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Beyond Nature-Based Rhetorics: A Prospect on the Potentials of Redundancy in Ecology-Oriented Design

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Abstract: Nature-Based Solutions are defined as infrastructures or systems which are inspired by, supported by, or copied from nature. This biophilic *leitmotif* has rapidly permeated and been prescribed in many fields, particularly in urban and architectural design, stimulating an invasion of green rhetorics not necessarily founded on genuine ecological performing. In this context, this article explores current gaps in the epistemology and rhetorics of NBS, expanding the field with alternative narratives such as cycle-based design and micro-scalar or process-oriented approaches. The concept of redundancy is here presented as a non-observable, still nature-based principle, already applied in disparate scientific fields such as information theory, cybernetics, or evolutionary biology, and introduced in design fields from a theoretical perspective. Novel applicability of the term will be articulated from design perspectives through various case studies, using a multi-scalar scope and concluding in a tentative taxonomy. Redundancy entails a shift from grammar-based to syntax-based design logics. Morphological redundancy is presented as an upgrade of NBS rhetorics, delivering a more advanced understanding of the hidden choreographies of nature.

Keywords: Ecological design; form-finding; ecological syntax; closed-cycle design; efficiency; redundancy

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1. Introduction: Exploring the Rhetorics of NBS

From a historic perspective, the coupling of ecology and design entangles a historical paradox since every act of building necessarily implies a shift of ecological relationships [1] (p. 576). In fact, the terms ecology and design appeared together right before the beginning of the ecological movement [1]. *Survival Through Design* was published by Richard Neutra in 1954, advocating for a sort of 'biological realism' but giving little indication of its practical applicability. The book remained quite neglected by designers until the 1960s, when publications as *Silent Spring* by Rachel Carson (1962) and *Design with Nature* by Ian McHarg (1969) provoked the spreading of numerous and fertile environmental design debates. In the early 1970s, interdisciplinary discussions among urban ecology and environmental design were able to operationalize how nature could empirically and accurately inform design agendas.

Currently, the sociopolitical acceptance of the Earth's climate crisis has particularly mobilized ecological design as one of the main political concerns in the European Union. That dissident counterculture of the 1960s transcends today to official policies and regulations. In line with the terminology of 1960s environmental activism, current European research programs such as Horizon 2020 have recovered former terms such as renaturation, resilience, or rewilding, with special emphasis on the so-called Nature-Based Solutions. In apparent opposition to earlier, technology-based approaches, Nature-Based Solutions

(NBS) are defined as infrastructures, systems or elements which are inspired by, supported, or copied from nature [2].

As shown in Figure 1, the term NBS has been recently and widely adopted in many fields. A rapid semantic interpretation can enlighten some of the related misconceptions of the term. The first one derives from the presumption of success implicit into the word *solutions*, leading to a certain prescriptivism on the NBS toolkit, a sort of cookbook with few ready-made globalized implementation formulas. The emphasis on the solution might also weaken the necessary effort to confront a problem scoping on a local basis able to display customized solutions (based on nature or not). The second misconception lies in the dialectical consideration of *nature* as an outer entity, which can be systematically re-produced inside the urban realm. In all, this nature-based reproduction is seemingly acknowledged to operate as a healing patch for climate-change-related issues [3]. All these assumptions are stimulating an invasion of green rhetorics and motivating the increasing adoption of ecological allegories in urban design [4,5]. Yet, nineteen-century urban designers adopted clear but ‘inexact metaphors’, such as the designation of parks as urban lungs [6] (p. 27). In the worst case, it is deriving what has been coined as a ‘sustainability fix’, or how urban regimes are incorporating the green agenda to ostensibly ‘greening the urban growth machine’ [7] (p. 224).

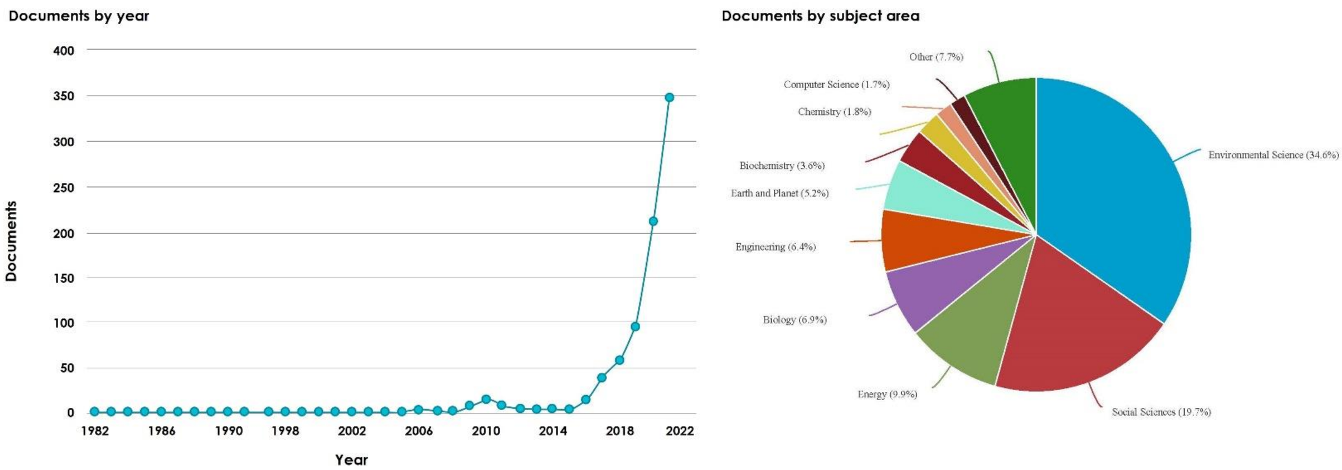


Figure 1. Frequency and prevalence of NBS cited documents, organized per year and subject area. Source: Elsevier Scopus.

This misinterpretation might also relate to the fact that most of the functions and relations among form and performance in natural systems are not observable naturalistically and are often simplified in their application. Even if urban ecology has largely contributed to understanding how urban ecosystems operate and how they differ from natural ecosystems, these studies often ‘simplify either the human or the ecological dimension’ of cities [8] (p. 10). In fact, this complex entanglement among natural and human ecosystems is rarely acknowledged. Conventional NBS approaches in cities, such as green roofs, floodplains, intensive greenery, or urban gardening, are not always accounting for ‘the processes through which humans affect or are affected by the urban environment’ [8] (p. 10). Intensive vegetation in cities can indeed help mitigate noise pollution, reduce heat-island effects, and improve air quality, but its indiscriminate use can also cause adverse ecological effects, which are barely mentioned in the state of the art. The introduction of some plant species can increase particle concentration levels and have effects on sensitive populations; planting the wrong tree species next to traffic hubs can complicate the dispersion and deposition of polluting particles; installing lawn areas entails the use of great amounts of organic and inorganic fertilizers, which filter through the soil, reaching subterranean water courses [9,10].

Alternative discussions are promoting more advanced nature-inspired strategies beyond conventional NBS green rhetoric, introducing novel scopes, other scalar magnitudes or even unscenic aesthetics. In the 1970s, early urban ecology research demonstrated that the application of ecological logics to the built environment subverted conventional design approaches, emphasizing that genuine design should rather deliberate on energy and matter cycles rather than on shape and form. Ulterior environmental findings advocated for *rewilding*, a process-oriented conception promoting the conservation and expansion of wild areas at territorial scale to restore the connectivity of natural ecosystems within urban and peri-urban contexts [11]. To some extent, rewilding can be considered the conceptual antithesis to Nature-Based Solutions, as instead of trusting in nature domestication, it relies on the devolution of nature in its wild state, perhaps laying below the urban ground. On the other hand, recent findings on *morphogenetic design* show that our urban systems are only 'conceptually and mathematically' accurately related to the metabolism of natural systems at a micro-scalar examination, and therefore require a dramatical methodological change [6] (p. 30). According to these studies, the robust design of natural systems is not based on optimization and standardization, but on 'redundancy and differentiation', hitting the bases of long-held design assumptions, as they have been for decades efficiency and optimization for the built environment [12] (p. 27).

This article explores the limitations and expansion of current NBS rhetorics with novel approaches and definitions from former and current agendas. In particular, the concept of redundancy, drawn from natural systems, will be centrally discussed and problematized from different disciplines. The results will demonstrate, from a designer perspective, how the strategy of redundancy is applicable to a range of scales, from urban networks to building structures. The replacement of efficiency by redundancy is unlocking novel possibilities beyond the NBS rhetorics, paving a possible agreement between the disparate concerns of form and performance in environmental design.

2. Methods

The method developed will be based on a historical correlational review of the purpose and validity of natural references in ecological design. The discussion will seek to define their legitimacy and practical limitations. In this context, the article explores alternative narratives such as cycle-based design, and micro-scalar or process-oriented approaches. This paper uses a methodological framework with the definition of three design parameters: efficient form, contextual form, and visual form. They will be discussed with alternative performance-related parameters, able to clarify the previous assets and propel novel questions. The concept of redundancy, drawn from natural systems, will be liaised with disparate fields such as information theory, cybernetics, or evolutionary biology. From a designer perspective, the term will be scanned through various examples using a multi-scalar scope and proposing a tentative taxonomy. The typological component has been intentionally neglected in the compilation of examples, merging disparate programs such as conservatories, cathedrals, ecological prototypes, or urban design. Many of them belong to experimental realizations, supported in many cases by academic research, and there are only a few realizations, as the article does not seek so much the ratification of an existing phenomenon, such as the clarification of its imminent appearance. This article will address the syntactical complementarity among the perspectives of nature-based form and performance though a design syntax.

3. Early Nature-Inspired Strategies: Cycle-Based Design

Despite the many efforts made by designers to take direct inspiration from nature, the most relevant contributions to environmental design came from distant fields such as aerospace engineering, evolutionary biology, or military research. The space program launched by Kennedy in 1961 pictured life in space as a voluptuous alternative to the Earth's ecological crisis. Even if the reference of nature was extra-terrestrial, it brought inspiration to environmental designers through novel archetypes and energy-saving devices literally taken from the spaceship repertoire [13] (p. 528). The Ecological Society of America launched a lectures series between 1963 and 1965 entitled Human Ecology in Space Flight, which established novel and fertile alliances between space researchers and ecologists, mathematicians, biologists, and engineers. This breeding ground prompted novel methods to quantify and map the complete set of energy and matter flows occurring inside closed aircraft ecosystems, a term which will be later coined as the *cabin ecology* [14].

One of the prominent contributors to this statement was ecologist Howard T. Odum, whose closed-cycle diagrams contributed to the understanding of the cabin ecology in qualitative, nearly visual terms. A pioneer in applying the language of information systems into ecological modelling, his looped drawings unlocked the full potential of energy mapping for engineers, and also for designers. The space capsule was presented by Odum not 'just as a vague metaphor', but as an ontological claim about ecological thinking [15] (p. 115). Even if sharply reduced to energy accounting, Odum revealed the obscure hardware of natural systems to a household arena, and provoked important reactions into many disciplinary fields beyond the boundaries of ecology. Buckminster Fuller was probably the first architect presenting the cabin ecology as a metaphor of life on Earth. Aware of Odum's findings, he unlocked the applicability of the cabin ecology for designers, driving a mandate of self-sufficiency for buildings and entire cities. As a remedy for the depletion of natural resources, his discourse Operating Manual for Spaceship Earth (1969) promoted the ecological management of cities and propelled a decisive influence on a whole generation of designers. Even if Fuller was self-described as a design scientist, he overtrusted on architectonic form and technological mediation to cope with complex environmental problems.

Even if ecosystems were crucial references for urban designers, the first empirical reproduction of a closed ecosystem—yet on a small scale—was developed outside the disciplinary boundaries of design. A new generation of ecologists and countercultural architectural groups combined cybernetics and biological science to decipher the logics of natural ecosystems and experiment with autonomous living, displacing the 'dominant views of nature' previously extant in US culture [16] (p. 21). Founded by biologists John and Nancy Todd and oceanographer Bill McLarney in 1969, the *New Alchemist Institute* was 'looking to the natural world to develop a science (...) mimicking its materials, processes, and dynamics' [17] (p. 194). In line with Odumian principles, they were able to fabricate so-called bio-shelters or Living Machines, as closed life-support systems with the goal of self-sustainable functioning. The Living Machines were able to assemble 'hundreds of species, ranging from small trees to anaerobic micro-organisms' but recombined in totally novel forms [17] (p. 195). With a minimum of three distinct intertwined ecosystems, the machine was able to perform basic ecological functions 'such as energy generation, waste processing, weather regulation, or all at the same time' [18] (p. 169). By means of connecting food production and waste processing, these experimental farms opened wide the standards of self-sufficiency and autonomous living.

A more fruitful application of Odumian learnings was drawn by Belgian botanist Paul Duvigneaud, director of the Belgian sector of the *International Biological Program* between 1964 and 1974. Duvigneaud was commissioned to measure the productivity of forest ecosystems at Mirwart, in the southeast of Belgium. The project required installation of a series of stations which initially measured metabolic activity of forest ecosystems. With the progress of the project, as the area was enlarged, containing rural settings, measures started to include the impact of human activity, ending with comprehending the full area of Brussels [19]. His cross section of the city showed the complexity of energy and matter flows travelling below and across urban boundaries, inaugurating a new way of mapping territorial relationships [20]. The metabolic modelling of the city was not a poor replication of the forest ecosystem, but rather a more complex organization able to 'inscribe the city's ecology with human-made systems' [21] (p. 9).

Early in the 1970s, designing with nature was openly operationalized as a matter of cycle syntax. The displacement of natural laws 'from the domain of wilderness to the domain of buildings' invoked unknown capacities for architecture and design [22] (p. 19). Todd's *Living Machine* anticipated that 'the real design is the cycle', and form—the classical idea of design—was only an image under permanent transformation [23] (p. 24). However, the biological paradigm tackled by Todd will not fully be understood by planners and designers until the arrival of more accurate observation technologies.

4. A Novel Nature-Based Rhetoric: Redundancy

As previously presented, the complex performance of natural systems is only accurately applicable to our urban systems at either micro- or macro-scalar examination. According to recent studies, the robust design of natural systems is largely dependent on non-observable strategies such as redundancy and differentiation. The strategy of redundancy in ecosystems requires a surplus to functional requirements, appearing when various species are performing similar functions. In biological terms, morphological redundancy is based on the repetition of apparently identical body segments of an organism, some of which might assume vital reproductive functions, while the rest would contribute to experimental change and adaptation. Redundancy explains the extraordinary rapid evolution of some animal species, (see Figure 2) and is an essential strategy 'without which adaptation and response to changing environmental pressures would not be possible' [12] (p. 27). The earliest scientific use of the term is due to Harry Niquist in 1948, who coined it in reference to the superfluous or duplicated parts of a given message, performing as a basic noise permeating the message [24]. At present, this definition is no longer valid as it has been demonstrated that redundancy ensures reliability and reduces the possibility of failure. The term has largely been applied in disparate scientific fields such as information theory, cybernetics, or evolutionary biology. Redundancy in our language, as in evolutionary biology, is indeed considered a 'source of creativity and innovation' [25] (p. 226). However, neither the engineering discourse of information nor the evolutionary discourse of biology 'have specified the dynamics of redundancy' [26] (p. 1187). This assumption may relate to the fact that redundancy is 'not observable naturalistically' and cannot therefore be the subject of positive theorizing [26] (p. 1185).

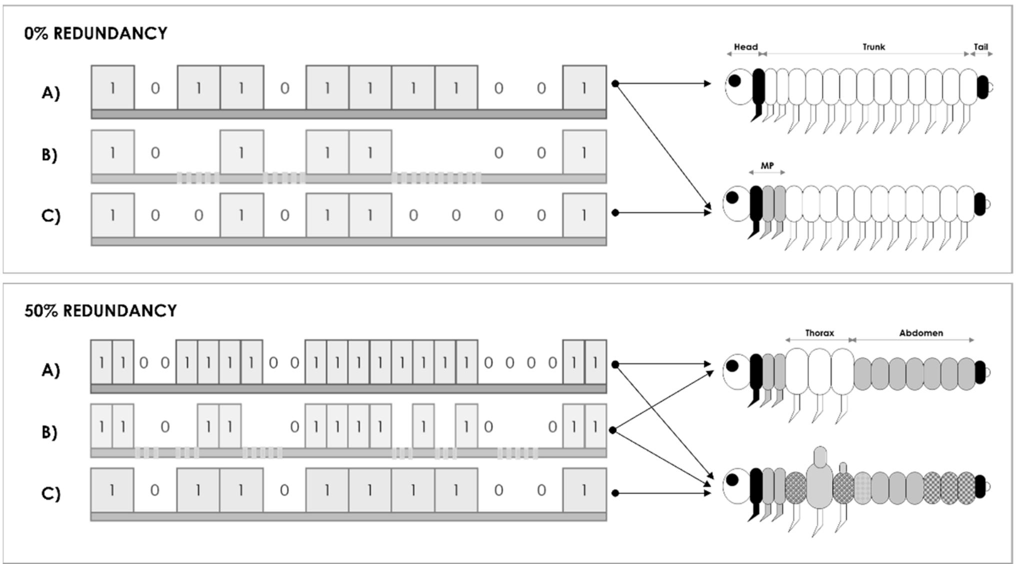
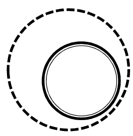
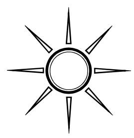
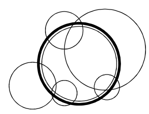
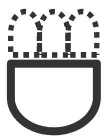
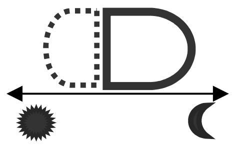
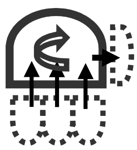


Figure 2. Redundancy principles applied comparatively to either information theory or morphogenetic evolution. (**A**) Signal transmitted, (**B**) signal received, (**C**) signal interpreted. Based on C. E. Shannon, Mathematical Theory of Communication (1948) and L. Gatlin, Information Theory and the living system (1972). Source: Authors, 2021.

The contributions of redundancy for architecture and urban design are however quite recent. Authors such as Lars Spuybroek, practitioner and teacher at the Georgia Institute of Technology in Atlanta, or Michael Weinstock, Director of the Emergent Technologies and Design program in the Graduate School of the Architectural Association, London, have published ground-breaking contributions around the conceptual, structural, and geometrical applicability of redundancy for the built environment. As stated by Lars Spuybroek, redundancy in design presents a 'morphology of the provisional, not the optimal', providing a full upgrade of the postmodern concept of efficiency [27] (p. 198). However, the term can still be further explored and extended to other scales and methodological means, giving consistency to this emergent state-of-the-art. Contributing to filling in this gap, the results of the article will be structured into a multi-scalar and multidimensional taxonomy based on three ecological design principles, namely *efficient form, contextual form, and attractive form* [28]. These parameters attend to current architectural theory and environmental practice, but also to a deep understanding of the formal strategies found in nature, namely conservation, connection, and attraction. Representative of different magnitudes, these criteria are arranged in Table 1 through a coherent spatial sequence attending to either position (1D), dimension (2D), or conformation (3D). They are thus presented as not mutually exclusive, but rather connected through a syntactical complementarity [29]. Considering that these parameters are described in a formal basis, the results in the following chapters will be centered around still nature-based but complementary performative aspects.

Table 1. Nature-based references applied to form and performance in relation with ecological design principles based on Hosey (2012). Source: Authors, 2021.

	Conformation/3D	**Dimension/2D**	**Position /1D**
Nature- Based Form Efficiency	**Efficient Form** Conservation Form-finding	**Visual Form** Attraction Visibility	**Contextual Form** Connection Symbiosis
			
Nature- Based Performance Redundancy	Morphological redundancy Form-coupling	Structural Redundancy Hyperstatism	Infrastructural redundancy Ecological syntax
			

4.1. Morphological Redundancy: Form-Coupling

Objects in nature exhibit a strong formal coherence. When wind and water erosion reveal a mountain wall of sedimentary rock, 'we can observe the fine horizontal strata resulting from these phenomena' [30] (p. 12). Buildings are subject to the same natural forces affecting natural structures, such as wind, sun, or gravity, but 'they rarely acknowledge these forces' in their configurations such as natural and biological structures do [31] (p. 50). Opposingly, recent experiments of morphogenetic design have led to the idea that nature-based forms (biomorphic) would enable buildings and cities to function like living organisms, but this possibility can hardly hold valid beyond the 'mimicry of engineering' solutions [32] (p. 45). While definitions of form-efficiency have been largely accepted by design discipline, the connection with specific formal parameters is a pending matter.

Form efficiency in nature is readable through the differentiated geometries of the sphere and the fractal, performing adequately to either conservation or distribution vital functions. The same form efficiency is clearly acknowledged in vernacular housing types such as the continental hut or the igloo, respectively advocated to solar exposure or thermal conservation. In this repertoire, form-finding mechanisms conventionally attend to stationary climatic conditions, giving preference to either summer or winter conditions according to the latitude. However, in most climates, the need for thermal conservation in winter is replaced by an equivalent need for solar protection and ventilation in summer, so environmental adaptation follows a dynamic pattern.

For the shake of precision, we will clarify some form-efficiency subsidiary concepts. As defined by thermodynamic physics, *thermal form* defines the conductivity of the outer surface of a given entity. An efficient thermal form would thus correspond to a low surface-to-volume ratio, so the sphere, as we find it in many natural forms, would be 'the best form of thermal conservation' [33] (p. 329). If looking into the built environment, thermal form would indicate compact envelopes, typically found in vernacular prototypes like the continental hut or the igloo. Conversely, *solar form* is responsible for an adequate sun-accepting ratio, and, unlike thermal form, it depends on surface orientation and size rather than on shape. While the sphere is the most efficient thermal form, a south-facing flat rectangle would provide better uptake for solar radiation in winter and an easier defense against summer radiation. In this sense, the tetrahedron presents the highest surface-to-volume ratio among the platonic solids, and therefore presents the best example of solar efficiency.

Great contributions on form efficiency were made by leading architects of the post-war arena. The geodesic geometries designed by Buckminster Fuller from 1940 onwards were able to reduce heating and cooling loads but were however insufficient to achieve acceptable comfort conditions in winter, as in them thermal form was prioritized over solar form efficiency. His experiments were later applied to the design of living environments proving that, even if domed geometries have an optimal surface-to-volume ratio, they were hardly adequate to cope with both summer and winter conditions. At the end of the 1960s, a new generation of architects acknowledged Fuller's principles evolving into 'nontraditional efficient structures' [34] (p. 80). Steve Baer's *Zomes* in New Mexico (1963) are considered a pioneer and successful hybridization of thermal and solar form. As we will demonstrate, Baer's dome-shaped zonohedron designs are closer to the typological findings of nineteen century hothouse tradition in UK than to any closer modern reference.

The apparent contradiction between solar radiation and thermal conservation was effectively solved by many nineteen century conservatories in the UK. The opportune assembly of domed and prismatic forms demonstrated to respond efficiently to either solar gain or thermal conservation. English gardeners and landscapers as Sir Thomas Wilkinson, Sir John McKenzie, James Anderson or John Claudius Loudon made important contributions in this regard, giving shape to audacious typological combinations. Curved glass roofs were attached to masonry walls, intertwined domed, gabled, or half-doomed roofs, acknowledging the benefits of coupling disparate forms and thermal inertias [35]. The production of greenhouse solar types along the Victorian period drove a 'random, multidimensional, combinatorial, radically novel process' similar to the creation of hybrid species in morphogenetic engineering [36] (p. 122). However, as shown in Figure 3, the advantages of form-coupling in the first prototypes were dismissed as soon as big conservatories were dependent on mechanical heating. In the second half of the nineteen century, big conservatories were formed according to rather symmetrical platonic volumes. The increasing dependance of big conservatories on artificial heating and the later fuel shortages of World War I in the UK would explain why the solar form-coupling tradition of nineteen century conservatories was not well accounted for by modern designers [37].

While form efficiency defines the contrast 'between buildings of one climate zone and another', morphological redundancy resolves the 'contrast of the building with itself' [29] (p. 8). The logics behind form-coupling strategies in bioclimatic architecture are not far from the morphological arrangements lying behind many adaptative biological processes. Duplication and differentiation are responsible for the robustness and adaptation capacity of many natural systems. As in Victorian conservatories, the coupling among disparate geometries inside the built entity is dependent of a syntactic logic, a distinctive compositional strategy of bioclimatic architecture and ecological design [38].

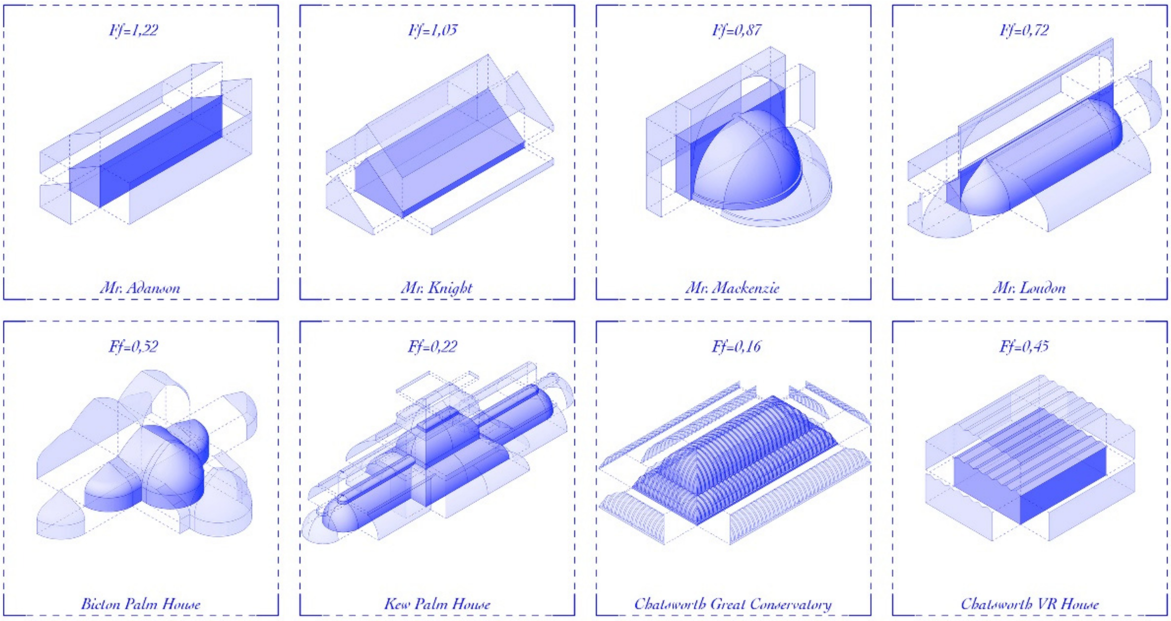


Figure 3. Evolution of form-coupling strategies according to surface-to-volume ratio in various nineteen century hothouses in England. 3D models are rendered according to research on original drawings and sketches from authors. Reproduced with permission from Moraleda, J. Mestre, N. 'The automatic garden. Typological variations in the hot-house architecture', published by UPM School of Architecture in 2017.

4.2. Structural Redundancy: Hyperstatism

Many scholars agree in requiring a visually appealing form to promote a novel and self-conscious experimental agenda for ecological design. Even if much research has focused on how to apply nature-based models in the built environment, the role of formal and aesthetic concerns has proved slippery [39]. The main examples described beforehand derived from a subtle polemic, a certain divorce among form and performance which is still reflected in the current discourse on ecological design. In fact, experimentation with form in architecture has been largely critiqued as formalism, considered by many practitioners a superficial parameter 'disconnected from the actual work of design' [40] (p. xxi). In the other hand, current agendas of ecological design assume that form is necessarily linked with the 'progressive automatization of form-finding computer processes', which appear as displacing the authorship of designer [41]. However, the fundamental relevance of form can be 'so obvious that might not receive the due attention' [42] (p. 20). This shift 'from metrics to aesthetics' will contribute to unlock the unexploited potentialities of alternative nature-based rhetorics [43] (p. 248).

In this sense, redundancy can again provide novel narratives. As it requires a surplus to functional requirements, it also relates to the idea of accumulation, which is directly opposed to the classical idea of efficiency or reductionism [44]. In classical engineering, redundancy is a desirable property as it ensures the safety of structural systems [45]. This condition typically stresses the ability of a structural system to redistribute loads among its various members or supports under accidental or unpredictable scenarios. The benefits of structural redundancy were in fact acknowledged, rather intuitively, by Gothic builders. Redundancy in Gothic structures defines the availability of an abundant, excessive number of supports and the initial indeterminacy of the available ribs, performing as robust hyperstatic structures [44]. By means of redundancy, Gothic structures not only proved to be robust but also succeeded in 'converging existing forces into form', defining a self-conscious and novel aesthetic repertoire for architecture [44] (p. 16). Similar searches for optimized structures were acknowledged by modern architects, such as Frei Otto at the Institute for Lightweight Structures or by Antoni Gaudí at the Sagrada Familia. Inspired by natural systems, their structural experiments consisted of processing gravity forces into physical models by transforming flexible materials, 'a special form of analog computing' [46] (p. 352).

Beyond the benefits of this sort of analog computing demonstrated by classic static calculation, redundancy is also applied in contemporary 3d printing software, such as *Autodesk Print Studio©*, *UltimakerCura©*, or *MeshMixer©*. The software calculates auxiliary structures (printing assistants) which are redundant with the main structure so can be removed when the extruded material is sufficiently solidified to be self-supporting [47]. The software operates with an algorithm that considers various parameters, such as the minimum use of material, the solidification speed, the optimal extrusion paths, or the smallest contact surface with the main piece they support. The geometries resulting from this algorithm are typically fractal or tree-like (see Figure 4). Applied to additive manufacturing techniques, structural redundancy might move from simple prototyping to inspire novel and 'eco-efficient' design solutions [48] (p. 183).

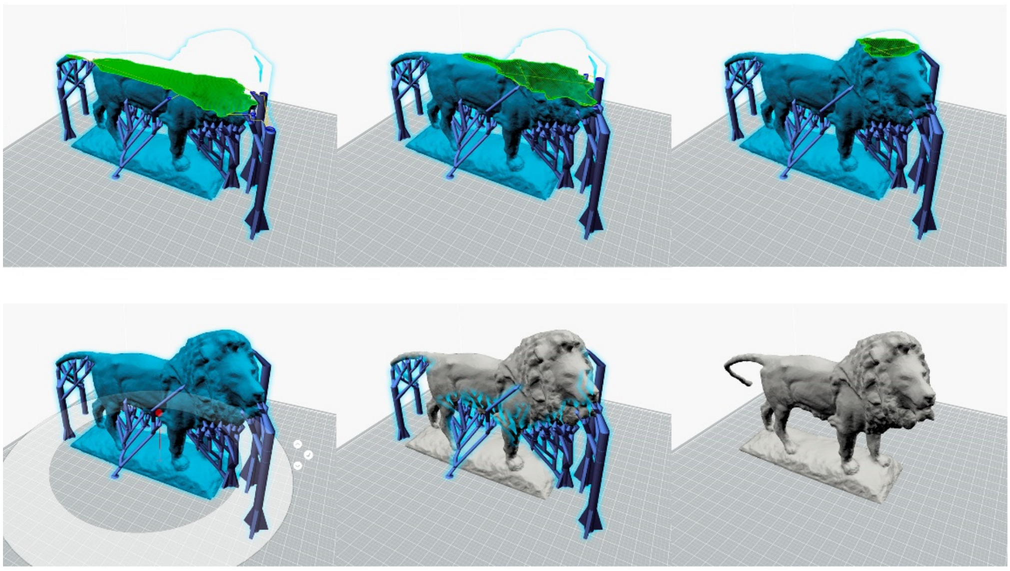


Figure 4. Redundant tree-like structures generated by *Autodesk PrintStudio* to fabricate a complex round-bump shape. Reproduced with permission from Galindo, J. & Mestre, N. Optimal and redundant: a historical retrospective on form from the round bundle to the 3d printing. Published by UPM in 2018.

4.3. Infrastructural Redundancy: Ecological Syntax

The highly demanding assets imposed by environmental comfort have led to the false conclusion that ecological design should be conformed from the sole consideration of efficiency, leading to over-trusting in form-finding techniques [32]. However, the concept of contextual form defines another condition, a 'non-resistive relation of architecture with the environment' [29] (p. 101). The concept of contextual form in natural ecosystems was for the first time translated to spatial diagrams by ecologist Howards T. Odum. His differentiated diagrams of horizontal and vertical ecosystems showed that natural ecosystems are typically nested at various levels, revealing that they 'do not only have the capacity to learn', but also to respond creatively to environmental uncertainties [16] (p. 20). As shown in Figure 5, subsequent analyses of Brussels city from Paul Duvigneaud showed that human activity was 'intimately connected' to botanical biodiversity, proving that urban ecosystems were biologically as productive as mature tropical forests [19] (p. 30). With the contributions of Duvigneaud or John Todd in ecosystem modelling, nature-based design was for first time defined as a matter of a cycle-syntax. As early demonstrated by urban ecology, cities might achieve 'the same interdependent efficiencies and life-saving' redundancies as those contained in natural ecosystems [49] (p. 32).

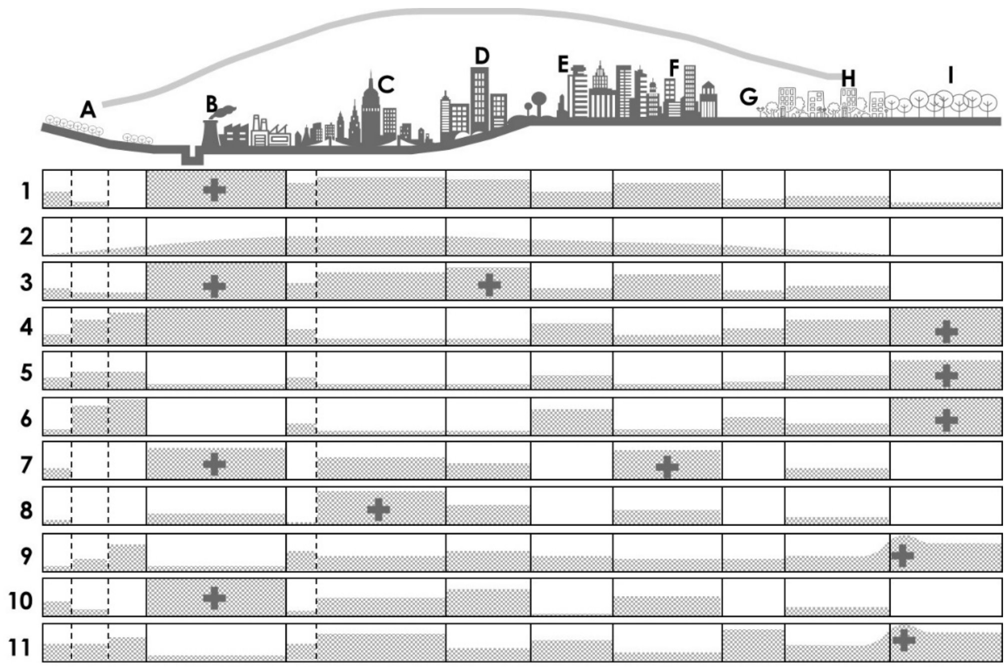


Figure 5. Brussels ecosystem, with subsystems (A–I) and ecological factors (1–11). Based on Duvigneaud, P., Denaeyer-De Smet, S. and Tanghe, M., 'Importance de l'écosystème urbain et des sous-systèmes'. (1975). Source: Authors, 2021.

The understanding of cities as coupled human-natural systems entails designing 'nested sets of adapted cycles' similar to, or even more complex than ecosystem networks. This assumption will start favoring infrastructural redundancy as an operative clustering among diverse infrastructural levels, reusing waste flows from one function into others. Infrastructural redundancy will allow for opportunistic coupling between complementary urban functions, connecting waste and demand flows in new metabolic pathways, following 'the symbiosis principle of nature' [50] (p. 268). As in Todd's Living Machine, it is crucial to establish the number of entangled species, as the level of 'functional diversity' required to make urban ecosystems resilient [8] (p. 92). Besides, a new type of exchange infrastructure would be required to operate at a smaller scale than our current energy networks, turning their current end-of-pipe lines into feedback loop chains. These entities have been recently coined by Dutch architects Jongert, Nelson and Korevaar as 'cyclifiers', metabolic processors that perform in ecological niches increasing resilience [51]. Urban metabolism is not presented as a spontaneous logical process, but rather as a 'laborious and highly asymmetric design effort' between the morphological, social and environmental systems [52] (p. 8). After the patent demonstration of the unsustainability of cities from the Brundtland Report, the transcendence of design 'is neither understood nor sufficiently acknowledged' [49] (p. 13). Instead of acting as an assembler of ready-made nature-based solutions, the designer is thereby accountable for the performance of intertwined ecosystem cycles.

5. Conclusions

The discussion presented provides an insight into the rhetorics and polemics among form and performance in nature-based solutions, updating them through a novel syntactical perspective. Through the presented discussion, this article provides a translation of the practical concepts of contextual form, efficient form, and attractive form towards the conditions of morphological, structural, and infrastructural redundancy, as found in natural systems. The intricate choreography that links form and performance in ecological systems is revisited from a complex and multi-scalar approach across diversely rooted design agendas, obtaining operative procedures such as form-coupling, hyperstatism, and cycle-based syntax. We have presented how natural systems offer structural and material organizations that present considerable challenges to traditional environmental design.

The article has shown how the reference of natural ecosystems has been largely misinterpreted by ecological design, evoking inaccurate metaphors, and applying self-sustaining principles at the wrong scale [6]. The proposed replacement of efficiency by redundancy as a design paradigm tries to unlock a possible agreement between the disparate concerns of form and performance, normally placed at opposite poles of the design process. Increasing interest in thermodynamic performance of buildings through either simulation or evaluation tools is challenging the tradition of 'grounding architectural design in tectonic intuitions' [53] (p. 113). The design process thus oscillates iteratively between form and performance, placing nature-inspired form and performance as the main inputs to the design process.

Redundancy, as a dynamic indeterminacy of nature, has been revealed through different examples arranged according to a non-typological scalar base. If biology has evolved 'redundancy as a deep strategy' to understand environmental adaptation mechanisms, likewise architecture and urban design might adhere to this paradigm [6] (p. 27). The current climate emergency shows that we probably need 'other-than designing' ways for responding to the environmental problems of our cities [54] (p. 26). Rather than invoking nature to treat what humanity has damaged, we need to broaden our understanding of the biosphere. With the relevance of cycle-sampling over form-finding, environmental design acquires 'its own modernism', an ecological modernity beyond the aesthetics of green [55] (p. 79). However, the article also questions the decision of placing the metabolic processes of nature as the sole basis of a new environmental nature-inspired rhetoric. The incorporation of three form-based principles, efficient form, contextual form, and visual form is preventing the tacit 'repudiation of architecture culture as a pragmatic response to the constraints of climate, topography and resources' [56] (p. 101).

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