteristics of the residential quarters with reported cases (Table 1).

3.2.2. Statistical characterization

A higher proportion of cases were reported in the lilong, the workers' new village, and the commercial housing areas. In contrast, a lower proportion of cases were reported in the apartments, villas, and garden lilong areas. About 59% of the workers' new village, commercial housing, and lilong show reported cases, while the figures for the villa and apartment are only 37% and 34%, respectively (Figure 4).

The proportion of reported cases is high and densely distributed in the residential areas of the seven districts in the central city of Shanghai, located in Puxi. Based on the geographical distribution of the residential quarters with reported cases, the distribution of the number of days with reported cases in commercial housing and the workers' new village is measured with the Kriging interpolation method (Kuntz & Helbich, 2014) (Figure 5).

The residential quarters with longer duration of consecutive reports of new cases do not generally have a large dimension, high average number of floors, or large volume ratio. The average number of days with new cases is 5.92 days for residential quarters with less than seven floors, 6.44 days for residential quarters with 7–15 floors, and 5.64 days for residential quarters with more than 15 floors.

6 https://map.baidu.com/ [Last accessed 2022-06-23]

7 https://www.udparty.com/index.php/detail/articledetails/?id=4992 [Last accessed 2022-06-23]

From the volume ratio perspective, the average number of days with cases is 5.07 days for residential quarters with more than three floors, 6.38 days for those with 1–3 floors, and 6.33 days for those with only one floor (Figure 6).

3.2.3. Site feature

In this research, a site in Shanghai was selected to explore and experiment with the implications of the epidemic for residential planning. The site is located in the Yangpu District, one of the seven districts in the central city of Puxi, Shanghai, with an area of 18 hectares. Yangpu District has a high population density (ranked fifth among all districts in Shanghai)[8], an elderly population ratio that is ranked sixth among all districts in Shanghai[9], and an average volume ratio of settlements. Yangpu District experienced a large impact from the epidemic in Shanghai, with a reported infection rate of 2.78% (data from the period of 3.1 to 5.23)[10], ranking sixth among the 16 districts in Shanghai.

The site is located in a lilong settlement undergoing demolition and renewal (Figure 7). First, according to the above conclusions, lilong is the type of settlement most affected by the epidemic. Second, the height of buildings in this area is generally <7 floors. According to the above study, the affected degree of such residential areas is higher than that of those with more than 15 floors. In addition, the site and the surrounding area have a large foreign and elderly population, and there is a severe lack of public activity space and green space for residents. These also exacerbate the risk of epidemic infection. Thus, this is meaningful for exploring planning and designing strategies that integrate epidemic prevention and control objectives with SDG 11.

4. Results

4.1. Space elements and socioeconomic goals

4.1.1. Privacy

Conventionally, Chinese courtyards, tulou dwellings that could resist foreign attacks, and gated communities all reflect the importance that Chinese people attach to the privacy of their living environment. In the context of epidemic prevention and control, the connotation of privacy has the additional meaning of restricting the flow and cutting off the spread of the virus with the aim of preventing the intrusion of outsiders and protecting privacy.

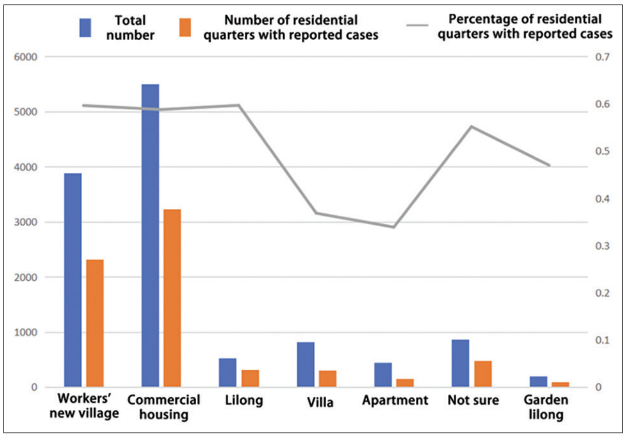


Figure 4. Relationship between different types of residential quarters and infected cases. Source: Bar chart by the authors

The epidemic poses a challenge to the privacy of Shanghai's residential areas. First, most gated residential quarters in Shanghai are managed independently by building a continuous wall around the edge of the site to achieve a complete spatial scope. In the prevention and control of the epidemic in some areas of Shanghai, corrugated metal plates to lock off the entrances to the units of residential buildings seemed to have been used[11,12], posing security risks. While protecting the privacy of residents, it is difficult to conduct meticulous management due to the large spatial scale. Second, for open residential blocks (including some mixed commercial and residential neighborhoods and campuses), the entrances and exits are directly connected with urban public space, and there is a lack of transition space between urban public space and residential private space. The management of the closure control of settlements affects the openness and mobility of urban space. Because the flows of people and vehicles are not separated, it is difficult to determine the scope of the closed space, and the difficulty of management is increased when it is necessary to conduct closure management in case of public health emergencies. In such residential quarters, it can be seen that there are many cases of using clutter to close off roads and entrances, which are too rigid and tend to aggravate people's anxieties.

We propose an optimized design concept. The new spatial model needs to break the fully closed form of a traditional commercial housing district and should avoid being completely open, which can follow the basic principle of "open over a large range, quarantine on a block of flats." First, the settlement boundary is opened

8 https://tjj.sh.gov.cn/tjnj/nj21.htm?d1=2021tjnj/C0206.htm [Last accessed 2022-8-27]

9 https://tjj.sh.gov.cn/tjnj/nj21.htm?d1=2021tjnj/C0202.htm [Last accessed 2022-8-27]

10 https://voice.baidu.com/act/newpneumonia/newpneumonia/?from=osari_aladin_banner [Last accessed 2022-06-23]

11 https://www.sohu.com/a/540817473_660811 [Last accessed 2022-07-10]

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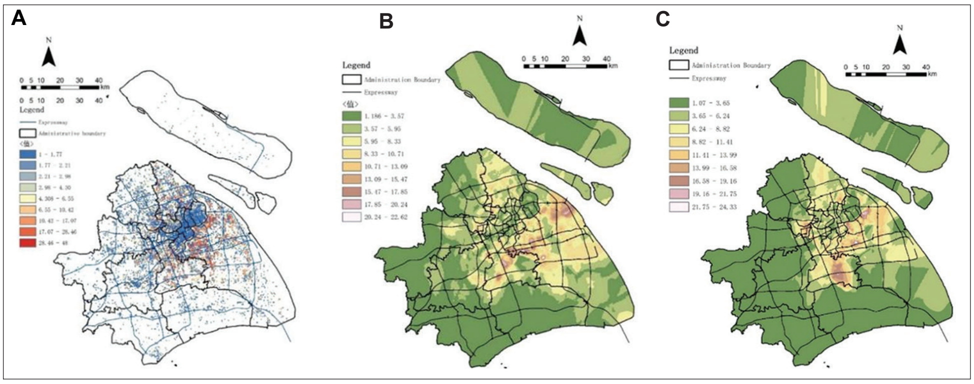

Figure 5. Distribution of the number of days with cases in different residential areas. (A) In residential quarters. (B) In commercial housing. (C) In workers' new villages. Source: Drawings by the authors

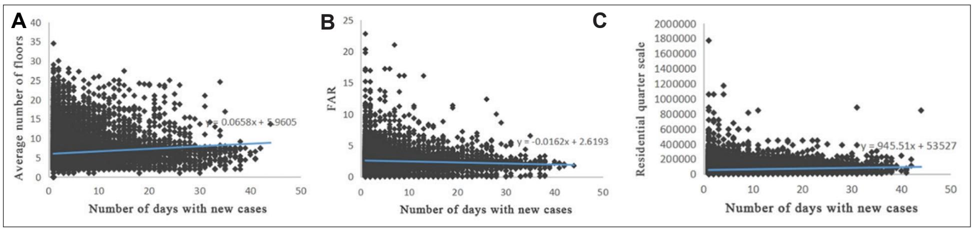

Figure 6. Relationship between the feature of residential quarters and the number of days with new cases. (A) The average number of floors. (B) The floor area ratio (FAR; total floor area/total area of the plot). (C) The residential quarter scale. Source: Graphs by the authors

Figure 7. Site location. Source: Drawings by the authors

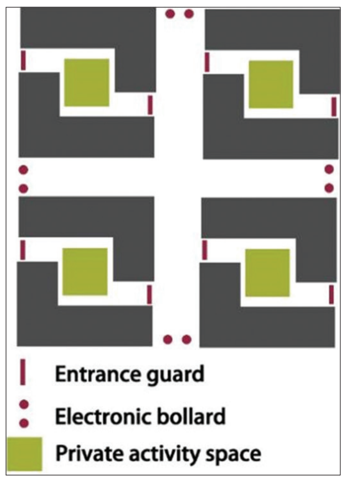

Figure 8. Spatial privacy concept analysis. Source: Drawings by the authors

to the city. Some roads are integrated into the city road network system. Electronic lift piles can be used to close the roads when needed. Second, the residential buildings are moderately enclosed so that the internal space has a clear sense of boundaries, and the internal courtyard forms a convex space (Hillier and Hanson, 1984) with no visual dead ends, which provides a clear sense of domain. Third, the entrance of the residential buildings is placed inside the enclosed courtyard. The number of entrances and exits of the enclosed units and public spaces is limited and the security is set (Figure 8).

4.1.2. Spatial flowability

Spatial flowability is the guarantee of the individual freedom of residents and urban development. In regular times, the transportation needs of residents should be fully met and non-motorized transportation should be encouraged. During epidemic, traffic control on local branch roads or streets can be conducted using electronic bollards while retaining the main traffic arteries, so that the service of public supporting facilities can meet the spatial flowability needs in special situations. This also guarantees the mobility needs of other residents in the city during partial closure control. We refer to the arrangement of medical and patient flow lines of medical buildings and the zoning of clean, semi-polluted, and polluted areas to diversify and split the flow lines of people and logistics to avoid cross-pollution and mutual interference.

We focus on the planning of the "four lifelines." First, the wrap-around logistics line is planned as a touchless delivery trolley transportation line at the edge of the settlement. For the case in which the main entrance of the district or the closed unit may have been overloaded, the spaces along the street of the settlement, such as convenience stores, are used as temporary supply receiving points for internal and external connections. Through these two detailed designs, the flow of people is separated and the logistics are opened up. Second, the emergency rescue route is planned. The emergency rescue path inside the residential quarter is reserved, and some old neighborhoods should also be renovated and widened to efficiently assist rescue operations. Third, the underground medical and domestic garbage disposal flow line is planned. During the period of lockdown, the original manual garbage disposal work was affected, so the domestic garbage of many residents in the management units could not be processed in time and was accumulated downstairs. In addition, medical garbage produced after medical testing led to secondary health problems, which need to be classified and processed. We propose an integrated design with the underground parking lots of residential buildings and reserve the temporary elimination treatment site to avoid crossing with other streamlines to the greatest extent. Fourth, the residents' flow line is planned. When a unit is blocked or restricted, management should ensure that the normal life of other units in the vicinity is not disturbed (Figure 9).

4.1.3. Accessibility

To increase the convenience in the residential areas in terms of daily commercial and service facilities, in recent

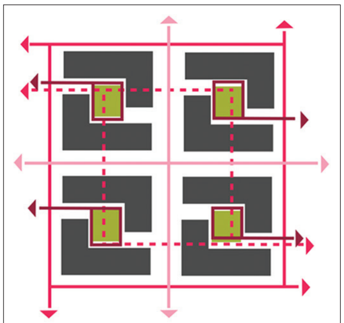

Figure 9. Spatial flowability concept analysis. Source: Drawings by the authors

years, the Shanghai Municipality has proposed a 5–10–15-min living circle initiative to increase convenience and accessibility through the arrangement of public facilities and activity spaces in the city to form a network-like distribution pattern. The closure and control measures implemented to interrupt the spread of epidemics have led to a wide range of reductions in the radius of people's activities, or even a staged halt.

Therefore, we propose an optimized design to realize the idealized concept of a living circle of public service facilities. First, this facilitates the decentralization and grassrootization of community public health service facilities. In areas with insufficient neighborhood health service stations, residents often have to walk long distances to reach medical facilities or even have to choose public transportation to travel, which can increase the chance of cross-infection. As can be seen, Shanghai organized mobile medical teams to conduct tests in each community from March 2022 to June 2022 to achieve the decentralization of health services. Thus, it is necessary to reserve adjustable space for temporary medical sites at the residential quarter level.

Secondy, temporary public shelter evacuation space is reserved. Small multi-functional sports fields, small office buildings, and other public service facilities can be used for temporary functional conversion and community emergency shelter space. In addition, the ground floors of residential buildings can be designed as flexible and changeable space units to increase the flexibility of usage functions. For example, using the ground floor commercial space along the street outside of the residential area, the units that are idle or poorly operated can be converted to shelter spaces and community service function spaces, such as activity rooms, care rooms, and neighborhood committee offices, which can effectively free up more space for quarantine and treatment during the epidemics.

Finally, supply, storage, and transit space, along with basic activity space for residents, should be taken into consideration. Community businesses such as convenience stores can be used as stations for supply storage and transit. However, when indoor gatherings are restricted, outdoor spaces and green spaces become the activity spaces that residents rely on. The planning and design should make full use of the local small-scale space formed by the residential enclosure to set up greenery or activity sites so that they can be reached right outside. Even the roofs of the medium and high-rise residences can be converted to activity floors or activity platforms (Figure 10).

4.1.4. Plasticity

Shanghai's three-zone phased lockdown policy faces the problem of different scales of management units, such as large residential quarters reaching more than ten hectares and small residential quarters with only two or three buildings. For residential quarters, having a scale that is too large will increase the difficulty and management cost, while having a scale that is too small will make it difficult to match the basic service function and public activity space requirements. If the same management approach is adopted regardless of the scale and population size, it may lead to failure of prevention and control or secondary disasters. Thus, we consider the flexibility and plasticity of the scale of the residential quarters in the design. From a household, an enclosed unit, to a combination of multiple enclosed units, the model allows the scale of the residential area to vary. The management units are based on flexible spatial units designed to better accommodate management policies (Figure 11). For example, in the early stages of the pandemic, small-scale units can be used to limit the spread of infections from door to door; with a slowdown of infection spread, medium or large-scale units can be used to hold activities of varying degrees of freedom for the residents.

Figure 10. Spatial accessibility concept analysis. Source: Drawings by the authors

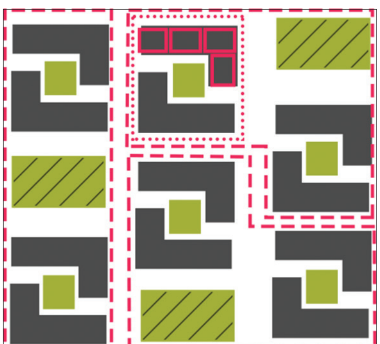

Figure 11. Spatial plasticity concept analysis. Source: Drawings by the authors

For the scale of the enclosed units, we consider two aspects. The scale should be conducive to precise management, allowing flexibility for the large combination of small-scale living spaces. However, factors such as economy, safety, convenience, and daylight requirements should be considered. We can refer to the concept of open residential quarter planning. According to the principles of New Urbanism, to ensure a coherent and uninterrupted street space, the scale of the block should be limited to 600 feet (183 meters) in length and 1800 feet (549 meters) in circumference (Zhou & Qian, 2017). Rudlin & Falk (1999) believe that the ideal block length scale is between 70 and 90 meters, which creates an orderly connection to the surrounding roads. According to the Chinese Planning and Design Standards for Urban Residential Areas (Ministry of Housing and Urban-Rural Development of The People's Republic of China, & State Quality Supervision Bureau, 2016), urban roads should be integrated with the layout of residential quarters. The intervals of roads should not be more than 300 m but rather in the range of 150–250 m. In summary, we propose that a reasonable enclosed unit size should be 0.6–1 hectare, for 120–200 people, in 4–6 floors.

4.2. Spatial mode

According to the four objectives mentioned above, we propose the following spatial mode of management units. First, to consider privacy, the enclosed building is taken as the basic unit, with 0.6–1 hectare and 120–200 people as the basic scale. Second, to consider mobility, the line of logistics and human flow is designed with diversion. Third, to consider accessibility, more attention is paid to the conversion of community medical, shelter, living necessities, and basic activity space during an epidemic. Fourth, to consider plasticity, a flexible and diverse spatial scale of the residential community is formed by using the composable residential space as the unit.

Based on the consideration of different spatial relationships between the enclosed residential quarters, four basic prototypes of spatial combinations that suit environmental characteristics of different sites are summarized proposed. The first prototype is the basic model. For two adjacent buildings enclosed to form a living space, the basic model can be combined to form a larger-scale living unit, which can also be regarded as a larger-scale management unit (Figure 12A). Second, considering the plasticity brought by public activity space and green space to the basic living unit, a shared activity space is added to the basic model, which can be a green space, a fitness activity space, or another type of open space (Figure 12B). Third, the open space that is used to increase plasticity, depending on the location and interrelationship of the surrounding traffic arteries, can also be arranged on the same side of two basic units, rather than placed between two units. It also serves as a separation between residential buildings and urban arteries (Figure 12C). Fourth, another special case, different from the above-mentioned two cases, is that the two basic units are crossed by urban roads without lateral traffic arteries, and the open space is also an urban street green space (Figures 12D and 13).

4.3. Site plan

First, we divide the 18-hectare site according to the road network. Two sites of approximately 5.5 hectares are reserved for school and commercial office functions. The rest of the site was reserved for residential functions. This arrangement provides the accessibility of public services to the residents, while the flexible space can also be used for evacuation and shelter in case of emergency (Figure 14).

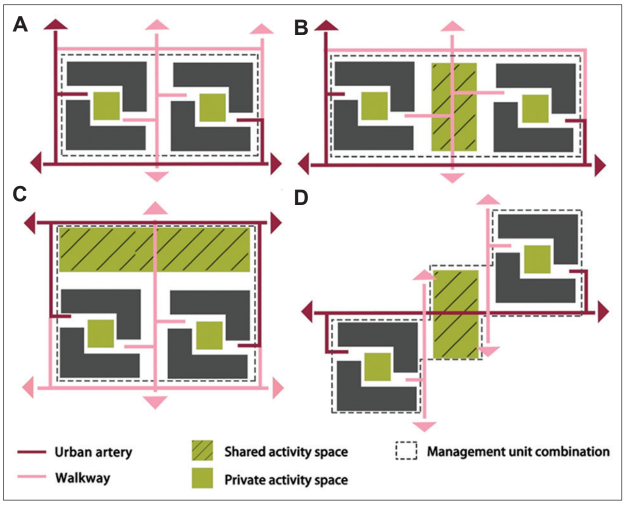

Figure 12. (A-D)Different space combination models. Source: Drawings by the authors

Second, the residential land is sliced according to the modulus of the previous spatial model (Figure 15) so that the spatial unit can be used as the basis for the management unit. To accommodate irregular site shapes, while ensuring the integrity of the internal living space of the building (including the indoor living space and the sunlight and ventilation needs of Shanghai residents), we conform to the irregular shape of the site by deforming the square unit plan. For the irregular and scattered corner spaces between the units, we reuse them as the public space and green space shared by two or three units. This not only ensures the efficiency of the land use and the homogeneity of the public space but also makes it possible to realize the combined management unit of enclosed units plus green space (Figure 15).

Third, the transportation system is considered as a whole. Full use is made of the site area for the excavation and construction of underground car park. Garbage collection and transfer routes are incorporated in the underground transportation space. The primary exit for each enclosed residential unit is connected toward the motor vehicle road to meet the demand for rapid supply transfer and medical treatment. In addition, to ensure that medical and nursing vehicles can travel freely to each residential building, the internal road of the enclosed courtyard is 5 m wide. The secondary exit for each enclosed residential unit is connected to the slow traffic system to create a dynamic pedestrian space. Both the primary and

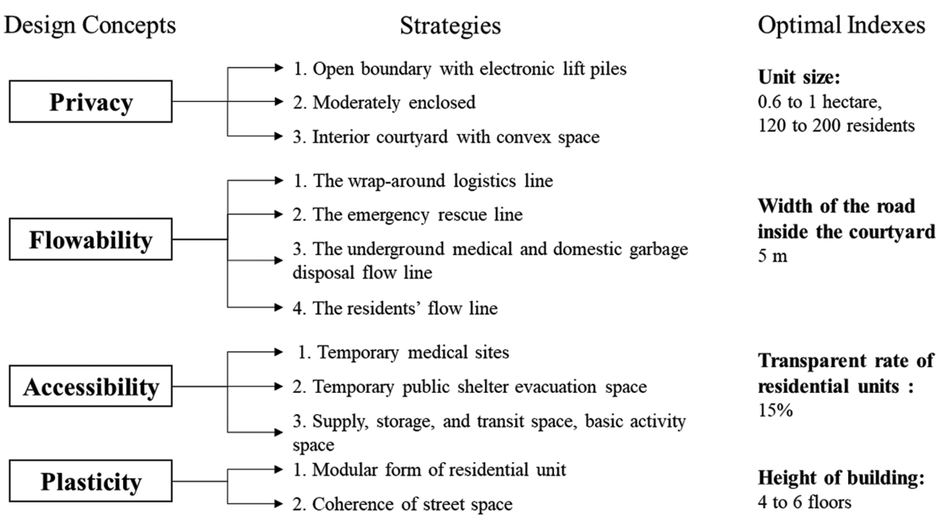

Figure 13. Diagram of the design and optimization strategy. Source: Drawings by the authors

Figure 14. Site plan. Source: Drawings by the authors

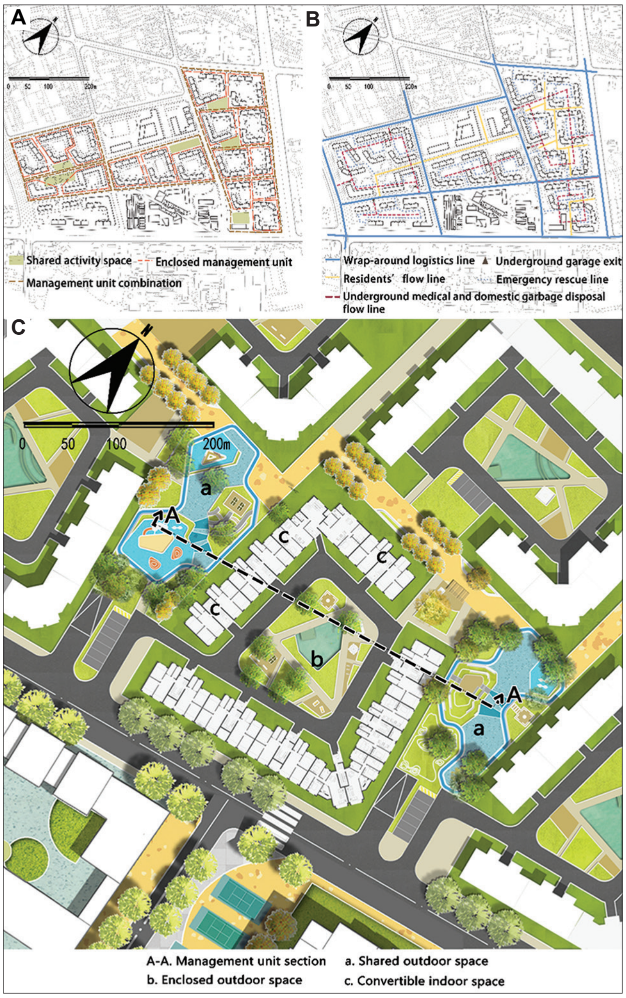

Figure 15. Management unit plan. (A) Management unit analysis. (B) Transportation streamline analysis. (C) Site detailed plan. Source: Drawings by the authors

secondary entrances are electronically barricaded to allow for partial closures when necessary (Figure 15).

Fourth, the enclosed unit on the north side of the site is taken as an example of detailed design. For the scale, according to the previous study, the enclosed unit is six floors with 126 households. For the form of spatial combination, the enclosed unit and its adjacent unit share open space (Figure 15). For the building enclosure mode, the plan transparent rate of residential units reaches 15% (Zhang & Chen, 2016) and a convex courtyard is formed, reflecting the concept of privacy. The main entrance and a secondary entrance are reserved in the south-east and north-west directions. These entrances are conducive to air circulation to improve the microclimate. Inside the enclosed courtyard, an enclosed outdoor space is set up with more natural elements and moderate ground elevation changes, providing a healthy activity environment (Figures 15 and 16). In the space along the street on the ground of the residential buildings, convertible indoor space, such as convenience stores and activity classrooms, is set up in response to an outbreak. For high-rise apartments, shared space is set up for the accessibility and convenience of residents during closed management period (Figure 17).

5. Discussion

5.1. Balance between individual freedom and collective health

In SDGs, there is always a potential conflict between individual freedom and the risk of disease transmission. Human contact increases social cohesion and the rate of infection transmission at the same time. To prevent the spread of diseases, it is always a challenge for urban managers to choose the extent and the spatial scale to moderately separate people and restrict their movements. Spatial planning and the design of residential quarters are some of the ways to achieve social governance goals through spatial interventions. The balance between privacy and mobility for residential space provides a governance tool and a basis for balancing between the human freedom of movement and the prevention of transmission to some extent.

The planning and design intention is to reconcile the conflict between health preservation and freedom to accomplish balance between privacy and mobility of living space. We attempted to find an equilibrium between a completely gated residential quarter and an open residential block to cope with the transition between daily life and epidemic prevention and control. This makes the use of space more effective and the management of space more precise. It is possible to avoid the collective inconvenience caused by over-management and also to guarantee the basic operation of each living unit.

Figure 16. Management unit section plan. Source: Drawings by the authors

Figure 17. West elevation of apartment. Source: Drawings by the authors

5.2. Balance of short-term emergency and long-term stability in social economy

Non-pharmacological interventions have an indirect negative impact on socioeconomic goals. The prevention and control of short-term emergency can be achieved by improving the functional resilience of residential community spaces for adaptation. In the long-term, the daily lives of residents will resume a normalized pattern at the end of epidemic. Spatial planning and design take the normalized state and bottom-line protection as the primary goals, rather than designing only for emergency purposes. In fact, urban economic and social development requires a stable and vibrant urban environment to support it, including the spatial environment of residential quarters.

There are many contemporary urban design theories that focus on residential areas, such as CPTED (Crime Prevention through Environmental Design), Open Block Theory, New Urbanism, and so on. In general, open residential blocks are more in line with this trend. Regarding large gated residential quarters and small-scale open residential blocks, management costs and social acceptance need to be considered. Based on the theory of New Urbanism, a reasonable scale of living space can meet the needs of various types of urban spatial governance and also help to create a sense of community belonging and atmosphere. The scales of residential units can help residents spontaneously establish community self-governance organizations to achieve synergy between spatial planning and design as well as community governance, which can improve the crisis response capacity of residential quarters.

5.3. Balance SDGs and epidemic control

Massive epidemics pose new challenges to the achievement of global SDGs. In our planning and design exploration, we integrate SDGs with epidemic prevention goals and find that SDGs are compatible with epidemic prevention goals. The concepts of accessibility and plasticity in SDG 11 coincide with the response strategy of flexible and adjustable urban space use in epidemic prevention and control.

We also determine how sustainable cities and communities can respond to epidemics in a sustainable way. The integration and accommodation of the two goals become another focus of our exploration. Our design strategy is simply a positive response to the core concept of SDG 11 and the three goal levels. Starting from the problems and deficiencies faced by basic residential spatial units, we enhance the spatial resilience, functional resilience, and social resilience of residential quarters, ultimately making spatial planning and urban governance mutually adaptive and reinforced.

6. Conclusion

The worldwide spread of COVID-19 has challenged the existing residential quarter planning and design techniques, prompting the re-examination of the path to achieving SDGs. The emergence and application of new technologies as well as the exploration of spatial models of residential space can help with designing residential areas with plasticity and resilience while integrating multiple objectives, such as epidemic prevention and sustainability.

Acknowledgments

None.

Funding

This work was supported by the National Natural Science Foundation of China (grant number: 51778436).

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Investigation: Zhi Wei,
Methodology: Fan Yang and Jiayin Wang
Writing – original draft: Zhi Wei
Writing – review & editing: Jiayin Wang and Fan Yang

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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Journal of Chinese Architecture and Urbanism

ORIGINAL ARTICLE

Bioregenerative algal architectures

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(This article belongs to the *Special Issue: Regenerative Architecture*)

Abstract

Contemporary biospheres will be needed in terms of life support in the face of climatic consequences of the Anthropocene and to sustain future space travel. For life to flourish on Earth and beyond, key elements are required — including carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorous — which need to regenerate through physiochemical alliances and symbioses with other life forms. Bioregenerative systems are defined as artificial ecosystems, which are made up of intra-relationalities with various species including higher plants, microorganisms, and animals. In this paper, bioregenerative architectural habitats are considered a solution for a planet that faces substantial ecological damage and for the likelihood of multiplanetary inhabitation in future. Mutually beneficial systems incorporating working with microalgae in conjunction with bioreactor technologies could constitute a means of survival on a damaged planet or to help start multiplanetary colonies. This paper illustrates the potential of a non-anthropocentric, bioregenerative life support strategy working with various microalgae species. Past- and present-related bioregenerative systems are reviewed and future applications of microalgae enhancing a *sympoietic* alignment (collectively producing systems) of the human and nonhuman with microorganisms are considered. Future alliances with microalgae, *Chlorella vulgaris,* are proposed to work within bioregenerative systems on Earth and in space. This paper clarifies how the combination of technology, speculative architectural design and microalgae can enhance carbon dioxide mitigation, furthering gaseous exchange for life support, enabling human and nonhuman species to flourish in harsher environments on Earth and beyond low Earth orbit.

Keywords: Microalgae; Ecological impact; Photobioreactor; Carbon dioxide mitigation; Sympoiesis; Biological *in situ* resource utilization

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Citation: Shergill, R. (2023). Bioregenerative algal architectures. *Journal of Chinese Architecture and Urbanism*, 5(3):179. https://doi.org/10.36922/jcau.179

Received: March 14, 2023

Accepted: August 16, 2023

Published Online: September 7, 2023

1. Introduction

The human body is intrinsically connected to the biosphere it is surrounded by (Margulis, 2008; Haraway, 2016). On Earth, the biosphere is made up of intra-relationalities and relies on the connectivity of *sympoietic* systems. Natural systems on Earth consist of crucial relationships with plants, animals, and gaseous exchanges, which actively co-exist in planet Earth's overarching biosphere. Without the inherent connected make-up of the ecological system, the human and nonhuman would find it difficult to function. Gaseous exchange — in terms of carbon dioxide and oxygen between plant and animal species — is conducive to the flow of life. Respiration and photosynthesis are essential for life systems to exist (Nelson, 2011). Radical imbalances within ecological systems force the Earth's biosphere to fail (Schramski *et al.* 2015; Bostrom & Ćirković, 2020). As we approach anthropogenic scenarios due to these radical changes, the human and nonhuman will need to adapt to each scenario it is placed in (Figure 1).

A possible solution to the anthropogenic changes in Earth's ecological environment is the construction of contemporary biogenic architectures which can benefit Earth's damaged atmosphere. Mini biospheres embedded into buildings and urban environments can enhance breathability when there is a lack of air. The human species has been able to adapt to highly extreme environments and conditions (Fong, 2013). However, when there is a point of no return (Bostrom, 2019), novel interventions through design, engineering and architecture must be innovated. Radical changes in temperature and lack of oxygen, nitrogen and other gases will require a contemporary miniature "spaceship earth" mindset. In the very near future, it will be pertinent to conceptualize novel regenerative architectures within and surrounding urban environments. These architectures can respond to the potential impact of future dystopian scenarios arising from climate change. Once realized, different types of bioregenerative architecture will need to be effectively managed through science and technology.

Philosopher Peter Sloterdijik asserts, "The construction of shells for life creates a series of uterus repetitions in outdoor milieus" (Sloterdijik, 2009). In this paper a continuum is suggested between the human body and an extended "microbiome" that is supported via a bioregenerative apparatus. The building and its bioregenerative parts can work in different forms of *sympoiesis*, growing together for a mutualistic furtherance of life, providing new ways for respiration through photobioreactors embedded into its structure. The anatomy of a building can be compared to the human *holobiont.* Disparate parts work in unison *becoming* a unique ecological unit. This analogy of the building as a body is comprised of an assemblage of species, containing a host of *bionts* incorporated as unique engineered architectures within. Bioregenerative photobioreactor systems work and evolve in a continuum of complex integrations within the building's interior and exterior walls.

Figure 1. Speculative design of body in extreme environment, the system can be furthered as a living system with bio-integrated design. Source: Creative Direction and photography, Ram Shergill, Robotic Sea Urchin by Jack Irving, Art direction by Daen Palma Huse

This paper first defines the field of bioastronautics in relation to bioregenerative algal architectures; second it discusses current bioregenerative systems; third it evaluates what species of microalgae can be worked with in bioregenerative systems. In this paper, I suggest that bioregenerative algal systems are defined as artificial ecosystems which comprise of sympoietic relationships with microalgae through architecturally designed photobioreactor systems. Bioregenerative photobioreactor (PBR) microalgal systems consist of microalgae and through a process of photosynthetic gaseous exchange they capture carbon dioxide to produce oxygen. Furthermore, these engineered devices can purify water and, in the long term, can create food from biomass. Once processed, harvested biomass can be used to create biofuel to produce energy.

Feminist and postmodern theorist Donna Haraway highlights that "*Sympoiesis* is a simple word; it means "making-with." Nothing makes itself; nothing is really autopoietic or self-organizing" (Haraway, 2016). Haraway, following Margulis (2008) and Gilbert *et al.* (2012), asserts that all living organisms are inter-relational and harmoniously coexist by assimilating and linking with "other" cells, becoming ecological assemblages. Equally, I assert that the future is reliant on a *critical posthuman practice,* where the human and nonhuman conjoin for mutually beneficial scenarios. In terms of my concept, the adjective "critical" has two relative definitions: first, re-negotiating anthropocentric thinking critically challenges the notion of the posthuman; second, it describes a condition in which a "critical practice" is developed through ecologically aligned praxis pertaining to human and nonhuman survival. Fundamentally, a future is speculated in which life cycles may have their foundations based on physiochemical alliances with nonhuman organisms.

The significance of endosymbiotic theory was proven by Lynn Margulis in 1967 and incorporated into the fabric of evolutionary thinking (Martin, 2017). Research in terms of symbioses and oxygenation of Earth's atmosphere is being continuously advanced (Lenton *et al.,* 2016; Yao *et al*., 2019). While there are various questions arising from which type of evolutionary theory is correct, this paper's main objective is primarily to discuss the benefits of bioregenerative algal architectures and not to authenticate any type of evolutionary process or theory. Therefore, it is important to consider that bioregenerative algal architectures rely on an integrated altruistic alliance with microalgae species. Posthuman theorizer Rosi Braidotti affirms that the body is not a singular species but is composed of a plethora of "other bodies" and becomes a "transversal force that cuts across and reconnects previously segregated species, categories and domains" (Braidotti, 2013). Bioregenerative systems in harsh environments, whether on Earth or in space, require new alliances with segregated and multispecies entities. It is fundamental to look at space scenarios reflexively to see how innovated systems can benefit a damaged Earth.

2. Earth and space

To produce bioregenerative systems for future scenarios, a multidisciplinary set of methods is required, incorporating a mix of science, architectural design, creative practice, and technology. Bioastronautics is the study of the biological, astronautical body in space flight scenarios (Young & Sutton, 2021), and investigates biological, medical, scientific, technological, and behavioral conditions of humans and other organisms in such conditions. Earth, space and multiplanetary atmospheres become inextricably linked — specifically when responding to environments the human and nonhuman body are not accustomed to or prepared for (Dominoni, 2020). Comparing one extreme environment to another can benefit each situation the body is placed in. An example of a worst-case scenario would be the Martian landscape, where there is a lack of atmosphere, high amounts of CO_2 and very low temperatures, amongst many other challenges in space (Mapstone *et al*, 2022; Verseux *et al.* 2016; Fahrion *et al.* 2021). Visualizing extreme environments and creating propositional responses to indeterminate situations through speculative design can be used as a method to see how design can be incorporated further with living systems (Figure 1). Biotechnology experiments carried out in space on the International Space Station enable a visualization and provide evidence of how microalgae in bioreactor systems react to harsher environments (Detrell *et al.* 2020b). Bioregenerative experiments are fundamental for assessing how life support systems can be adapted on Mars. They will be pertinent both for an unknown future on Earth and for the potential inhabitation of multiplanetary surfaces (Verseux *et al.*, 2022; Häder, 2020).

On Earth, or in space, the medical, biological, and behavioral aspects in the administration of human and nonhumans in a space flight environment are required for future scenarios. One of the objectives of bioastronautics is to improve possible futurist habitable systems beyond low Earth orbit. In space, there are many factors to consider in terms of successful plant growth, such as *gravitropism* and the workings of Closed Ecological Life Support Systems (CELSS). The CELSS is a system that uses physiochemical methods through the application of miniature enclosed ecosystems (Olson *et al.,* 1988). Algal space research has been considered fashionable since the 1960s (Hendrickx *et al.*, 2006). The model organism *Chlorella vulgaris*, widely used in research, has been one of the most responsive organisms for experiments in life support systems (Niederwieser, 2018). Extra Vehicular Engineer, Dr. Emily Matula, who is based at the NASA Johnson Space Center, contends that closed systems can be advanced on exponentially, stating that they have the potential to produce substantially more oxygen than pre-existing closed (smaller) systems export. Furthering economies of scale, a larger system incorporated into thermal loops of space craft have the potential to create large photobioreactor systems which have advantages in future scenarios.

Matula & Nabity (2019) hypothesizes the benefits in producing a large-scale ECLS (Environmental Control and Life Support) system;

> Algal photobioreactors have been researched as potential solutions to air revitalization in a spacecraft cabin environment by absorbing CO_2 and producing O_2 through photosynthesis. This photosynthesis and consumption of produced biomass, theoretically provides a closed-loop solution for long-duration spaceflight. Addressing multiple spaceflight requirements simultaneously with algae has the potential to reduce launch mass, power, and volume of future Environmental Control and Life Support (ECLSS) systems (Matula & Nabity, 2019).

Matula suggests that if an incorporated system of inoculating algal cultures were placed into water-based cooling loops[1] on a large scale in the International Space Station, the algae would "thrive" through a large photobioreactor system in the cooling loops of the craft. While this can be advantageous in many ways, it is important to realize that systems can have difficulties, such as biofilm formation and blockages to cooling systems.

[1] The International Space Station's cooling loops through the Active Thermal Control Systems (ATCS), which are the thermal control systems, allow fluids to pass through the system, using liquid ammonia to keep the solar panels at a controlled temperature. Through photovoltaic systems from the solar panels, the system proves to be successful, which is also used for electricity generation.

This, however, can be overcome with system overrides as well as manual and autonomous technologies, which enable a smooth flow of algal broth within a system.

Incorporating photosynthesis in such a system would explicate air revitalization as well as thermal control into a common system (Matula & Nabity, 2019). Matula goes on to suggest that more research is needed in terms of algal cultures responding to thermal and gravitational conditions in low Earth orbit relating to oxygenic production. The analysis, failures, and successes of the previous experiments with microalgae are used as aids to assess and innovate bioregenerative life support in photobioreactor systems, allowing Matula to evaluate feasibility factors of photobioreactor systems being used for future planetary inhabitation (Matula & Nabity, 2019). On Earth, finding solutions to carbon dioxide concentration, and for areas requiring air revitalization in dystopian environments, photobioreactor research is crucial, as it could potentially prove to be a mitigation method for planetary damage. Tobias Niederwieser, the Research Associate at BioServe Space technologies USA, asserts:

> Through new innovative designs, biology and engineering can exist in symbiosis that benefits both sides. In addition, while this technology development is tailored for spaceflight life support systems that might 1 day allow us to travel to and live on Mars and beyond, it might also help us to make life on Earth more sustainable by reducing the carbon dioxide concentration (Niederwieser, 2018).

Niederwieser's concluding statement for his doctoral thesis is significant for the future implications of life on Earth and for future life beyond low Earth orbit. Future advanced life support systems would be necessary for multiplanetary and interstellar travel (Volponi & Lasseur, 2020). Similarly, Zheng *et al.* (2008) assert that Bioregenerative Life Support Systems (BLSS) would radically improve living conditions in terms of working BLSS being placed on space stations, enabling potential inhabitation on the Moon and Mars, also furthering the uses in transport vehicles relating to Extra Vehicular Activity (EVA) on the lunar and Martian surfaces (Dempster *et al.*, 2004). It is crucial to reflect this back to Earth, as conditions on Earth are imminently changing and environments where you will not be able to breathe are becoming inevitably uninhabitable due to the harsh and radical changes in the environment. It is in this context that algal photobioreactor research can be seen as existentially fundamental.

3. Environmental immunology

The demise of the planet is predicted by many thinkers, scientists, and writers (Bostrom, 2019; Lewis & Maslin, 2018). However, detailed and rigorously researched the problems of the planet are, practical solutions relating to the source of the problems are rarely addressed. There needs to be an affirmative, radical, and catalytic response to the results of the huge amount of research that has been undertaken. Moreover, one might consider in this decade of the 2020s that there is an urgent need for a novel form of architecture, responding to the effects of disease, pollution, and anthropogenic atmospheres. A critical posthuman architectural solution will be necessary for human and nonhuman survival.

In the 1960s, design group Archigram's work was created at a time when architects were fascinated with the futurist aesthetics of the Moon Landing and the notion of astronauts in space. Archigram took these inspirations and merged them with their desire to make cities mobile. They looked at standardized minimum spaces, creating new and "futurist aesthetics," enabling mobility through design, and juxtaposed it with large-scale modernist architecture. The work they produced was experimental, neo-futurist and took inspiration from technological advances, imagining speculative worlds and scenarios through their collage design and pamphlets. The group experimented with consumerist imagery, modular machinery, mobility, and neo-futurist space capsules.

Archigram conceptualized modular systems for potential ways of living and was followed by the architectures emerging from the *Existenzminimum* concept (see The Capsule Hotel by Kisho Kurokawa in Tokyo, completed 1972). Archigram and their futuristic visions, designs, imaginings, and aesthetics set precedents for what could be imagined and achievable in terms of designing for Anthropocene and "bare life" type scenarios.

4. The Biospherians

There have been many experiments carried out over long durations of time related to bioregenerative systems and considered as failures. Biosphere 2 (1991) was a large-scale vivarium which covered an area of 3.14 acres of the American land, designed as a futurist pneumatic architecture. The reason for calling the project Biosphere 2 was that planet Earth itself is perceived as Biosphere 1. The biospheric architecture housed a "complete ecosystem" and set out to test the possibilities of how humankind could potentially survive for long durations in outer space. The biosphere was made up of seven types of biome areas, including a rainforest, ocean, coral reef, mangrove, wetlands, fog desert, and many other individual experimental habitats. The original crew had been inspired by the books *Silent Spring* (1962) by Rachel Carson and *Mount Analogue* (1952) by Rene Daumal, and *Operating*

Manual for Spaceship Earth (1967) by Buckminster Fuller, as well as *The Last Whole Earth Catalogue* (1968). The crew was also inspired by William S. Burroughs who thought that the countdown to ecological disaster had begun.

Whilst this high-budget enterprise was seen as a failure, it could be argued that the experiment did not altogether fail, for over a period of 2 years the crew of eight people survived in an enclosed ecosystem and successfully grew vegetables, fruits, and a host of other crops (Zimmer, 2019). Most of the data and records of the experiment mysteriously vanished, and the results from several of the experiments have never been published. This was due to takeovers by different companies who had commercial interests. There were many complex reasons proposed for Biosphere 2's failure, none of which have, to this date, been scientifically proven (Hüpkes & Dürbec, 2022). The fact the construction was made chiefly of concrete and was the project's main downfall, as the concrete contained calcium hydroxide. The carbon dioxide was not reacting with the soil within the biosphere and plants could not produce enough oxygen, the carbon dioxide was reacting with calcium hydroxide in the concrete, forming calcium carbonate and water (Cohen & Tilman, 1996; Marino and Odum, 1999). To move forward with potential bioregenerative systems, it must be realized that working with any living organism has its complexities in which mitigation of potential hazards must be taken into consideration.

5. Current bioregenerative systems

To understand what is needed on a damaged Earth, it is pertinent to look at bioregenerative systems that have been conceptualized for space. This gives us unique insights and allows us to consider and imagine how these technologies could be applied to Earth. In space, humans require the essentials in terms of "requirements of the body." Specifically, for survival, the body requires (per day) "1 kg of oxygen, 1 kg of food and 3 kg of water" (Anderson *et al.*, 2018). This is documented in the in-depth NASA study of The Baseline Life Support Values and Assumptions Document (BVAD). To travel and live on another planetary body, robust regenerative environments are needed which mirror biogeochemical cycles on Earth (Young & Sutton, 2021). It is feasible that for long-haul space travel or for successful inhabitation in harsher environments, human essentials (food, packaging, and waste management) required for existence are not sustainable unless regenerative systems are put into place. We will now look at some related experiments and projects that can be seen as foundational for bioregenerative algal futures.

Rack-like unit for consistent on-orbit leafy crops availability was an analogous experiment based on Earth and used higher plants in extreme environments (Antarctica). The project was carried out on EDEN ISS, which was a ground demonstration of plant cultivation technologies for food production in space. The project encompassed unique ideas and methodologies in fertigation, which researched oxygen-producing systems for Earth and for interplanetary travel, experimenting with gravity as well as autonomous cultivation techniques.

Another notable experiment, Euglena and Combined Regenerative Organic-Food Production in Space (*Eu: CROPIS*), was a mini satellite from the German Aerospace Centre by Deutschen Zentrum für Luft- und Raumfahrt (DLR) program. Its purpose was to study plant life and food production for long manned space flights (Häder, 2020). The experiment worked with the photosynthetic microalga *Euglena gracilis,* which is considered to be an optimum organism for working with gravity and liquid for photosynthetic growth (Häder, 2020). The species uses light (photoaxis) and gravity (gravitaxis) to maneuver in its environment (Häder & Hemmersbach, 2017; Häder *et al.*, 2017). The organism was put on a rotating satellite, which mimics the axial rotation of the gravity levels on the Moon and Mars. Both experiments (one to replicate lunar atmosphere and one replicating a Martian atmosphere) lasted for 6 months (Schulze *et al.*, 2016). The objective was to produce biomass out of urine to fertilize crops, indicating a possible bioregenerative system. Due to software upgrade issues on the satellite; this experiment could not fulfill its objectives. The section of the vessel, which was to propagate six tomato seeds, including "two greenhouses hosting a symbiotic community of bacteria, single-celled microalgae *(Euglena)* and synthetic urine as a fertilizer" (Shulze *et al.*, 2016), remained dormant. Biologist Jens Hauslage, who was the principal investigator of the experiment and is based at the Institute of Aerospace Medicine, asserts that "in principle the experiment works, and it is functional. Through our work on *Eu: Cropis* we have developed a long-term test bed for biological research in space" (Hauslage, 2018). The importance of this experiment portrays that a bioregenerative system could be feasible to house a system holding bacteria, rejuvenating human liquid waste via microalgae leading to growth of higher plants (tomatoes) on a satellite. In principle, if it were not for the software upgrade issue, this experiment could indicate that future possibilities through life regeneration systems are possible in harsh gravitational and environmental conditions. *E. gracilis* produces oxygen and biomass to protect the whole system against ammonia concentrations (Hauslage, 2018). Artificial light (LED) is used in combination with a pressure tank to mimic the atmosphere on Earth, a type of "regolith" is applied through inoculation of soil onto lava rock, allowing various microbial organisms to *bioleach* into porous rock, creating a new habitat for "cosmic tomatoes" to grow symbiotically with urine. In *Eu: CROPIS*, *E. gracilis* is part of a system, as it provides the Combined Regenerative Organic-food Production (C.R.O.P.®) filter with oxygen allowing urine to convert to nitrate, aiding tomatoes in the experiment to gain sufficient oxygen to photosynthesize. Specifically, *E. gracilis* acts as an aid to oxygen production where it is part of a larger experiment, for an investigation into hybrid combined biological life support systems.

Urine processing and water recycling systems are an integral part of any BLSS, as systems should incorporate circular closed loop or partially closed loop systems to produce food, water, and oxygen from what is considered as human and nonhuman "waste" (Verbeelen *et al.*, 2021). More research is needed for furthering methods pertaining to the nitrification of urine via ureolysis. Bioregenerative systems for multiplanetary surfaces would benefit from research incorporating "closed loop" human and nonhuman waste management systems combined with finding innovative ways of biological in-situ resource utilization BISRU.

5.1. Micro Ecological Life Support System Alternative program (MELiSSA)

Photobioreactor systems are placed within the European Space Agency's MELiSSA to create a circular regenerative system. The system replicates a mountain lake ecosystem (Volponi & Lasseur, 2020; Häder, 2020) and creates a circular bioregenerative system for manned space flights — recycling everything to form a mini ecosystem. First, a liquefying stage uses bacteria to rejuvenate human waste into ammonium, carbon dioxide, fatty acids, and minerals (Volponi & Lasseur, 2020; Häder, 2020). The degradation is processed through proteolysis, saccharolysis, and cellulolysis. The second stage is the "photoheterotrophic" phase and uses bacteria *Rhodospirillum rubrum,* discarding and destroying undesired products of the liquefying stage such as fatty acids and other unwanted degraded products.

In the third phase, bacteria are used for nitrification — combining urine and "good outputs" from the first and second stages. The chemolithoautotroph *Nitrosomonas europaea* is used to oxidize ammonium NH_4^+ into nitrite ions NO_2^-. Furthermore, bacteria *Nitrobacter winogradskyi* is used to oxidize nitrite into nitrate NO_3^-, creating a form of nitrate, which is used by higher plants and microalgae (Hendrickx *et al.* 2006).

In the MELiSSA loop (Figures 2 and 3), forms of bacteria work together in symbiogenesis. Nitrogen fixing is established, enabling microalgae and higher plants

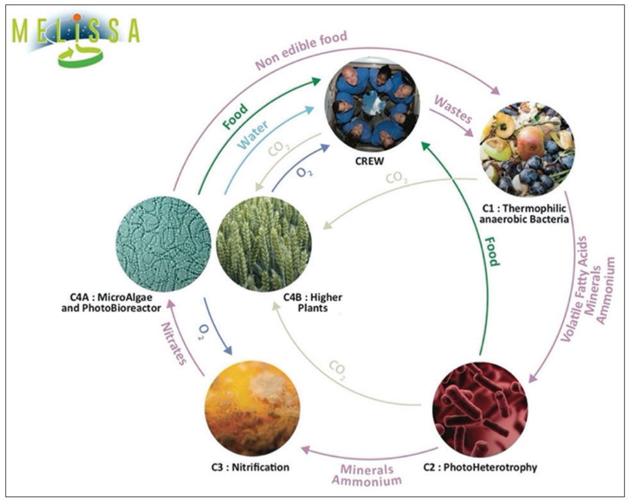

Figure 2. A schematic representation of the Micro Ecological Life Support System Alternative program (MELiSSA) loop, with the five compartments and their relations highlighted. Source: Courtesy of the MELiSSA Foundation

Figure 3. Micro Ecological Life Support System Alternative program (MELiSSA) proposes regenerative life support technologies to produce food, recovery of water, and atmosphere regeneration, together with waste reclamation. Source: MELiSSA Foundation

to grow. The nitrification stage of MELiSSA requires oxygen to be a necessary factor in the workings of the process. The photoautotrophic phase splits into two parts for the next stage — first the "algae stage" and then a "higher plants" stage. A photobioreactor is used to house spirulina (Hendrickx *et al.*, 2006), which is also known as *Limnospira indica* (Poughon *et al.,* 2020). This can be used as a source of food protein for the crew/inhabitants. Through the photobioreactor, spirulina is formed through photosynthesis and turns into an edible mass — it produces oxygen as well as a nonedible biomass (which would need to be processed before it is eaten) and is then furthered through the cyclical loop, moving to stage one and being processed (Figure 3). MELiSSA becomes a closed loop bioregenerative system, which could regenerate life in remote conditions. The MELiSSA core goals are the "production of food, recovery of water and regeneration of the atmosphere, with a concomitant use of wastes, that is, CO_2 and organic wastes, using light as a source of energy" (MELiSSA Foundation, 2020). MELiSSA is part of the European Project of Circular Life Support Systems, which is continuously researching into current and future ways of regenerative life support systems for long-term space missions.

5.2. MarsOASIS

MarsOasis is a concept originating from the University of Colorado, Boulder, researching ways of utilizing *in situ* resources for crop production in the Martian atmosphere (Darnell *et al.,* 2015). The objective is to plant crops in preparation for human consumption on the Martian surface. Sunlight and ultraviolet rays are used in a greenhouse-type architecture. In a crop production experiment, Outredgeous lettuce grew autonomously. The motivation came from NASA's VEGGIE food production system, which is a way to provide fresh food in an enclosed system to astronauts on the International Space Station. A prototype lunar greenhouse was made by the University of Arizona, with an architecture that has collapsible and expandable bellows. The technology inside maintains humidity, power for LED lighting, and root mats which provide nutrients to the plants (Darnell *et al.*, 2015) The system becomes a space greenhouse allowing for life to thrive (Furfaro *et al.*, 2016).

Any project aiming to allow for human life to thrive on the Martian surface is ambitious, as the challenges of harsh environments include (and are not limited to) reduced gravity, intermittent inhospitable surface temperatures, low atmospheric pressure, absence of a magnetic field, radiation, and wind-induced dust storms. However, Mars and several exoplanets do have some positive conditions that can benefit the harvesting and growing of crops. The MarsOASIS team visualized a system using *in situ* CO_2 and Martian sunlight. Simulation was provided by AcroOptics, allowing the team to simulate Martian sunlight for their experiments. In any space environment, there are many obstacles that must be overcome. Unfortunately, the PBR@ LSR algae-based photobioreactor experiment on the International Space Station (2019) was functional for only 2 weeks. The premise of the experiment was to assess the feasibility of axenic cultivation of *C. vulgaris* for long periods of time (over 180 days) under microgravity conditions in space through a hybridized life support system (Helisch *et al.,* 2020). The power source to the engineered PBR@LSR failed after 15 days (Detrell *et al.*, 2020a). Resilient design and contingency planning are fundamental for working with complex bio-integrated systems. The MarsOASIS system becomes a precursor for Earth, as it has benefits in understanding what is required in terms of contingency planning, designing, and how researching Mars as a twin allows us to see how Earth architectures can benefit from resilient bioregenerative structures. MarsOasis is being further developed with various projects situated in the Bioastronautics Department at The University of Colorado, Boulder, USA.

6. Back to Earth

Leading on from Archigram's futuristic premonition of the 1960s, there have been many projects that take into consideration algal design in terms of architecture. While there are concepts in adopting algae façades (Elrayies, 2018; Talaei *et al*., 2020; Warren *et al*., 2023), to date there has not been an implicit type of bioregenerative architecture that has been conceptualized. Previously, living façades have been at the cutting edge of urban architectures (Armstrong, 2016). Algae building technology (ABT) was used in the BIQ house in Hamburg (2013) and led by a team of engineers, architects from ARUP, and the Strategic Science Consulate of Germany for an International Building Exhibition. The building consisted of 200 m^2 PBRs (Wilkinson, 2018). A bioreactor façade was built, with the maximum temperature in the algal broth controlled at up to 40°C (Wilkinson *et al.,* 2017). Building algal-based façades for architectural applications has become increasingly "in vogue" and was perceived to be similar to the way, in which biophilic green buildings were previously imagined.

The key difference is that algal façades do not encompass closed loop systems incorporating life support, food, waste, water, biofuel, and energy, which are portrayed in a true bioregenerative system, such as the MELiSSA closed loop system. Bioregenerative algal architecture would encompass metabolic cycles, improving oxygenation of an environment whilst addressing nitrogen, phosphorous, and carbon dioxide regeneration. When humans or animals produce urine, the urine should not be considered a waste product as it contains essential nitrogen and phosphorus supplies, which could be used for fertilization in plants, as nitrogen is formed in ammonia (Hogle *et al.*, 2023). A unique autonomous system has been developed by the Living Architecture project, which is a modular selectively programmable bioreactor system wall and operates through the application of microbial fuel cells (Figures 4-6).

Wastewater and air are used to generate oxygen and proteins creating a micro-agriculture, using methods of

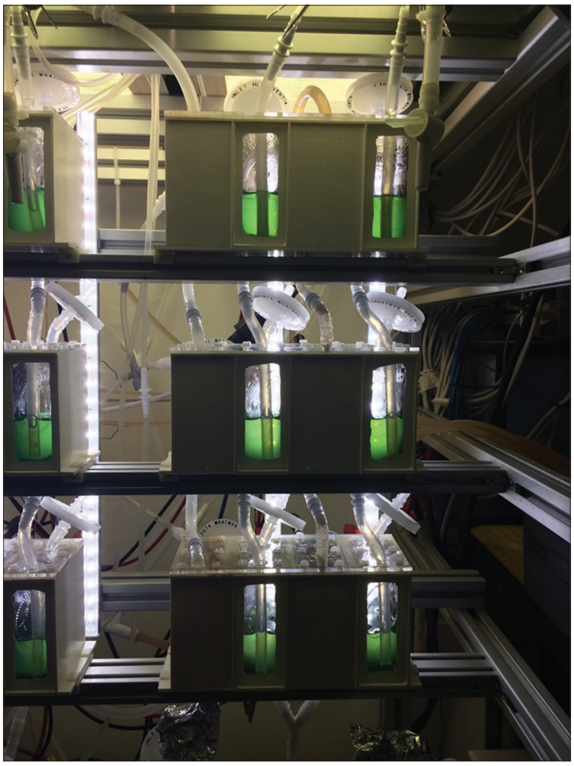

Figure 4. Living Architecture "wall" series of bioreactor. Source: Photograph courtesy of the Living Architecture project, 2019

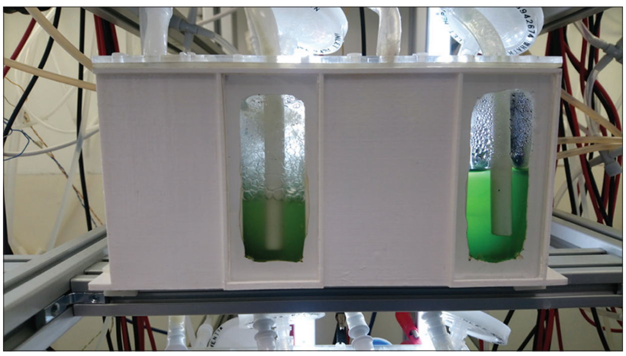

Figure 5. "Wall detail" in the Living Architecture bioreactor installation. Source: Photograph courtesy of the Living Architecture project, 2019

bioremediation, biophotovoltaics, and bioregenerative implementation in the design. Biophotovoltaics incorporate clean power generation and uses self-renewing organism-mediated photosynthesis to capture solar power for generating electric currents (Zhu *et al.*, 2023).

Wastewater and organic waste are passed through a series of three bioreactors to produce clean water, electricity, biomass, and phosphate as well as other by-products. The concept of the project was to find a way to create pertinent resources from household waste utilizing the work of microbes. The living architecture system has the potential

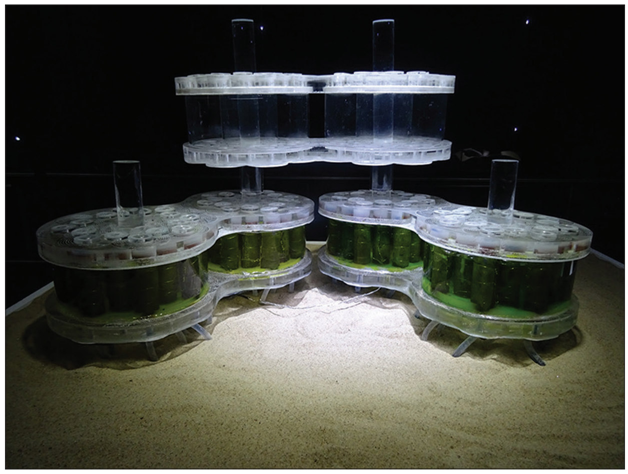

Figure 6. Complex combined "brick" structure with rod-based assembly system that co-houses photosynthetic and anaerobic populations of microbes. The photo shows the prototype by Simone Ferracina for the Living Architecture project. Source: Photography courtesy of the Living Architecture project, 2017

of being integrated into the walls of high-rise buildings and architectures in which biological processes use waste urine to provide multiple functions for a building. Modular bioreactor units are used (microbial fuel cells, synthetic microbial consortia, and photobioreactor) which integrate into one hybrid system (Hogle *et al.*, 2023). Prototypes created are stackable horizontally and vertically — this has positive implications when constructing buildings as the algal bioreactors can be embedded into walls. Outputs include polished water, fertilizer, and recoverable biomass (Hogle *et al.*, 2023). Algae are embedded and provide oxygen through a system of biophotovoltaics, thereby creating a microbial fuel cell. The living architecture system prototype speculates a partially closed loop system, which has the potential of producing oxygen and biomass, and regenerating liquids and waste, and becomes a multifunctional architecture in the elucidation of a mini ecosystem (Figure 6).

Systems such as Living Architecture are pertinent for counteracting future instability and for survival. Bioregenerative algal architectures would specifically consider contemporary dynamic cities, where the building adapts to the environment and becomes an extension in which the human works *sympoietically* with the nonhuman (microalgae) for the furtherance of life. Architecture designed through artistic and speculative means allows for the visualization of habitats, which can exist in extreme environments.

7. Speculative bioregenerative algal design

Working with architectural PBR systems and designing physiochemically with life has its obstacles. However, if a unique bioregenerative algal architecture was innovated with a resilient species in mind, or a multiple species that could be *worked with* in harsher environments — such as extremophiles or diatoms — the advantages of such a system would be numerous. The need to revitalize the air that we breathe is intensifying. Having unique systems embedded into architectures would benefit air revitalization and much more.

A bioregenerative mask system was created and displayed at The Museum of Contemporary Art (MOCA) (Figures 7 and 8; Shergill, 2022). The mask system is an iteration in speculative design, projecting how contemporary bioreactor systems can work together as a modular set of devices. The Bioregenerative Mask System works cohesively as an intra-connected contemporary gaseous exchange system for potential use on multiplanetary surfaces. The system incorporates addressing issues, such as not being able to breathe pure clean air efficiently, carbon dioxide management, conducive gaseous exchange, and protection against pathogens. The elucidation of the mask system is the starting point in the birth of a "Critical Posthuman Practice" (Shergill, 2022) — this praxeology was clarified at The Museum of Contemporary Art, London in 2022.

Figure 7. *Bioregenerative Algal Mask System*. The photo shows the mask created by Ram Shergill. Source: Photo by Ram Shergill, The Museum of Contemporary Art (MOCA), 2022

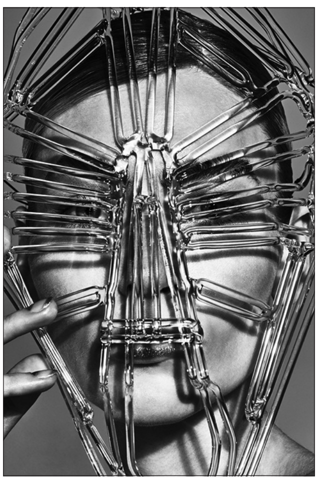

Figure 8. *The Birth of a Critical Posthuman Practice*, Borosilicate Glass Mask. Source: Ram Shergill, MOCA Gallery, 2022

The critical posthuman can be defined as a *being* of multiple becomings, transformations, and intra-connections with the nonhuman — applying forms of *sympoietic* hybridization. Whilst the notion of the critical posthuman has risen from a critical theory perspective, I have embedded this theory and conceptualized a new form of *critical posthuman practice*, which is critically and ecologically aligned. In terms of my concept, the adjective "critical" has two relative definitions: first, it re-negotiates anthropocentric thinking and critically challenges the notion of the posthuman; second, it describes a condition in which a "critical practice" is developed through a type of ecotechnology to further human and nonhuman survival. Ecotechnology is defined as a branch of science that works with natural resources to cause minimum ecological disruption. Therefore, my definition of a *critical posthuman practice* is a twofold combination of ecologically focused design practice and theoretical underpinning, diffractively intertwined for the furtherance of life. Creative photobioreactor design allows for working with a variety of species, and therefore advantageous for many applications — whether on Earth, in space or for multiplanetary surfaces.

8. Species

Whilst species from the genus *Chlorella* are considered a model species for space applications (Niederwieser *et al.*, 2018), it is important to contemplate that there are many species that can be beneficial in bioregenerative architectures. There is not just one "ideal species" that benefits all locations — be it on Earth, the surface of Mars or the Moon. Each site will need a plethora of species which can aid the specific site — for example, the extremophile *chroococidiopsidales* can be stored desiccated for long durations. The species *Anabaena* and *Nostoc* with their harvest index may be good for bioleaching in industrial applications (Helisch *et al.*, 2018). In prior space-related research, microalgae *C. vulgaris* has shown great potential (Niederwieser *et al.*, 2018), and *Anabaena cylindrica* also has potential growth capabilities on Martian rocks (Mapstone *et al.*, 2022). Research, laboratory testing and *in situ* applications have shown that these species are optimum for various applications. Each species will need to be nurtured, and aligned with — in terms of nutrients, conditions and solar irradiation required for the species to survive.

It is important to be aware of the difference between microalgae and cyanobacteria in terms of what species could be beneficial for bioregenerative futures. Cyanobacteria were previously known as blue-green algae as large density in water would make the color of the water bluish or brownish green. However, cyanobacteria are technically bacteria. Microalgae are, in general, unicellular eukaryotic or prokaryotic plant-like organisms that possess a nucleus, chloroplasts and mitochondria, and can photosynthesize. Examples of microalgae are *Chlamydomonas* and *Chlorella*. Examples of cyanobacteria are Anabaena and Nostoc, which can fix nitrogen from the atmosphere into ammonia. In research for extreme environmental applications, there has been generic favorite species for space-related possibilities. However, more research is needed into which species will benefit each condition. A potential way to work with cyanobacteria in terms of nitrogen fixing on the surface of planets could be the use of novel photosynthetic biomineralized living tissues (Figure 9). This way living tissue can potentially photosynthesize by being embedded with cyanobacteria to produce oxygen, and at the same time fix atmospheric nitrogen. BioServe space technologies, DLR, MIT, and Saarland University are working in collaboration with NASA on a Space Biofilms project, and its primary objective is to characterize fungal and bacterial biofilm in space in a controlled way.

NASA and their team aim at assessing mechanisms that aid biofilm formation in space. Working with photosynthetic tissues, hydrogels and biofilms could alleviate relying on suspension-based microalgae in liquid forms. Supplying water to multiplanetary surfaces will be a gargantuan task as microgravity and mass transport of water must be considered. This transfer of liquids and water may prove to be unnecessary as systems could be developed to produce water on multiplanetary surfaces (Zubrin, 2023). To sustain life on a planet such as Mars from the outset, *in situ* resource utilization is required (Pazar, 2020). Working with immobilized photosynthetic biomaterials in regenerative structures could have many advantages for multiplanetary built environments. However, it is important to consider the use of correct bioregenerative PBR systems for each specific location and application. Liquid suspension can be used for creating oxygen through hybridized PBR systems efficiently, whereas biocomposites may be beneficial to be used on architectures and be an asset for building materials.

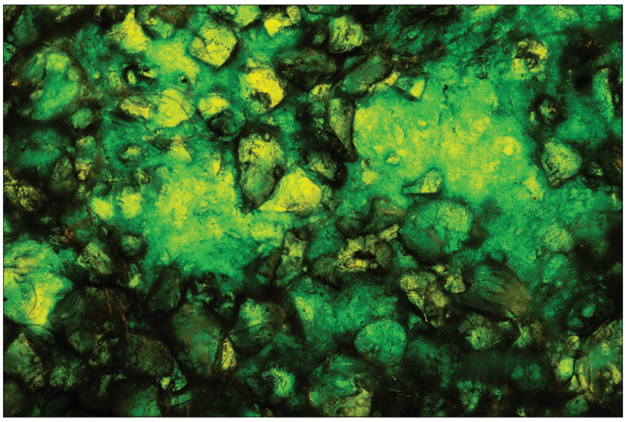

Figure 9. *Tectonic Conferviance*. Emergent texture of photosynthetic biomineralized living tissue formed by the growth of filamentous cynobacteria biofilm (*Oscillatoria animalis*) in hydrogel scaffold. This project was led by Prantar Tamuli, together with Brenda Parker, Anete Salmane, and Marcos Cruz. Source: Image by Ram Shergill (UCL)

The microalgae *C. vulgaris* is considered a resilient species and is an all-round resilient species for bioregenerative applications (Matula & Nabity, 2019; Detrell, 2021; Niederwieser *et al*., 2018; Fahrion *et al*., 2021). The portfolio of species is vast and there are many species of microalgae that require further research. In future research, it will be important to experiment with many species to understand the applications that each species can be of special benefit for, specifically which species would benefit in bioregenerative immobilized biocomposite building materials (Caldwell *et al*., 2021). Therefore, it is feasible that not only one species will benefit bioregenerative algal architecture, but that multiple species will be able to be used for differing applications in space or on Earth. It is not practical to rely on one species.

9. Microalgae: Promising organisms

Photoautotrophic growth with microalgae presents us with the following formula in which *C. vulgaris* conducts photosynthesis.

$$6\ CO_2 + 12\ H_2O + \Delta H_{hv} \rightarrow C_6H_{12}\ O_6 + 6\ H_2O + 6\ O_2$$

(Where $\Delta H h\nu = 2870\ kJ\ mol^{-1}$ glucose)

Photosynthesis of microalgae and cyanobacteria produces O_2, as well as, in some cases, edible biomass from CO_2 and H_2O in Biomass Production Chamber (Helisch *et al.*, 2018). The addition of microalgae and higher plants into a habitat enables breathability and allows humans to be enclosed for long periods. A resilient species of microalgae in a photobioreactor system can allow for breathability for the human in varying atmospheres. Evidence suggests that microalgae have a high harvest index (Hi>95%) with high light utilization (>10%) and do not require as much water as higher plants (Helisch *et al.*, 2018). In photobioreactor systems, microalgae are cultivated in liquid medium (water enriched with the necessary nutrients), enabling long cultivation periods.

Photosynthetic organisms are ideal for absorbing human exhalations of CO_2 in an enclosed environment, as oxygen is produced from photosynthetic activity (Häder, 2020). The exchange rates of CO_2 and O_2 between the human and species are dependent on many factors; these factors can depend on size and body type of the human and how much CO_2 and O_2 the human body produces in an enclosed environment. It would be important to measure CO_2 exhalations from a species, because excessive production of CO2 by the species could be detrimental to a human in an enclosed environment. Any systems created would need to be rigorously managed. Many experiments have been carried out with the *C. vulgaris* strain (SAG 211-12) and research indicates that this strain is a promising candidate and can benefit from long-term cultivation (>180 days). Microalgae can be ideal companions to support humans for long durations if the correct systems and architectures are in place, as they possess the ability to recycle human waste, remove CO_2 and become a provider of O_2 through photosynthetic activity. Even though green algae have the potential to provide life support, it can also lead to certain digestive problems as side effects; however, forms and relational species including cyanobacteria could be digested without huge impact to humans (Escobar & Nabity, 2017). The chosen companion microalgae/cynobacteria species is crucial to the success of a BLSS — for example, MELiSSA has proven that cyanobacteria and microalgae have benefits in bioregenerative systems. This is because certain species, like spirulina, are multi-functional. Various iterations in cyanobacteria biofilms have been created at University College London's bio-integrated laboratory (Figure 9). Emergent photosynthetic living tissue in hydrogel scaffolds could take up CO_2 emissions and be a promising building material.

It is important to assess which species could prosper best in each location, as each species functioning within a designed system will have benefits for each environment it is placed in. On harsher parts of planetary surfaces, temperatures can reach extremely low levels. In these harsher environments, diatoms could be possible candidates to align with sympoietically. Diatoms have the ability to inhabit a great range of hostile environments on Earth. They can be found in polar regions, hot springs and geysers, hypersaline and hyperalkaline lakes and pools. Certain species (*Chaetoceras fragilis* and *Fragilaria sublinearis*) function in extreme low temperatures (Sterrenburg & Hoover, 2011). Diatom frustules can protect the organism through a type of exoskeleton (Figure 10). Having this extra layer of protection can enable the species to be resilient and adaptable to harsh and extreme conditions. The frustule can provide the necessary protection against adhesion, gliding, drying out and forming biofilms and colonies (De Tommasi *et al.*, 2017). In terms of new alignments with species, various species of microalgae can thrive in harsher climatic conditions — such as *Galdieria sulphuraria* and Prochlorococcus *(Hume et al., 2015)* — as

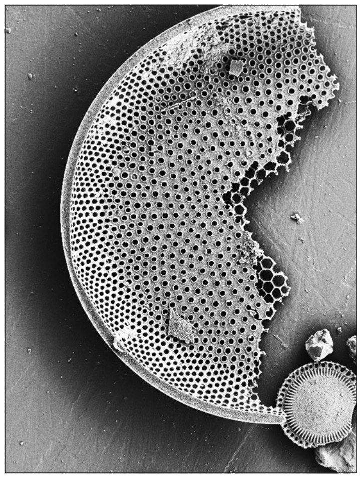

Figure 10. Diatom frustule of *Coscinodiscus*. Source: SEM image by Ram Shergill, Natural History Museum, 2022

well as in space, and these species can photosynthesize in lower/higher light conditions. Recent experiments such as ATMOS (an experiment that studies a species in a 96% N_2 and 4% CO_2 gas mixture with 100 hPa pressure) have shown that cyanobacteria *Anabaena* sp. is suitable for a cyanobacterium-based life support system (Verseux *et al.*, 2021).

The resilient single-cell organism *C. vulgaris* is a eukaryotic green algae species that has an average diameter of 6μm (Vander Wiel *et al.*, 2017). The species can adapt to a range of climatic conditions and pH temperatures; it is resilient to contamination (Lakaniemi *et al.*, 2012) and is competent when facing shear stress. The species was first discovered by the Dutch researcher Martinus Willem Beijerinck in 1890. Etymologically, the name comes from the Greek word "Chloros", with the Latin term "ella" elaborating on the organism's microscopic size (Safi *et al.*, 2014). In the growth of the cell as it reaches maturity, a chitosan or chitin type layer compound of glucosamine is formed (Weber *et al.*, 2022). Once maturity is reached, environmental conditions can change this rigidity, depending on where the species is placed (Němcová & Kalina, 2000). *C. vulgaris* reproduces asexually and at a fast continuous pace; in optimal conditions, it multiplies manifold through *autosporulation* forming daughter cells within its cytoplasm (Yamamoto *et al.*, 2005). These protoplasts divide into groups of 2, 4, and 8 until the mother cell is broken, thus leaving the *autosporangium*. Once this process occurs within 24 h, the daughter cells are set free. *Chlorella* can be seen as a multifunctional species that can be used on Earth for food production, vitamins, minerals, biofuel, bioremediation, wastewater treatment, human health, bioethanol and more. The benefits of working with *Chlorella* become manifold whether the organism is placed in liquid in a photobioreactor, or robotically extruded with hydrogels (Malik *et al.*, 2020).

Fundamentally, a species that can adapt to harsher climates will benefit bioregenerative systems. Algae has been used in many studies and show positive signs of being the optimum organisms to produce oxygen. On Earth, algae produce 50%–80%[2] of the world's oxygen through capturing carbon and creating oxygen by photosynthesis (Pennisi, 2017). Studying the organism in extreme bare-life conditions, allows us to gain insights into how microalgae revitalize air through PBR devices in differing environments. Oxygenic production and CO_2 sequestration needs to be evaluated. It is important to consider that oxygen is not the only primary gas that humans require, as a heady mix of nitrogen, oxygen, and trace gases allow the human and nonhuman to thrive in varying environments.

10. Conclusion

Bioregenerative systems are being implemented and speculated primarily for space applications and multiplanetary surfaces. A large number of possibilities are being considered, such as incorporating and hybridizing bioregenerative cyanobacteria systems with bioleaching on Mars (Verseux *et al.*, 2016), creating new breathability scenarios, extravehicular activities, and much more. While it is good to think of novel ways of interaction with multiple species and habitats on multiplanetary surfaces, it is especially necessary to visualize how bioregenerative algal architectures will enable adaptation to harsher environments. On Earth, there are many current and speculative projects incorporating algal walls and structures into the façades of buildings. However, it is important to consider that bioregenerative algal architecture encompasses structures that are multifunctional and "closed loop" or "partially closed loop systems".

When constructing a bioregenerative algal architecture, the algal species "aligned with" must be managed with care to ensure provision of nutrients. Exchange of resources and many factors need to be considered, as when "designing with life" things can go drastically wrong — such as lack of light, dust storms, power failures, and more. Mitigation measures and "contingency" plans are required in the case of an operational bioregenerative system failure.

Lack of breathability, power, recycling of liquids, urine processing, food, and lack of oxygen will facilitate the needs of projects, such as living architecture on earth (Hogle *et al.*, 2023) or MELiSSA in space. Newer hybrid technologies that mirror the bioregenerative life support systems in space are being speculated for use on Earth. The addition of Sabatier, Bosch and biohybrid engineered architectures embedded into the structures of the built environment on Earth can benefit the future of bioregenerative algal architecture. These types of systems could enable failure-proof methods in living in harsher anthropogenic environments or on multiplanetary surfaces. It is important to acknowledge that bioregenerative algal systems are complex and continuously evolving. Working with living organisms such as microalgae in environmentally fragile atmospheres on Earth, or for surviving in multiplanetary alien atmospheres, will require high levels of maintenance of bioregenerative systems. For efficient bioregenerative systems, it will be fundamental to carry out further research into failure-safe systems, which are hybridized and fully autonomous. In the future, bioregenerative algal architectures will enable physiochemical human and nonhuman "closed loop" life support systems — supporting the necessities of life and existence on multiplanetary surfaces.

Acknowledgments

Thank you to Professor Marcos Cruz (UCL), Dr. Brenda Parker (UCL), and Professor Saul Purton (UCL) for their academic guidance and support in the writing of this paper. Special thanks to Mark Garcia from the Bartlett School of Architecture (UCL).

Funding

None.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

[2] The National Ocean Service, U.S. Department of Commerce, state that 50 – 80% of the world's oxygen is produced by drifting plants, algae, plankton, and photosynthetic bacteria such as *Prochlorococcus* which produces 20% of the oxygen in the biosphere. Anthropocentric issues such as hypoxia create dead zones, where life in the oceans cannot thrive, including eradication of algae and any life systems; this is called *hypoxia* – dead zones.

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Journal of Chinese Architecture and Urbanism

BOOK REVIEW

Building colonial Hong Kong: Speculative development and segregation in the city – A book review

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Abstract

Cecilia Chu, an urban historian, was surprised at her studies that unmasking the 19th-century colonial land tenure system resulted in "good government" in Hong Kong. She found the colonial governance evolved to respect traditional Confucian values of impartiality, integrity, and a commitment to the public interest. The need for Hong Kong government to be self-sufficient by Britain was the original driver for this to happen; that is, the requirement to sell public land to raise revenue from the European and Chinese Speculators essential for the development of Hong Kong. Chu's research revealed that both events and politics over time required the government to move beyond laissez-faire economics and to become interventionist to tackle diseased slum areas and unsafe buildings and to shape new urban development to deliver healthier housing and better environments. Overseas experience of epidemics had led to a growing understanding of the relationship between health and economy in the 19th century. Populations fleeing Hong Kong during epidemics served to demonstrate that the city needed to be healthy if it was to prosper. This caused the government to adopt interventionist policies. In particular, the government intervened in its land sales strategy to reduce fiscal revenue income from sales to induce the private sector to contribute towards social provision in public health, housing and modern town planning. It also had a bearing on colonial segregation strategies to reflect d ifferent ex pectations of th e Eu ropean an d na tive Chinese communities. Crucially, while the colonial administration remained in power, greater involvement of the Chinese elites in the bureaucracy gave legitimacy portraying Hong Kong as a "land of justice." This demonstration of "good government" helped maintain the loyalty of the Chinese merchant elites and native Chinese population.

Keywords: Hong Kong; Land tenure; Fiscal system; Laissez faire; Economy; Health

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Citation: Walls, J. (2023). Building colonial Hong Kong: Speculative development and segregation in the city – A book review. *Journal of Chinese Architecture and Urbanism*, 5(3): 1110.
https://doi.org/10.36922/jcau.1110

Received: June 20, 2023

Accepted: July 6, 2023

Published Online: July 27, 2023

Building Colonial Hong Kong: Speculative Development and Segregation in the City. By Cecilia L. Chu. Routledge. 2022, 228 pp. ISBN 9781138344655

Cecilia Chu's book on Building Colonial Hong Kong emerged from her research on the development of Hong Kong between the 1880s and 1920s. As an urban historian, she marveled at the realization that her studies revealed the colonial land tenure system established in the mid-19th century had led to "good government," namely, a form of governance which emphasized impartiality, integrity, and a commitment to the public interest. For the Chinese, Chu concluded that the defining feature of Hong Kong was its civil order, rule of law, and market freedoms not available in their home country.

How this evolved in a freeport established by a British Colonial Government committed to laissez-faire economics is exposed in a series of histories outlined in Chapters 2 to 6 of her book. Her opening chapter sets the scene for her arguments and includes her conclusions. The requirement by Britain for the Hong Kong colonial government to be self-sufficient was the original driver to raise revenue from land sales to European and Chinese Speculators who were needed to build Hong Kong. As most land in Hong Kong is owned by the government, the regular sale of leaseholds as Hong Kong grew produced a good proportion of the fiscal budget. (Overseas readers unfamiliar with Hong Kong's fiscal system will find it useful to read *Land Premium and Hong Kong Budget: Myths and Realities*, a short paper by Liu (2015), Chinese University of Hong Kong).

Chu's research reveals over time that both events and politics required the government to move beyond laissez-faire economics and to become interventionist to tackle diseased slum areas and unsafe buildings and to shape new urban development to deliver healthier housing and better environments. Populations fleeing Hong Kong during epidemics showed that cities need to be healthy if they are to prosper. This tallied with overseas experience because there was a growing understanding of the relationship between health and economy in the 19th century. The result was to induce a shift in colonial land strategy to accept reduced land premiums and rely on the private sector to help pay for social provision. This also had a bearing on colonial segregation strategies to reflect different expectations of the European and native Chinese communities. The measures adopted reflected the need to maintain the loyalty of the Chinese merchant elites and native Chinese population.

It is not possible to do justice to Chu's histories fully illustrated by contemporary photos, maps, drawings, and plans in this short review. However, a few examples below help give a flavor of her research. They give illustrations of how the forces for change emerged through the operation of the land system and why the government intervened in the public interest. Chu's narratives include "people" stories and their influence on shaping public policy, which adds to the book's strength.

In Chapter 2, Chu describes how the colonial land system took on its form in the mid-19th century under Captain Elliot, the first administrator. With the 1842 Treaty of Nanking (present Nanjing), all lands in Hong Kong were ceded to the British, and with that Elliot established a leasehold system for land sales, later known as premiums. The key benefit was that the leases provided a strong statutory power over development. Despite this power, the colonial government allowed the market to dictate the pace of urban growth which was central to Hong Kong's success.

In 1894, there was an outbreak of bubonic plague, which came after many years of concern about the unsatisfactory growth in water supply to match the growing population and concerns about poor sanitary arrangements, especially in the working-class native Chinese tenements. As described in Chapter 3, the plague victims were mostly located in the dense Chinese district of Taipingshan. A Sanitary Committee was established to investigate the causes and they concluded that the area should be demolished and redeveloped to protect the wellbeing of the population. However, rather than being seen as a triumph at the time, the resumption (i.e., compulsory acquisition) of the area necessary to do this was challenged by the landlords on costs. In government, the decision to resume was only carried by one vote. The game-changing vote was cast by Dr. Ho Kai, an unofficial member who also sat on the Sanitary Board and the Housing Committee. He had long sought to educate the native Chinese about Western medicine and ideas of public health.

Despite this intervention, the bubonic plague continued to return on an annual basis. In Chapter 4, Chu outlines another step forward in colonial administration. In 1903, Governor Henry Blake tried an experiment in the Sai Ying Pun area. He persuaded the Sanitary Board to transfer the management of two tenement blocks to him when the disease risk was high. Blake asked for volunteers in the local community to form a *kaifong* (a street committee, a traditional, informal Chinese governing unit). This appeal was successful and gained the support of the Chinese merchant elites. While the initiative did not ultimately eradicate the plague, no bodies were abandoned in the street and residents willingly reported sickness, unlike previously badly handled epidemics. This approach helped cement mutual dependence between the British administration and the Chinese merchant elites.

Chu also looked for evidence of colonial racial segregation in her studies including Singapore (Yeoh, 2003) and Calcutta (Chattopadhyay, 2005). Her research revealed that the use of discriminatory policies in all places was hindered by corruption, a need for public funds and vested property interests. Bowing to speculator pressure and public sentiment, European reservations made provision for "respectable persons", namely, anyone who had adopted Western ways of living and had achieved commercial success. Thus, colonial attempts at segregation were tempered (Lugard, 1965). Interestingly, a local planning historian, Lawrence Lai, provided a "nuanced analysis" which pointed to the early colonial Hong Kong administration protecting the European community from powerful speculators (Lai *et al.*, 2011). The downside was that European property values were lower, something eventually challenged by European owners after World War II, when they appealed to government to lift the protection to obtain the best prices.

These histories of Chu's reveal the colonial government's recognition that public health and economy are interlinked. The events she covered include disease outbreaks (2500 died in 1894 from the bubonic plague), building collapses (43 deaths in 1901), and the colonial government's recognition of the health benefits of modern construction, sanitation, and town planning. The lessons learned led to the government introducing the following interventions:

- Land resumption to enable redevelopment
- Changing speculators' behavior with low interest loans allied to delivering better building standards
- Crafting special leases to promote modern tenements for Chinese workers and "garden city" enclaves for Europeans
- Rent controls to discourage land speculation (for instance, a new Town Planning Scheme in Kowloon triggered land price increases of up to 400% in 1922).

These histories of Chu's confirm that the Hong Kong colonial administration changed from being totally laissez faire to one which was prepared to intervene in the public interest, not to mention, willing to embrace Chinese elites in the bureaucracy of government. Of course, one cannot forget the 19th-century corrupt and dysfunctional Qing, and later Republican, governments in mainland China during the formative stages of the colonial government. For the native Chinese, elite or otherwise, Hong Kong was a place of stability, opportunity, market freedom and prosperity, unlike the corrupt and dysfunctional Qing, and later Republican, governments in mainland China.

I enjoyed reading this scholarly, well-researched, and richly illustrated book, which greatly enhanced my knowledge of Hong Kong's history. This book will appeal to a wide range of audience, including historians, urban geographers, government policymakers, architects, engineers, surveyors, and public health and housing experts. While the pricey hardback issue is not likely to appeal to students and the general reader, the paperback issue due out later this year will make the book more accessible.

Acknowledgments

None.

Funding

No funding support was received for the preparation of this book review.

Conflict of interest

The author has no competing interests relating to this book review.

Author contributions

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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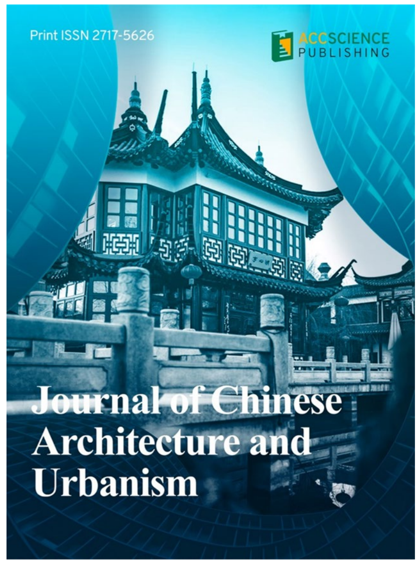

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