




Smart Sustainable Cities of the New Millennium: Towards Design *for* Nature

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Received: 4 February 2021 / Accepted: 22 July 2021/Published online: 25 August 2021

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Abstract

Urban environments consist of a mosaic of natural fragments, planned and unintentional habitats hosting both introduced and spontaneous species. The latter group exploits abandoned and degraded urban niches which, in the case of plants, form what is called the *third landscape*. In the Anthropocene, cities, open spaces and buildings must be planned and designed considering not only human needs but also those of other living organisms. The scientific approach of habitat sharing is defined as *reconciliation ecology*, whilst the action of implementing the ecosystem services and functioning of such anthropogenic habitats is called *Urban Rehabilitation*. However, urban development still represents the main cause of biodiversity loss worldwide. Yet, the approach of planners and landscape architects highly diverges from that of ecologists and scientists on how to perceive, define and design urban green and blue infrastructure. For instance, designers focus on the positive impact that *nature* (generally associated with indoor and outdoor greeneries) has on *human* well-being, often neglecting ecosystems' health. Instead, considering the negative impact of any form of development and to achieve the *no net loss* Aichi's objectives, conservationists apply mitigation hierarchy policies to avoid or reduce the impact and to offset biodiversity. The rationale of this review paper is to set the fundamentals for a multidisciplinary design framework tackling the issue of biodiversity loss in the urban environment by *design for nature*. The method focuses on the building/city/landscape scales and is enabled by emerging digital technologies, i.e., geographic information systems, building information modelling, ecological simulation and computational design.

Keywords Urban ecology · Biodiversity · Holistic design · Design *with* Nature · Nature-based solution · GeoBIM · DeMo

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Introduction

The urban sprawl linked to population growth and other human activities, such as the production and transportation of goods, are the main causes of habitat fragmentation and biodiversity loss [1–3]. The conflict between people and nature in urban areas (e.g., allergies, anxiety and unawareness) limits the chance of wild species survival in the built environment, also because land price discourages investments towards nature conservation in favour of more lucrative infrastructure (e.g., housing, construction of shopping centres and other places for entertainment). Moreover, our cities are often characterised by the unequal access of the population to green spaces, the distance of semi-natural areas from city centres and the scarcity and poor quality of suburban and peripheral recreational areas, often polluted, degraded or neglected [4, 5]. The above-mentioned issues are some of the reasons that brought to define benchmarks like the sustainable development goals (SDGs) [6–8] and the Aichi biodiversity targets [9], but also to set up monitoring programmes strongly addressed to policymakers [10]. It is clear that we must take responsibility as human beings and act to protect our life-supporting system: planet earth [11]. As the ecologist Odum pointed out, ecology can act as *trait d'union* between natural and social sciences [12]. The deterministic and sometimes dogmatic understanding of science drove to the revolutionary thinking that motivated and inspired the first ecological designers and planners [13].

Design with Nature

In the popular and inspiring book *Design with Nature*, McHarg [14] explained the *ecological planning method* he developed with his multidisciplinary team. This method aimed at identifying the most suitable land for human activities (urbanisation and hard infrastructure) to reduce or exclude their impact on the most sensitive areas, i.e. vulnerable and rare ecosystems. The reasoning behind the ecological planning method relied on what we would call today *ecosystem services*, considering that McHarg affirmed that nature *performs work for men* (e.g., water purification, atmospheric pollution dispersal, drought and erosion control and topsoil accumulation) and it does it at the natural stand at its best. This concept was known as *physiographic determinism* where *development should respond to the operation of natural processes* [14].

The ecological planning method was one of the first to integrate social and economic spatial data (e.g., urbanisation, agricultural, historical and recreational) with geographic and ecological ones (e.g., topography, erosion risk, plant ecology and wildlife) into urban planning and design. In this method, the first step was to collect the major scientific ecological data (e.g., concerning climate, human history, geology, physiography, hydrology, soil properties, plant ecology, habitats and land use), then to select the most relevant data for each macro-category (e.g., within climate the air pollution or within physiography the slope) and finally to interpret them in terms of values and tolerance/intolerance for certain type of development/land use. General targeted uses were future recreation, conservation, residential and industrial/commercial development drawn on maps of hierarchical land fitness or optimum: these *thematic gradient maps* were produced by representing each value adopting a greyscale, from most to least or vice versa, then by superimposing all of them in colour. This approach demonstrated that a certain region was suitable for multiple compatible uses showing the degree of *inter-compatibility*.

McHarg's legacy is visible in both humanistic and scientific fields of research because, on the one hand, this approach aimed to reconcile men with nature and to increase human well-being, whilst on the other, it showed the possibility to implement a systematic and rigorous approach also in a creative field like landscape and urban planning [13]. In fact, the proposed method was rational and reproducible thanks to the traceability of the data sources and the deterministic choices. For example, the novelty of working with superimposed layers is used to produce landscape suitability maps using modern geographic information systems (GIS) technologies for geodesign purposes [15, 16], environmental analysis [17–19] and past and recent modelling [20–23].

Mitigation Hierarchy

Despite the intent McHarg had to pervade landscape architecture with scientific ecological knowledge, in the end he aimed at getting *the maximum social benefit at the least social cost*. Therefore, his method responded to the current practice, where environmental protection was still seen as a development restraint, conditioning its expansions or its orientations [24, 25]. This mechanism persists up to now wherever natural reserves are often located in remote and unproductive areas which are not necessarily representative, in terms of biodiversity, of a certain region [26].

Another tool emerged in the late 1990's, developed to serve the ambition of limiting the impact on ecosystems: the *mitigation hierarchy*. This hierarchy, applied indeed as a sequence, states that impact of human activities should be assessed, avoided, reduced and finally, offset if needed [27]. Yet, too often, the first step, i.e., the avoidance is neglected [28–30] to privilege the *overuse* of biodiversity offsetting [31, 32, 33]: a compromise not efficient enough to stop biodiversity erosion [34]. Several examples show that biodiversity offsetting does not fully compensate the impacts of urban development on past and ongoing losses of our life-supporting system [35–38].

Another weakness of the mitigation hierarchy is the emphasis set on the local scale. Instead, the biodiversity functioning must be considered first at the landscape scale and the mitigation hierarchy sequence should be integrated within urban planning. This, to address the impact of urban development and to serve as a major constrain and orientation guide for any development [39–41]. Thus, the socio-economic development shall be considered at the very last stage of the process of landscape planning, once the ecological network and the conservation priorities are understood and set [19]. In their paper, Calvet et al. [19] proposed to consider as the first step of urban planning a comprehensive and robust understanding of the ecological functioning at the city scale (habitat description and conservation quality assessment, species occurrence and rarity, functional connectivity evaluation, etc.).

In this respect, the identification of the sites to spare from the development on the base of their role in the ecological functioning and resilience, as well of the sites where urbanisation would have less impact, could be of great interest for conservation planning. Besides, such functional work permits to identify in the built part of the landscape the most interesting places to foster biodiversity functionalities (habitat restoration or creation, corridor improvement, etc.). This approach would allow for instance the urban development to implement a natural grid, functional enough to keep species resilience within the territory under development [39, 42]. Maximising both the sustainability of the built landscape and the benefits to local ecosystem dynamics, development projects must reflect a larger context/scale to obtain a systemic biodiversity conservation planning [26, 39, 41] yet linked with urban development targets [19, 43, 44].

The Potentiality of Digital Technologies to Foster Biodiversity by Design

Standard tools might not be efficient enough to cope the entire complexity of biodiversity within a landscape [45], but they must be implemented to evaluate the costs of the conservation and the ecological functioning within a territory, in line with conservation targets set by landscape managers [46–48]. Once the conservation targets are clearly defined, the conservation strategy, namely, the mitigation hierarchy adopted in the urban development plan, can be properly implemented, with both optimal time and right spatial scale [19, 39, 49]. Following this framework, urbanisation is designed to contribute to biodiversity preservation and restoration as well as producing services for inhabitants. This shift fits perfectly with the *mainstreaming* of biodiversity conservation, recommended by the latest frameworks of mitigation and conservation hierarchy [50].

The technological and the *digital innovations* in real estate known as PropTech [51] would offer solutions not only to the common challenges among real estate stakeholders—such as cost overruns, lack of transparency and fragmentation of the real estate industry—but also to address critical sustainability challenges such as the integration of life cycle analysis (LCA) [52] or biodiversity features. Live environmental data are more and more freely available in form of building information modelling (BIM) data and geographic information system (GIS) datasets. This would facilitate the implementation of biodiversity components into the early phases of a project, but this option is not yet empowered [53]. Instead, BIM and latest developments in GIS have proved to be useful merely in typical design and construction use cases, generally categorised in the following eight groups [54]: time-saving, material-saving, cost-saving, improvement in health and safety, reduction in risk, improved asset utilisation and improvement in asset quality for the end-user. By overcoming interoperability issues, the integration of BIM models, embedding data and information linked with the virtual and even real buildings (*digital twins*) with GIS datasets (GeoBIM) [55] would offer more opportunities to integrate crucial sustainability issues such as biodiversity loss and habitat fragmentation.

Aims of the Paper

To reduce the growing impact of the building sector on biodiversity loss, some of the possible actions are the conservation of remnant ecosystems, the reduction of their fragmentation and their restoration across the built environment [56]. In other words, conservation must be integrated within urban planning and the built landscape matrix shall become less hostile for wild plant and animal species. To fulfil these aims, there is the need to integrate *scientific ecological knowledge* in the design and planning of built-up areas (landscape-urban-building scales) by implementing on the one hand *multidisciplinary frameworks* enabled by *digital technologies*, and on the other hand, adequate *sustainability* assessment procedures and standards.

In this work, we present a new multidisciplinary framework and *holistic design approach* to tackle the issue of biodiversity loss and habitat fragmentation across multiple scales (landscape, urban and building). The DeMo framework is developed within the international project *Design and Modelling of Urban Ecosystems: A spatial-based approach to integrate habitats in constructed ecosystems* (hereafter: DeMo). The ambition of this framework is to enable ecologists and designers to cooperate from the early stage of a project to integrating habitats and facilitate the species colonisation of, and the movement through, built areas. Here, *digital technologies*, such as GIS, BIM, and ecological modelling shall enable and activate the

necessary synergies among different disciplines through iterative and consultative processes. Besides, it is crucial that the framework we present here is well set within the *SDGs and Aichi's targets*; thus, it is necessary to identify the relationships among the two agendas and to find out how to structure a framework fitting both of the agendas from the beginning.

Our hypothesis is that some of the obstacles preventing the implementation of truly multidisciplinary environments are the *disciplines territoriality* and the framework-specific *degree of novelty*, but how to overcome these barriers? How to activate the synergies by joining approaches and techniques generally used separately? Another critical issue we identified is that in the era of *open data*, the myriad of spatial and ecological information might hinder the collaborative framework if not thoroughly screened, evaluated and properly selected. For example, are the data informative enough? Which environmental parameters (e.g., climate, topography and hydrology) and biotic data (e.g., habitats and species distribution) should be considered when designing through different scales (landscape–urban–building)? At which level of detail and spatial resolution? In terms of novelty, how to make meaningful use of ecological data for a multifunctional and across-scale design and how to integrate ecological information from the very beginning of a project? Finally, how to translate ecological data into urban and architectonic forms?

To start answering these questions this paper presents an *expert-based literature review* whose results constitute the *theoretical background* of the new designing approach we intend to develop during the ongoing DeMo Project. This review shall highlight how each discipline could contribute to the paradigmatic shift from *design with nature* to *design for nature* in terms of mainstreamed practices, innovative computational tools, and semi-automatic processes. Also, we believe that at the building scale, the *performance-driven design* is a standard common praxis probably because it got boosted by the introduction of green building standards, e.g., LEED, BREEAM and DGMB [57]. These standards define quantifiable performance requirements, but do they give enough weight to issues like habitat loss? To which extent do they consider the ecological role that buildings might play in supporting urban biodiversity? With this paper, we aim at identifying the gaps of such assessments, believing that their thorough revision under the lens of biodiversity would boost *biodiversity-oriented design*.

In short, the steps and aims of this paper are the following ones:

- (1) Develop an expert-based transdisciplinary literature review, constituting the theoretical underpinning for our vision of *designing for nature*
- (2) Identify crucial shortcomings of green building standards and smart cities assessment in properly considering biodiversity aspects
- (3) Propose a novel framework for designing for nature that is well set within the SDG and Aichi's biodiversity targets

Procedure to Develop the Theoretical Underpinning

The Expert-Based Literature Review

The first core contribution of this paper is an in-depth literature review over the fields of conservation biology, environmental and architectural design. The review aimed at identifying on the one hand innovative approaches to design for biodiversity, on the other hand,

information and communications technology (ICT)-enabling processes suitable to be used in biodiversity-sensitive design according to the following procedure (Fig. 1):

1. The first step was to disentangle environmental design approaches through an expert-based review (not systematic). Special attention was set on (1) the scale of intervention, i.e. landscape, urban and building scales and (2) the possible synergy and transdisciplinary applications.
2. The second step was to highlight the computational tools and the ICT-enabled processes used in innovative design and conservation biology approaches.

Smart Cities and Building Sustainable Assessments

Applied research on smart cities and sustainable building assessments was screened to find out into which level of complexity these assessments take into consideration biodiversity measures. To this purpose, we reviewed the Japanese Comprehensive Assessment System for Built Environment Efficiency for Cities (CASBEE-City) and the German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen) (DGNB) multicriteria.

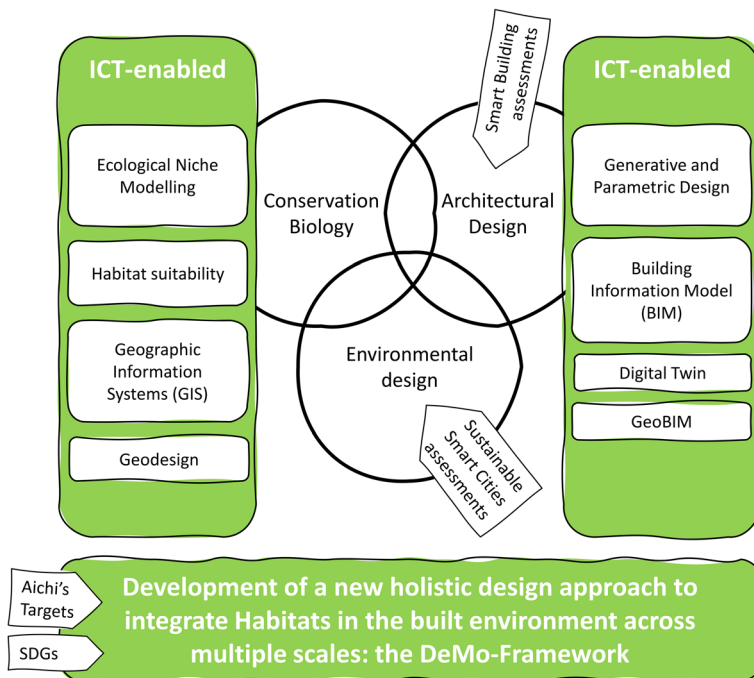


Fig. 1 Graphical description of the methodology used to develop the theoretical background of the holistic framework. The circles envelope the core disciplines under review; the arrows point the determinant standards, assessments and sustainability agendas out. The two embedding green vertical rectangles present ICT-enabled synergies and doomed to expand the possibilities of the core disciplines towards *design for nature*

Theoretical Background and Critical Literature Review

Highlighting the Synergies Across Scales and Design Disciplines

Eco-Positive Design

Times are mature to mainstream the paradigmatic shift from *environmental-sensitive* to *eco-positive design* [58]: a *positive development* in which the core idea is to *design for nature* as well as for people. Tratalos et al. [59] showed that the ecosystem services (measured according to tree cover, green open areas, storm water run-off, temperature and carbon sequestration) decrease with the increasing of urban density and that it is possible to intervene on the type of development and housing to maximise ecological functions. For example, according to the *eco-positive design* approach, the built environment shall give back to nature more than what it takes/consumes [60]. Going beyond *regenerative development* [61], *positive development* is possible only if we learn to design *integrated eco-services* and to *eco-retrofit* our cities [58]. Thus, changing perspective, *urban eco-services* (vs. ecosystem services) [62] aim at regenerating local habitats in a logic of *net-positive offsetting*, namely, overcompensating the negative impact of the construction, going beyond the pre-settlement conditions [35]. In this sense, *eco-retrofitting* implies the integration at the whole urban scale (building, city and infrastructure) of small strategic improvements which solve urban problems while increasing both natural and social capital [63]: like in a *sybiotic development–environment relationship*, cities shall both preserve and enhance biodiversity. The action of repairing the ecosystem structure, functioning and services is generally called ecosystem rehabilitation, [64, 65] and by extension, we could refer to *urban ecosystem rehabilitation* when it is related to urban *novel ecosystems* [64]. These sorts of actions fall not only within *ecological engineering* but also within *applied ecology* [66].

Biodiversity-Sensitive Cities

Supporting and conserving biodiversity in urban environments is challenging [67, 68]; nevertheless, several works show promising opportunities to do so [69]. For example, Apfelbeck et al. [70] in the *wildlife-inclusive design* framework (Fig. 2a) suggest to select target species starting from both the *regional species pool* (georeferenced species data) and the *local species potential* determined by the existing habitat type around and within the development site (filter habitats). Furthermore, the authors suggest to analyse the site to address implementation strategies based on the animal-aided design (AAD) approach [72], finally, to consider the interaction human–animal traits to obtain the final species selection (before involving local stakeholders). The most important feature of the AAD is the *species portrait*, which contains the general traits of the species and their life cycle, thus providing designing aids based on species life stage and specific needs [72].

A complementary approach refers to *habitat analogues* [73, 74] used to inspire the plant species selection (see also the *habitat template* approach in the following paragraph) based on the similarity between both *urban hybrids* and *novel ecosystems* [75]—where some native species still thrive—and the *natural analogues*, namely, both urban natural remnants (or historical ecosystems *sensu* [76]) and natural areas, where these species live. This approach fits well within the concept of *reconciliation ecology* or *win–win ecology* [77], where people live and work [78]. It is possible to intervene on urban hybrid and novel ecosystems either by

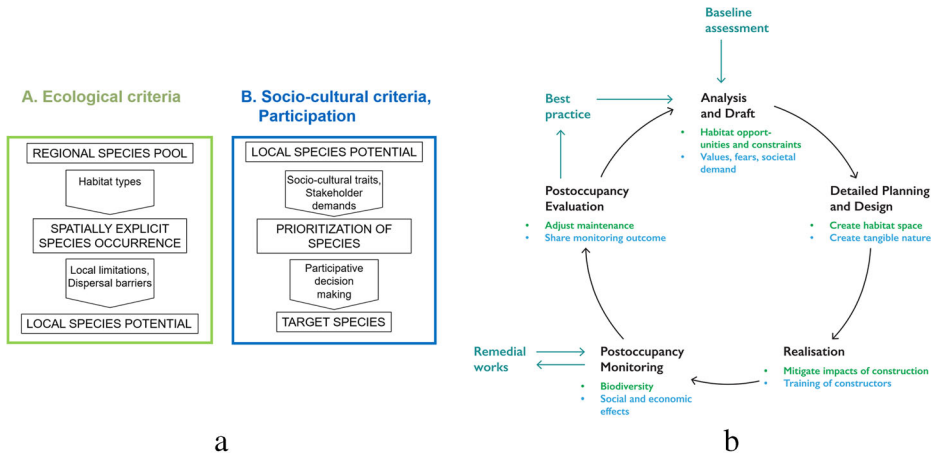


Fig. 2 a Ecological and socio-cultural criteria adopted in the *wildlife-inclusive design* framework (from [70]). b The planning cycle of the *wildlife-inclusive urban design* framework (from [71])

introducing propagules from natural analogues and/or altering them to support more native species (e.g., creation of brownfields) or just preserving *ordinary biodiversity* [79]. In any case, to design *wildlife-inclusive* [71] and *biodiversity sensitive* cities [80], conservation biologists will have to be involved in the whole life cycle of the project (Fig. 2b), from the beginning of the designing process to the management and monitoring [81]; and vice versa, designers shall be incorporated into applied ecology frameworks [66]. Thus, the exchange between designers and ecologists needs some work to align perspectives and approaches or—as Parris et al. [82] argued—to *turn on the lamps*.

Interestingly, within the discipline of Urban Ecology, the *ecology for the city* approach evolved from the *ecology in the city* and the *ecology of the city*, with a paradigmatic shift towards the stewardship, thus involving not only scientists but also citizens, professional practitioners and decision makers [83]. For example, the *meta-city* term was introduced in 2007 by UN-HABITAT to identify large agglomeration of cities with more than 20 million inhabitants, polycentric and with diffuse governance [84]. McGrath and Pickett [85] intend the *meta-city model* as a conceptual framework to integrate ecology, architecture and urban design, incorporating digital sensing and communication technologies to achieve social sustainability and ecological resilience [86]. Cities evolve and, regardless from their dimension and type, the urban *patchy system of systems* is connected worldwide with fluxes of *matter, energy, organisms and information* (see the concept of metapopulation and metacommunities in ecology [87, 88]). The meta-city framework was adopted for the Baltimore Ecosystem Study over two decades reflecting the *biological–physical–social nature of the Baltimore ecosystem* [89].

The ecology of the meta-city is characterised by the urban meta-mosaic of landscape patches (both natural and artificial) and human infrastructure. To set up the tool of the meta-city framework [90], recognition, history and evolutionary chances for every patch are also crucial to understand its dynamics. This framework of urban meta-mosaic can be applied in old central cities, suburbs, edge cities, exurbs and fringe, and it is constituted by three mosaic components in a feedback loop: *process* (e.g., biogeochemical fluxes, demographic change and information flux), *choice* (e.g., decisions made by organisms and individual people) and *outcome* (e.g., spatial patterns issuing from choices and processes). Finally, urban adaptation

and resilience come into play [91]. *Engineering resilience* refers to the ability of the system to resist and come back to the level of equilibrium after disturbance; *ecological resilience* instead refers to the ability of the system to adjust to changing or unstable conditions (based on non-equilibrium theory). The *adaptive cycle* that derives from the latter approach is related to resilience, connectivity and accumulation of resources (capital): a system is prone to be less resilient if the dominating components are conservative (K strategy) and connected; vice versa, if the dominating components can promptly and effectively respond ('r' strategy) and are less connected one another [91]. The adaptive cycle model is quite relevant in urban environments, which are evolving into complex systems changing land use at high speed, thus exacerbating inter-intraspecific competition. Thus, the transition towards sustainable cities can be done only by adopting holistic design approach, a circular economy model for resource management and implementing nature-based solutions [92, 93].

Biodiversity-Sensitive Buildings

The species which can thrive and withstand urban conditions (e.g., mechanical disturbance, non-native species competition, steep and sterile surfaces, urban heat island effect, and habitat fragmentation) shape what Clément [94] defined the *third landscape* but also *unintentional landscapes* [95] or *informal green spaces* (IGS) [96]. These species exploit ecological niches which were not created intentionally, so that they form communities that appear to the most as messy and untidy [97]. Nevertheless, the strategies adopted by the species populating unmanaged interstitial habitats can not only inspire designers to intentionally replicate such conditions in buildings [98, 99] but also help to define strategies for urban biodiversity conservation [75]. In the optic of reconciliation ecology (see the previous paragraph on the urban scale), green roofs and walls offer a great potential to support biodiversity [100] while providing several ecosystem services as multifunctional units [101].

Even if sustainable architecture is generally related to energy and resource consumption efficiency (paradigm which is mainstreamed in sustainability assessment tools, see the first section of this contribution), there are several schools and fields of applied research which can lead to *net-positive* buildings [60]. For example, when renovating or constructing a new low- or zero-carbon building or renovating one, the loss of biodiversity must be considered too, and ecologists must be addressed early enough, for instance, to allow architects to integrate suitable nesting and roosting habitats for building-reliant species like birds and bats [102].

According to the *net-positive design* approach [103], "Buildings must not only become eco-productive (i.e., eco-produce clean energy, water, soil, air, and food), but must reverse the impacts of previous development and expand indigenous ecosystems and ecosystem service in absolute terms". This is exemplary put in practice in some imaginative projects inspired by natural forms and functions (biomimicry) such as the *eco-skyscrapers* conceived by Ken Yeang [104] and the big floating self-sufficient structures of Vincent Callebaut [105]. In both these projects, the link between eco-design (e.g., LCA) and biomimicry is quite crucial. Nevertheless, the main question here arises: which kind of biodiversity is supported by such projects? How to shape the building envelope so to host target flora and fauna?

In the pioneering building by Chartier-Dalix architects for the *Boulogne Billancourt Biodiversity School and Gymnasium* constructed in 2014 in Paris [106, 107], the building was seen as a holistic system allowing to work with architecture and biodiversity

simultaneously [108]. The collaboration between architects and ecologists enabled to integrate into the building not only extensive, semi-intensive and intensive green roofs but also to conceive a living habitat façade to host animals and plants by designing various gaps and voids meeting the requirements of targeted birds, arthropods and stress-tolerant plant species (Fig. 3).

The building was designed to fulfil the school activities, functions and requirements, but at the same time to host plant and animal species considered as part of the body of the building rather than as mere add-ons. This shift of perspective and this new manner of approaching the project turned the school into a life-size tool for experimentation: the structure is a living observatory in a dense urban environment apt to monitoring the reciprocal influence between plant and animal species and the building. This also implies a total and profound change of the way urbanisation is defined, maximising the ecological functionality within the landscape and the rationalisation of costs and efficiency to preserve it. To this respect, the selection of the target habitats and, therefore, of the species to favour on the building should be driven by the conservation targets at a higher planning scale, maximising the efficiency of buildings aimed at supporting biodiversity [43, 109].

One practical key/tool enabling architects to design life-hosting buildings proved to be a *catalogue of ecological niches and species requirements* [99, 102, 106, 110, 111] containing descriptions and sketches illustrating key biophysical aspects to host animals and plant assemblages (Fig. 4 and Table 1). For example, characteristic shapes (e.g., access and nesting dimension), suitable material properties (e.g., rough, smooth and metal, wood), likely position (e.g., minimum or maximum height from the ground or distance from the roof), proximity to certain structures providing different services (e.g., foraging, hiding and roosting), favourable aspect (e.g., north/south), sun exposure and temperature (e.g., light/shade). To this regard, *attractive visualisation* [112] of the urban section showing adaptation to biodiversity along streets, houses but also private gardens, proven to be useful to raise awareness and encourage people of willing to have more nature in *their own backyard*.

City and Building Assessments

SDGs and Aichi targets are starting to be integrated into the rich panorama of sustainability assessment systems, which are crucial to predict and evaluate the impact of human activities on ecological systems, and supporting decision making. However, smart and sustainable is not necessarily a synonym of biodiversity-friendly. In fact, a proper evaluation of biotope quality or biodiversity status is often neglected or poorly considered in city assessments at both urban and building scales, as highlighted in the following paragraphs.

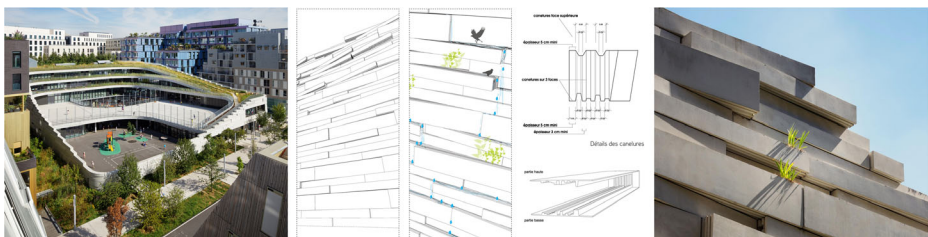


Fig. 3 Boulogne Billancourt Biodiversity School and Gymnasium constructed in 2014 in Paris by ChartierDalix architects. (photos and drawing credits: Chartier-Dalix architects)

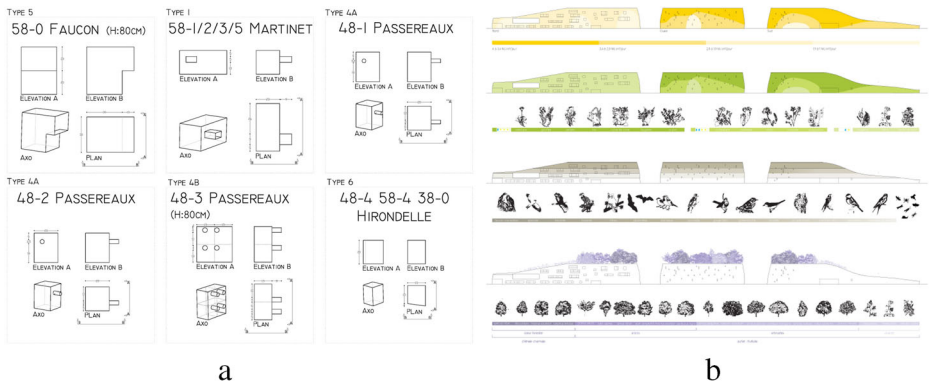


Fig. 4 **a** Illustration of some bird species requirements (*faucun*: falcon; *passereaux*: passerines; *hirondelle*: swallow) and **b** distribution of the selected plant and animal species on the façades and the roof of the Boulogne Billancourt Biodiversity School and Gymnasium in Paris (drawing credit: ChartierDalix Architects)

Sustainable Smart Cities

Several definitions of smart city exist [113, 114], but there is a certain common agreement on the 6 dimensions characterising them: (1) smart economy (industry and competitiveness), (2) smart mobility (transport and information and communications technology (ICT)), (3) smart environment (natural resources), (4) smart people (social and human capital and education), (5) smart living (quality of life) and (6) smart governance (participation). Some uncertainty in terms of definition arises when dealing with sustainable city or urban sustainability, also

Table 1. Relationships between spontaneous plants and urban man-made habitats (translated and modified from [99])

Relationship between plant location (PL) and water-capturing surface (WcS)	Geometry	The slope of the surface	Orientation	Topology	Materials	Position of the roof gutter
<p>Continuity between PL and WcS</p> <p>Distance between PL and WcS</p>	<p>Flat</p> <p>Upper horizontal dihedral</p> <p>Lower horizontal dihedrals</p> <p>Vertical dihedral</p>	<p>Horizontal</p> <p>Tilted</p> <p>Vertical</p>	<p>N ↑</p> <p>E →</p> <p>S ↓</p> <p>O ←</p> <p>Z [zenith]</p>	<p>Crevice</p> <p>Material porosity</p> <p>Junction</p>	<p>Steel</p> <p>Aluminium</p> <p>Concrete</p> <p>Bitumen</p> <p>Ceramic</p> <p>Wood</p> <p>Brick</p> <p>Coat on concrete</p> <p>Coat on stone</p> <p>Cast iron</p> <p>Granite</p> <p>Sandstone</p> <p>Marble</p> <p>Mortar</p> <p>Limestone</p> <p>Siliceous stone</p> <p>Plastic</p> <p>Stabilised</p> <p>Soil</p> <p>Zinc</p>	<p>Pavement- edge</p> <p>Pavement- surface</p> <p>Column- basement</p> <p>Grating</p> <p>Fencing- wall</p> <p>Wall- base</p> <p>Staircase</p> <p>Dry- stone- wall</p> <p>Gutter</p> <p>Wall</p> <p>Headwall</p>

because these two terms sound like an oxymoron to most people [115, 116]. What is of common understanding is that a sustainable city must fulfil the balance between social equity, economic development and environmental protection [117, 118]. Even if both smartness and sustainability concepts seem to be similar, smart assessments lack of environmental indicators and generally prioritise ICT efficiency on their environmental impact, while the sustainable assessments prioritise environmental and social sustainability indicators at the expense of the economic ones [117].

To overcome the discrepancy between smart and sustainable approaches, the term *sustainable smart city* emerged in the last decade [116, 119, 120], qualifying a city that [120]: “[...] meets the needs of its present inhabitants, without compromising the ability for other people or future generations to meet their needs, and thus, does not exceed local or planetary environmental limitation, and where this is supported by ICT”. The smart sustainable city embraces the challenge to adopt a holistic approach in line with SDGs but it is still at the early stage of conceptualisation and put into practice [121].

Each of the above-mentioned six dimensions of a smart city can be assessed (smart city ranking) using specific factors and indicators [113, 122, 123]. The indicators proposed by Lombardi et al. [124] are determined by linking the six dimensions of the smart cities to a *modified triple helix* model which is at the base of the process of knowledge creation and capitalisation: university, industry, government and civil society (a model of four helices). In this framework, within the *smart environment* figure several indices, which however did not target biodiversity conservation issues:

- the assessment of CO₂ emissions strategies of the standards for buildings efficiency (university helix)
- energy and water consumption, green areas (m²), containment of urban sprawl, air pollution, citizen participation and engagement and use of clean transport means (government and civil society helix)
- recycled waste and number of sustainability assessments (industry helix)

Although the indicators of environmental sustainability prioritise ecological issues, there is still a lack of qualitative measures as it happens in one of the most advanced sustainable assessment tools, i.e., the Japanese Comprehensive Assessment System for Built Environment Efficiency for Cities (CASBEE-City) [125, 126]. Among CASBEE-City indicators, only one of them deals with nature conservation and is based on the ratio between the sum of green and water areas and the total surface included in the political boundary of the municipality (i.e., merely a quantitative measure). However, a recent update of CASBEE-City has been proposed to assess cities worldwide (pilot version). This is inspired by both the SDG goals (and indicator) and ISO37120: 2014 (Sustainable development of communities) [127–129]. As a result, the category tackling the environmental performance (Q1) got several candidate indicators more than in the actual edition. Among them, the ones relevant to nature conservation are the green areas (hectares) per 100,000 inhabitants, the annual number of trees planted per 100,000 inhabitants, the share of coastal and marine areas that are protected, the annual change in forest area and land under cultivation, the rate of forest surfaces managed according to sustainable silvicultural practices, the annual change in degraded or desertified arable land, red list index, the effective overlap of protected areas overlay to fulfil biodiversity conservation policies and the percentage change—in terms of number—of native species.

The pilot version of CASBEE-city seems to be the first case of partial integration of the City Biodiversity Index (CBI) also known as the Singapore Index on cities’ biodiversity [130]. The CBI

was endorsed by the convention of biological diversity in 2009 [131, 132] and is based on three pillars: (1) native biodiversity, 2) ecosystem services (e.g., cooling effect of the vegetation), and (3) governance and management of biodiversity (e.g. budget devoted for biodiversity conservation initiatives). Probably, one of the reasons why the CBI index was not adopted more extensively might be the difficulty to find adequate data (open access data availability) or the high effort to gather high-resolution spatial data. Nevertheless, some of the issues can be overcome by analysing land use datasets [133, 134] like the free available global land use datasets [135]. In detail, the CBI performs a quantitative assessment of the native biodiversity component by using the following 10 indicators: (1) proportion of natural areas in the city, (2) connectivity measures or ecological networks to counter fragmentation, (3) native biodiversity in the built-up area (only bird species), (4–8) net change in the number of native species ((4) vascular plants, (5) birds, (6) butterflies and (7, 8) any other taxonomic group), (9) proportion of protected natural areas and (10) proportion of invasive *alien* species. Even if the 23 indicators are quite robust, some recent studies proposed to implement the second indicator on the connectivity of natural areas by taking into account also the within-patch connectivity/barrier [136].

Sustainable Buildings

There are plenty of building sustainability assessments worldwide [125]. Going beyond the single-dimension assessment, based, for instance, on the energy consumption (i.e., cumulative energy demand, such as the zero-energy buildings) or environmental load (i.e., life cycle assessment (LCA)), the multidimensional assessment accounting for the total quality assessment enables to evaluate the different sustainability dimensions (i.e., economical, ecological and social).

In Europe, the German Sustainable Building Council (in German: *Deutsche Gesellschaft für Nachhaltiges Bauen*, DGNB) multicriteria for the building sector aims at measuring the quality of the three (environmental, social and economic) pillars of sustainability giving to them equal weight, but accounting also for technical processes and site quality, in this order of importance (Fig. 5) [137].

Moreover, each of these criteria was recently screened to determine its contribution to the SDGs [138]. As a result, since 2018, the *biodiversity at the site* figures within the six criteria related to environmental quality (Fig. 6). However, this criterion sums up to 1.2% of the total certification score, having the lowest relevance among the indicators contributing to the whole assessment. Among them, the *biotope area quality* is a function of the *property-specific biodiversity index* (calculated by a provided excel tool, © DGNB GmbH) and is measured on the base of land cover (with and without vegetation), water infiltration, soil contiguity with the ground and presence of green walls and green roofs.

Further, the value for *species diversity* in the proximity of the site and on the building is obtained by evaluating the measures adopted to support the existing species (the status quo) and to encourage the colonisation of new ones through either direct introduction (e.g., planting new native plants) or designed features. The latter measure intends to make the outdoor area and the building more attractive for target species of birds, bats, butterflies, wild bees, wasps, amphibians and reptiles. The DGNB endorsed to this respect the AAD approach [71, 72].

Summarising, building and urban sustainability assessments seem to be more centred on the rational use of environmental resources than on biodiversity issues, allowing to design *less unsustainable buildings* [63] instead of *net-positive buildings* [139]. For instance, the highly detailed DGNB system adopts an extremely simplified biotope index, which does not include qualitative

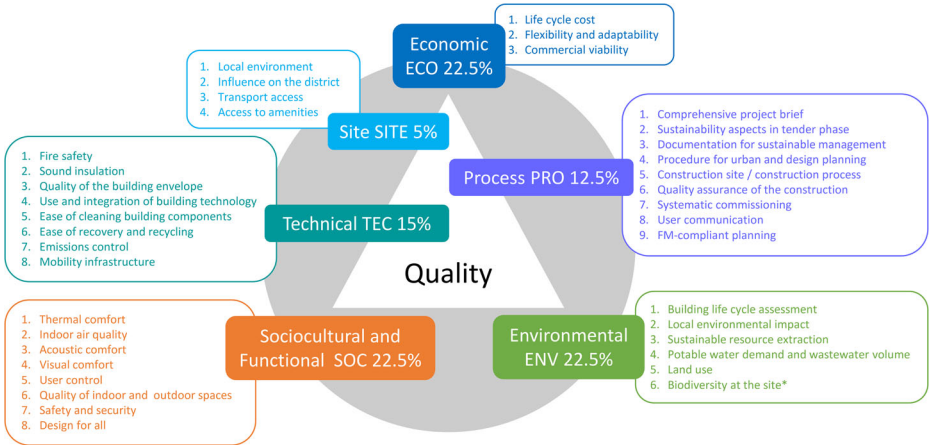


Fig. 5 DGNB criteria for new buildings [137]. In brackets for the main pillars the relevance factor and share of total score in %

measures (e.g., species richness and diversity) but focuses mostly on greeneries and ratios of impervious surface. Moreover, this kind of assessments is limited to evaluate ecosystems on the base of their performance and services, yet neglecting biogeographic factors such as the real and the potential species and habitat distribution patterns (similarly to what happens in the case of several green roofs guidelines, see [109]). Besides, these indicators are poorly linked to the environment at a larger scale, thus strongly limiting their ecological reliability and their ability in contributing to Aichi’s goals. Similarly, there would be the need to adding indicators accounting for the ecological niches offered by the whole building (i.e., not only green roofs and green wall) and to consider the effect of neighbouring semi-natural habitats on built-up areas.

ICT-Enabled Design Processes

Cities are considered a configuration of relationships, whose knowledge is more important than the elements that determine it [11]. The shift of focus from elements to relationships does not happen easily, because while elements can be quantified, measured and weighted, relationships need to be mapped. This is what we call *pattern*. Mapping relationships and studying patterns implies a qualitative, more than a quantitative, approach. In a holistic approach, the

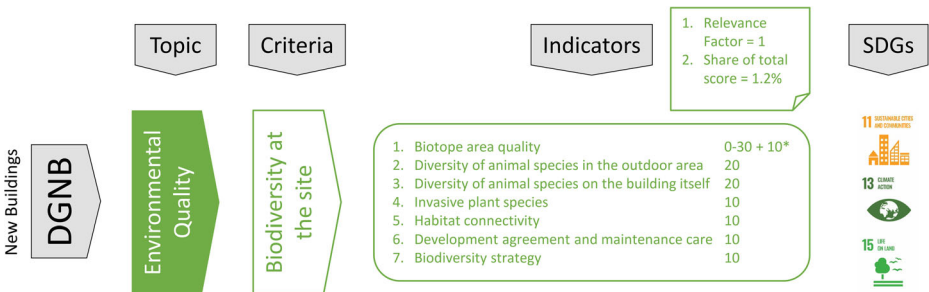


Fig. 6 Indicators for the biodiversity at the side criteria (DGNB). *Additional 10 points bonus available if further sustainable targets are fulfilled (Agenda 2030 bonus—climate and species protection goals)

transition from quantity to quality is therefore implicit, as well as from structural elements to processes and interaction between the elements of the urban ecosystem. These interactions have been neglected in the sustainability assessments and their integration requires a radical change of perspective and a consequent revision.

GeoBIM-Embedded Ecological Modelling: the Challenge of Integrating Biodiversity in Designing Frameworks

Ecological models such as species distribution models (SDMs) are GIS-oriented tools inspired by the species–environment relationship. In fact, SDMs predict species distribution across the landscape combining species occurrence/absence (or abundance) with estimated environmental factors including land cover classification [140]. SDMs cover various tools and approaches which could be deployed depending on the ecological question users may answer. For example, MAXENT may only require basic information such as simple occurrence maps and abiotic variables to predict habitat suitability for the considered species [141], while more comprehensive approaches like environmental niche models (also known as bioclimatic modelling or envelope modelling) are able to predict species presence and abundance or colonisation patterns [142–144] (Fig. 7).

However, SDMs provide relevant information only on the habitat suitability but not on the species population dynamics, which can be addressed by using complementary modelling approaches based on population viability analysis (PVA). PVA aims at predicting meta-population functioning and is used since the 1980s for conservation planning (reviewed in [145]). Modern PVA models are individual based and spatially explicit, so they permit to estimate population viability and size but also flow rate of individuals [23, 146, 147], and sometimes even the flow rate of genes [23, 148]. The BIM-oriented functionalities, such as complex data management and simulation (embedded within GeoBIM), would automatize or semi-automatize crucial steps of ecological modelling such as the complex data management (e.g., local and/or external storage, IoT-based survey and satellite imagery) and model parameterization [149].

The possibility of using BIM data in a GIS context for designing with nature is crucial for the development of smart sustainable projects. As reviewed by Carvalho et al. [150], there are several BIM tools for green building design and sustainability certifications. Early studies promote BIM processes and tools to manage environmental and biodiversity issues at the landscape scale [149, 152], but there is a lack of data models to enable BIM dimensions for geospatial and temporal landscape analysis [153]. The integration of BIM with GIS (known as GeoBIM) has matured [154] and supports sustainable development through accurate urban analysis. By using geospatial information with BIM, policymakers, landscape and urban planners, as well as real estate owners/investors, can make truly ecologically responsible decisions during the lifecycle, not only predicting the energy performance. The benefits of GeoBIM analysis of the abiotic conditions are already acknowledged by real estate developers. Moreover, ecological modelling embedded in GeoBIM would also facilitate the interoperability between tools and, more importantly, improve the ability of the other GeoBIM users such as planners or designers to integrate the modelling predictions to their conventional designing process [155, 156]. For example, to analyse the project impact on the surroundings, to better understand where and when the building will overheat, to plan and estimate the total amount of solar energy, etc. However, a gap has been identified in integrating the biotic environmental data to be used in a design project.

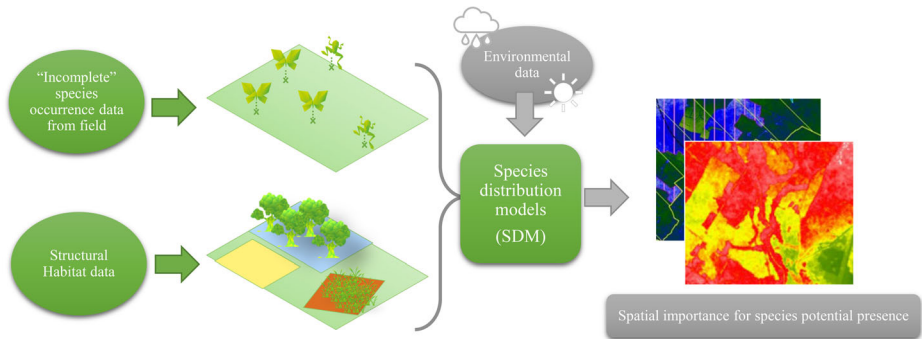


Fig. 7 General workflow of species distribution models. As inputs of the SDM there are land use and field sampling data; as outputs maps of spatial probability of species presence (from red to green).

Digital Twins for Smart Cities—the Potential for Integrating Biodiversity in a Geodesign Perspective

The evolution of environmental design and planning is geodesign [157]. According to Ervin [158]: “Geodesign enhances traditional Environmental planning and Design activities with the power of modern computing, communications and collaboration technologies, providing on-demand simulations and impact analyses to provide more effective and more responsible integration of scientific knowledge and societal values into the design of alternative futures. [Moreover] The technical infrastructure for geodesign has been achieved by using the tools of existing GIS, CAD and BIM systems, coupled with spreadsheets, databases and emergent web techniques. This ad-hoc approach has not been altogether satisfactory, as there are still many interoperability issues to resolve; and, perhaps more critical, there is still considerable debate about whether and how design is supported and enabled (or thwarted) by these existing tools”.

Digital twin systems are the most evolved ICT solutions which have proven their benefits in the development of sustainable smart cities such as cost efficiency [155] and increased collaboration. Digital twins of the built and natural environment start to emerge in different countries driven by government initiatives [159]. Grieves [160] first describes the *digital twin* in 2003 as a virtual, digital equivalent to a physical product which mirrors a real-life object, process or system. According to [161], in order to create a digital twin three main rules should be met: first, having the physical built components in real space; second, the virtual built components in virtual space and third, ensuring a real-time connection of data and information connects the virtual with the real building. Digital twin could be implemented with further layers including biodiversity-related information.

The interoperability issues are being solved in the common data environment (CDE) enabled by open BIM data standards such as Industry Foundation Classes (IFC), which is a recent approach yet unexploited in the context of designing with nature [149, 162]. *Open BIM* creates new opportunities for applications and services because the integration of technologies such as laser scanning, extended reality (XR)—which includes virtual, augmented and mixed reality—data analytics, GIS, Internet of Things (IoT) and blockchain with BIM. For example, as proposed by de Laat and van Berlo [163], the CDE can connect the GIS data of the local context with BIM. In this regard, within the BioBIM project, Moulherat et al. [149] developed a *BIM demonstrator* (technological prototype) integrating features dedicated to the planning/management of environmental measures and focusing on (1) the integration of standard data

from environmental assessments and monitoring of environmental measures, (2) the integration of numerical simulation data related to animal and plant population dynamics and (3) the integration of plant growth simulation and landscape dynamics data (relevant for the management of the green infrastructure).

Computation and Automatization in Urban and Architectural Design

Computational design is getting increasing attention among architects and planners [164]. Nevertheless, when it comes to definitions (as in the case of smart cities), there is the frequent confusion among terms which were adopted before being truly settled and deeply investigated. In other words, what is the relationship between generative design (GD) and parametric design (PD)? Is it possible to use the two terms interchangeably?

PD in synthesis is “a design process based on algorithmic parameters and rules to constrain them”; likewise, BIM establishes “dependencies among different design elements”, turning them into “symbolic parameters that have specific domains” [164]. This approach allows the designers to change the final design by changing defined parameters. GD was defined as a “design paradigm that employs algorithmic descriptions” [164] that compared to PD are more autonomous, namely, rely less on the user, and are set in an evolutionary context. In fact, according to Frazer et al. [165], GD and evolutionary design use computers as virtual space “in a manner analogous to the evolutionary process in nature”. In the urban context, parametric urbanism (PU) emerged to give solutions in the context of complex urban development projects [166]. Its origins can be traced back to the 1970s when the first definitions of *generative systems* were formulated [167]. Christopher Alexander was one of the first to come up with a GD approach using more than 250 patterns and subpatterns organised so to create a systematic method: the *pattern language* [167, 168]. Recent ICT developments are causing the shift from urban parametric design towards GD systems by integrating machine learning and applying artificial intelligence to enable several alternative design solutions to be generated by different sets of parameters [169].

In the last two decades, bioclimatic architecture and design experienced remarkable progress driven by a broader designer (and social) interest towards sustainability issues and enabled by the latest ICT advances. In the early 1990s, the eco-design stepped beyond the simple resource-saving approach towards the environmental efficiency one, intending to reduce the impact that buildings and human activities had on the natural environment (nature-conscious design) [170]. In this scenario, *architectural generative eco-design* aims at finding low-environmental impact solutions based on the spatial bioclimatic contexts, combining in a multidisciplinary way architecture, ecology and engineering. The synergy among multiple disciplines is possible thanks to computing technologies enabling designers to cope—at early-stage phases—with high levels of complexity, for example, enabling them to run sophisticated LCA or integrate interactive and generative processes employing evolutionary design tools [171]. The first software enabling to integrate LCA targets in the upstream phase using a generative approach is the VizCab© software, developed at the Polytechnic University of Lausanne (EPFL) [170, 172]. By integrating BIM with LCC and LCA the application of these types of sustainability analysis in the early stages of a project becomes possible [52, 173, 174].

In the context of performance-oriented design, VizCab offers a *LCA-based data-driven design method* based on the “combination of LCA, parametric analysis, data visualisation, sensitivity analysis, and target cascading techniques” [175]: to make the most efficient and

sustainable choice, the user first sets the overall hierarchical targets and constrains (e.g., that of the 2000-watt society vision); then, the software assesses each sub-target (*target-cascading technique*), followed by the visualisation of multicriteria graphics (*parallel coordinates data visualisation*), which allows the user to check the impact that certain parametric choices have on the environmental targets (*parametric analysis*). This process is replicated several thousand times in feedback loops to feed the *design alternative database* (also *knowledge database*) which is eventually queried on a sensitive analysis base; this kind of analysis explores only among the most sensitive and relevant solutions [175, 176]. The strength of the LCA method is that it is site specific and provides guidance at the beginning of the design process (with few details); nevertheless, the software is still in a prototyping stage and the visualisation of the knowledge database is not very user-friendly [176]. Attempts to solve the latter issue were made using Rhinoceros© and Grasshopper© graphical algorithm editor, whilst emissions and other physical analysis were simulated with other Rhinoceros plug-ins, i.e., Ladybug (analysis of climate data) and Honeybee (daylight simulations) (Fig. 8) [177–179].

The centrality of computing engine interface and architects is instead one of the priorities of the generative eco-design tool EcoGen©, which combines the computational generative process with architect's cognitive one [180, 181]. This software resulted as the output of the Generative Eco-Design project (Eco-Conception Générative) (2011–2012, funded by the French National Research Agency (*Agence Nationale de la Recherche, ANR*)) initially involving the National School of Architecture of Lyon (MAP-ARIA) and Nancy (MAP-CRAI) and the University of Nancy 2 (Codisant-Sitcom, Interpsy) [181]. The software is under constant upgrade [171], and it is thought to support the designers in the sketch phase by proposing several set-into-context solutions, as in the VizCab software, computed on the base of efficiency analysis. The software engine optimises bioclimatic, ecological and economic criteria to the local context: urban (plot of land and surrounding blocks), environmental (climate–solar model) and programmatic (urban planning rules, e.g., buildable area and distance from roads). The computation is based on population evolution which uses one morphological engine and a genetic one in a systemic loop (morphogenesis, evaluation and optimization), thus generating random families of solutions (Fig. 9). In the assisted interactive mode, the software let the designers/users select the most suitable solution in different steps on the base of a subjective choice (e.g., aesthetic) or objective (e.g., functional) so that the whole generative process is also driven by user-specific choices.

Performance-based or -oriented design (PeD) is also an emerging approach based on computational information boosts; nevertheless, when compared with PD and GD, it is not yet quite in use [164]. Probably, the most representative examples of PeD are given by the Oslo School of Architecture and Design, intended also as a data-oriented design [182]. In their methodology, Hensel and Sørensen [183] merge computational-based design with *system thinking* intending to link architecture with the local setting, both environmental and cultural (patterns of space and land use) on both multiscale and multivariate bases. For example, the

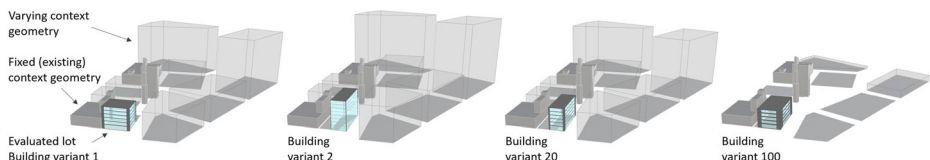


Fig. 8 Examples of the buildings alternatives automatically generated with the integration of Rhinoceros and Grasshopper (from [177]). Original figures: courtesy of the authors

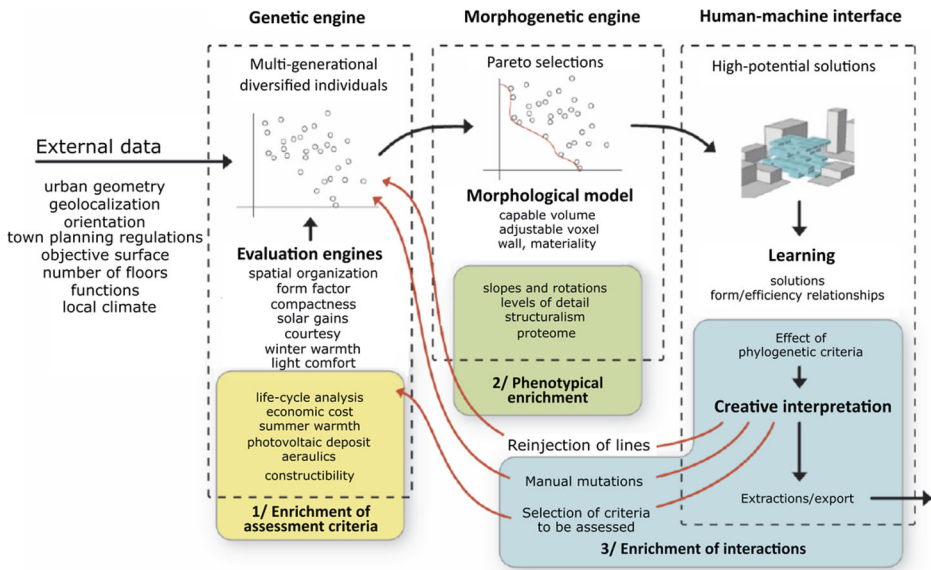


Fig. 9 Conceptual functioning of the EoGen2 generative eco-design tool (from [181])

case study of developing low-rise and high-density settlement along the Oslo Fjord responded to the aim of solving the research line inquiry to design areas at the urban edge, focusing on local bio-physical conditions. Key environmental parameters (feeding the associative model, see [184]) were the slope, the substrate, the water run-off and the sensitive habitats. Evolutionary algorithmic methods were used to find the best solution followed by analysis and rate.

The new developments in PD, GD, and PeD, identified in this review, shed light on the potential integration of context-specific biodiversity figures (e.g., derived from species distribution models) in the early stage of the design process (vs. post-design optimisation).

Synthesis: the DeMo Framework

Towards the Integration of Habitats in the Built Environment

Modern cities consist of a meta-network of complex technologies and interactions, involving many feedback switches that operate far from equilibrium and produce a variety of emerging properties. The innovativeness, adaptability and carrying capacity of urban networks is a prerequisite of smart sustainable cities. However, among the emerging properties of modern cities, there is no temporal stability, which is a fundamental property of natural ecosystems. Processes and interactions of the urban ecosystem are so fast and involve such a multitude of sources that it is extremely difficult to control and predict emerging properties. However, the *sustainable city*, as promoted by The Aalborg Charter [186], looks like an ecological modernization of planning criteria, a kind of greenwashing unable to veer towards new paradigms.

Projects not mediated by a site-based scientific ecological knowledge, projects neglecting the importance of integrating local habitats and biodiversity in the built environment, will perhaps be able to create better housing solutions but will not change the relationship of a city with the surrounding nature, landscape and ecosystems. The smart sustainable city, instead, should be a

resilient city, with a reduced ecological footprint and with a strong relationship with the local ecosystems (which define the reference eco-region). Perhaps, before planning and constructing new cities or new districts (such as the Vauban district in Freiburg, Bedzed in Sutton, Houten in Utrecht and Dongtan in Shanghai), architects and planners should first focus on how to inhabit the existing cities differently.

“The city, which for centuries has operated according to the formula of the ‘place where everything is exchanged’, should become Noah’s ark destined to ensure the survival of the species despite the flood. A great autonomy, a great autarchy will therefore be necessary” [187]. Ecological research teaches us that a wide array of forms and functions (i.e., what we call “biodiversity”) is the only way for ecosystems to perpetuate themselves over time and to adapt to environmental changes. For a smart and sustainable development of cities, this translates, first, into a change in the habits of those who live there, and the acceptance of interventions aimed at integrating natural habitats in the built environment. In the DeMo project, the development of a holistic workflow has tried to respect the basic principles of ecosystem functioning and, therefore, has some characteristics in common with natural ecosystems: it is deeply rooted to places and the local scale, is energy conscious and community oriented.

The Integration of SDGs and Aichi’s Biodiversity Targets in the DeMo Framework

The DeMo framework is anchored in both the SDGs and Aichi’s targets, tackling them at different levels and degrees. Some of the focal targets shaping DeMo vision are *resiliency*, *participation*, *traditional knowledge* and of course as core target; *biodiversity conservation* as deepened in the next paragraph focused on the framework (Fig. 10).

Resiliency

In simple words, a system is resilient if it can withstand or come back to the original equilibrium and health after the ceasing of the disturbance factor(s) [188–191]. Considering highly urbanised ecosystems, it is utopic to believe that they can be resilient enough to come back to their equilibrium before urbanisation itself. In our vision, however, greening urbanised systems should contribute to change them towards a more biodiversity-favourable equilibrium, contributing, thus global Aichi’s goal of no net biodiversity loss (NNL) [44, 192].

Participation

New participative designing ways, such as system-oriented design (SOD), have been developed and used in the last years in Northern Europe to disentangle complex systems collaboratively (e.g., in groups of experts, users and stakeholders) [193, 194]. Central to SOD are *gigamaps* and the innovative representation and understanding of the relationships among the parts; these relationships types, yet not dogmatic [194], are included in the *library of systemic relations* (e.g., structural, semantic and casual). Here, we refer to this approach as inspiration to merge designers’/planners’ perspective with that of ecologists who are not yet sufficiently integrated into this framework leading to the under-representation of biodiversity management during the infrastructure design [43, 195].

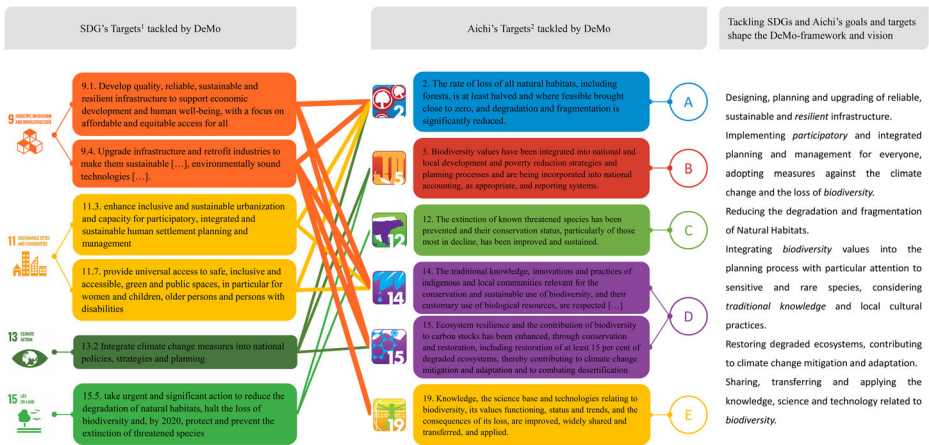


Fig. 10 Selection of SDGs [7] and Aichi's target [9] tackled by the DeMo framework. Thicker lines join targets and goals tackled the most by the project. ¹Sustainable development goal-icons: United Nations/globalgoals.org; ²Aichi's target logos. Copyright BIP/SCBD

Traditional Knowledge

Some researchers have identified conflicts intrinsic to SDGs when it comes for instance to building efficiency (goals 9 and 11) and biodiversity conservation targets (goal 15). For example, in a study case investigating 104 villages in Poland, the abundance of building–nesting birds declined at about 50% due to building modernization and renovation [196]. The Polish example suggests that to mitigate this alarming and underestimated phenomenon, designers should build innovative and bird-friendly houses taking inspiration from traditional architecture. For this reason, setting up the ecological network of protected areas and corridors connecting them [197–200], it will be not enough to obtain resilient systems, but it is also important to reduce the pressure on ecosystems [201] and to change the way we plan our cities and understand human society [202]. In our case, traditional and vernacular architectures [203] and other traditional spontaneously colonised manmade structures will be looked-up to inspire the design.

The Holistic Framework: from *Design with Nature* to *Design for Nature*

In this paper, we highlighted that biodiversity in its complexity is poorly integrated into the current practices of both the sustainable evaluation of cities and buildings. Nevertheless, we assist to a growing demand by inhabitants and governmental institutions to meet the sustainability targets and the growing involvement of ecologists to obtain *more nature in the city* [204]. In fact, ecologists are pledging for a planned efficient integration of biodiversity issues in landscape and city planning [50] as well as for the design of biodiversity-friendly building [43]. To this regard, the development of large-scale ecological modelling allows us to handle and take into account the complexity of biodiversity and biological processes [45, 205].

Here, we forecast a new horizon where also ecology is considered in the architecture, engineering, and construction industry, which becomes *nature, architecture, engineering and construction* (NAEC). The DeMo framework shall consider, on the one hand, the expectation of conservation biologists to better integrate biodiversity features in cities and buildings, on the other hand, that planners and designers are willing to rewild cities and increase human well-being. This shift *from*

design with nature to design for nature (Fig. 11) is inspired by the designing practices of geodesign [16] and the *Design with Nature* of McHarg [14], by landscape-specific conservation planning practices [26, 46, 48], reserve site selection [40, 41] and current target-based approaches [206, 207]. The framework takes into account the three components of biodiversity, as described in Noss [208]:

- 1) The *composition*: component corresponds to a list of genes, species, habitats, ecosystems, etc. It is a catalogue of elements found in the object under study.
- 2) The *structure*: component deals with the physical organisation of elements (distance from one to another, habitat aggregation, etc.).
- 3) The *function*: component relates to processes and ecological dynamics underpinning the common understanding of ecosystem services and ecological functionalities.

To transform artefacts (e.g., constructions, buildings and walls) into suitable habitats for some species, several criteria must be fulfilled [88, 198, 209–213]:

- (1) Provision of favourable microhabitats, enough food, appropriate shelters, etc. (validated thanks to SDM)
- (2) Connection with the local ecological network to permit species settlement and ensure their persistence in these habitats (proved by PVA)

In this respect, the BIM-embedded modelling process will allow us to determine whether artefacts are as follows:

- (1) Suitable for targeted species (the habitat niches are favourable)
- (2) Integrated into the ecological network and thus susceptible to be colonised
- (3) Viable habitats for targeted species thanks to their suitability and/or their appropriate integration in the ecological network

To overcome the limitations derived by the complexity of the analytical process needed to properly integrate the biodiversity component into architectural design and urban planning, the DeMo framework is multidisciplinary, holistic and is enabled by ICT tools. At the local scale, our process would permit to test/simulate scenarios related to real/virtual constructions, while determining at the large-scale the design which best fits the biodiversity management goals [41, 46]. This evaluation should be done for each building and design scenario, iteratively so to optimise the overall workflow and get to the final design. At the landscape scale, the procedure will also permit us to determine the potential of green buildings to become refuges for some species [214–218]. To this respect, thanks to embedded parametric modelling, GeoBIM already allows the comparison of multiple design solutions at the beginning of a project [219] or provide constraints like in the case of building permit [220]. Furthermore, algorithmic and parametric design tools, used in conjunction with the GeoBIM process, would allow to generating alternative solutions [221] stimulating designers creativity [180].

Crucial phases of the DeMo framework are (Fig. 12) as follows:

- (1) Retrieving and processing biotic and abiotic data at multiple scales and resolutions fitting the ecological modelling tasks and objectives (strategic planning project and design definition)

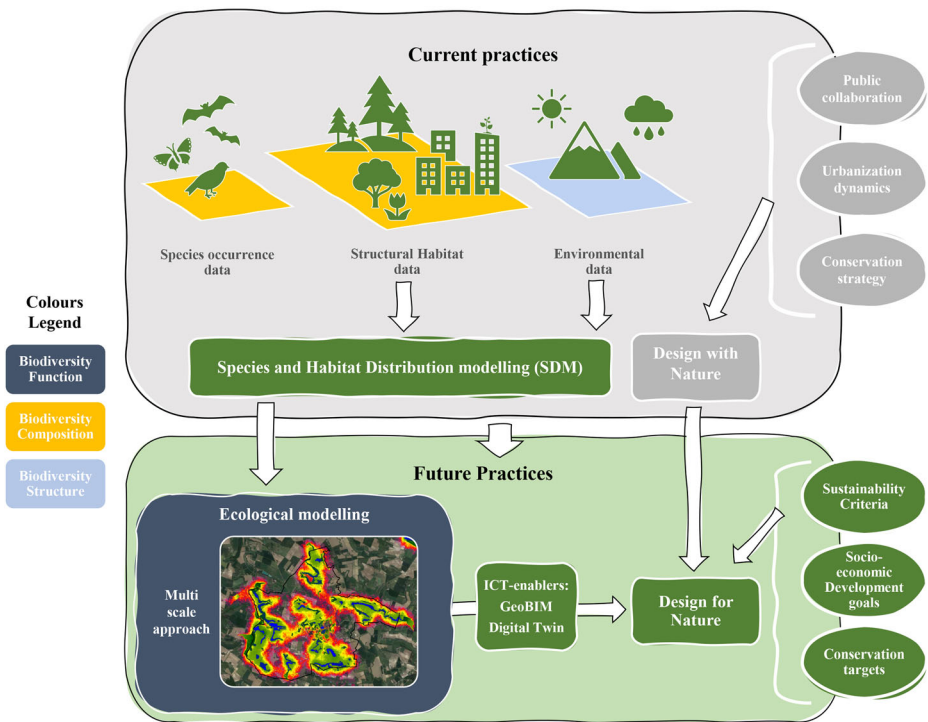


Fig. 11 The workflow leading from the current practices design with nature to design for nature at multiple scales

- (2) Processing and implementing the ecological data at urban/municipality and building scales in a feedback-loop workflow with ecological modelling at small scale
- (3) Selecting the best designing solution fitting both sustainable development goals and biodiversity targets
- (4) Monitoring of wild plant and animal species behaviour and dynamic with respect to the created ecological niches (e.g., on building walls and roofs), with the final aim to feed the parametric and ecological design feedback loop

Concluding Remarks

Discipline territorialities are difficult to cross but can truly profit one from each other in multidisciplinary projects. This seldom happens, either because of perspective conflicts (development vs. conservation for example), or because the society where we live nowadays forges highly specialised individuals. The intent of this paper is to pile up the pool of knowledge serving not only as a basement of the multidisciplinary DeMo framework (allowing, for example, architects and conservation biologists to merge their standard workflows) but also to streamline the tools and disciplines that would boost the integration of the biological conservation targets in the practice of architectural design and urban planning. Thus, the examples we brought in this paper may prove to be useful, on

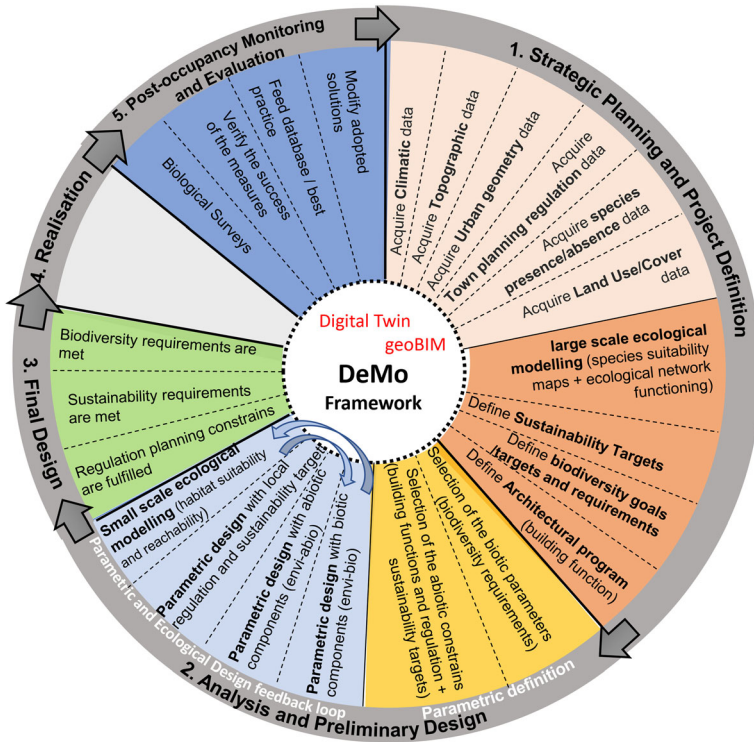


Fig. 12 DeMo framework hierarchical steps and feedback-loop relationships

the one hand, to inspire and feed the DeMo project workflow, and on the other hand, to identify overlooked synergies and cooperation opportunities.

So, in simple words, if it is possible to simulate the movement of an insect depending on the complex plant architecture and morphogenesis [222], it must be possible, indeed easier, to do the same depending on parametric architectural models. Thus, playing with Goddard et al.'s [223] words, we envision to design *wildlife-friendly* buildings connected to gardens and surrounding open green spaces. Mainstreaming building design and biodiversity conservation strategies *via* landscape and urban biodiversity-informed planning (*Design for Nature*) has the potential to strongly contribute to the Aichi target [224]. Indeed, McHarg's intuition that ecological knowledge shall play a fundamental role to educate contemporary society proved to be right. Fortunately, his philosophy is still traceable in significant education initiatives such as the schools for ecoliteracy [225, 226] and in new curricula development aiming at merging design with ecology [227].

The first study case of DeMo, not presented here, will be the University Campus of the Zurich University of Applied Science (ZHAW) in Wädenswil (Switzerland) and will be the focus of a forthcoming research paper.

Acknowledgements The authors thank Salvatore Pasta (Institute of Bioscience and BioResources (IBBR) of the Italian National Council of Research (CNR)-Unit of Palermo) and two anonymous reviewers for their valuable comments, which improved the final version of the paper.

Author Contribution CC led the paper writing with substantial contributions of MM, SM and JB. CC, MM and SM conceived the paper and run its critical revisions. CC, MM, NB, SD and SM obtained the grant. All the authors contributed to the paper revision and approved the final version.

Funding Open Access funding provided by ZHAW Zürcher Hochschule für Angewandte Wissenschaften. The DeMo Project is financed by the Zurich University of Applied Science (ZHAW) to support the multidisciplinary and inter-institutional research on environmental issues (Campus@LSFM, duration of the project 2020-2021). This work also contributes to the CONAQUAT research and innovation project grant by the French Region Occitanie.

Data Availability Not applicable.

Code Availability Not applicable.

Declaration

Conflict of Interest On behalf of all co-authors, Chiara Catalano as the corresponding author declares that there is no conflict of interest among them.

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