Green-blue infrastructure in the built environment – sustainable and resource-saving designs for urban structures and open spaces

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Abstract. Urban grey infrastructure, as it generally consists of monofunctional, sealed, impervious, heating up and reflecting surfaces, has led to a series of serious challenges (urban heat stresses, loss of biodiversity, flood risks and natural hazards) decreasing urban resilience. Ongoing construction activities result in irreversible soil consumption and loss of its numerous and vital functions. However, a common understanding has been evolving that the establishment of green-blue infrastructure (GBI) supports compensating for functional losses, as they are integrative and provide pervious, absorbent, shading and non-heating up surfaces. We present a concept to holistically interconnect stand-alone approaches to improve and support constructional design for transforming green open spaces addressing specifically urban landscape construction and building greenery. The underlying state of knowledge emerges from currently four ongoing projects on advancing GBI for re-establishing ecosystem functions and diverse habitats: 1. The Circular Soil Concept targets the reuse of excavated soil materials from construction sites to produce engineered soils. These are applied as functional vegetation substrates for landscape construction and installing building greenery, saving scarce soil resources while generating large scale and vegetated areas with climate change adaptation performance. 2. The StreetTREE-Planter is designed to install urban trees in a given street infrastructure. The advanced planter systems will support extended tree lifespans, microclimatic benefits, flood protection and urban resilience. The design is based on targeted rainwater harvesting for irrigation management in alignment with water requirements and the desired microclimatic performance. 3. The GLASGrün projects generates plant-based shading designs for glass facades. As plants and their leaves do not heat up from solar radiation, vertical greenery is promising, however challenging, for green shading of glazed surfaces and for indoor and outdoor microclimatic regulation. 4. The INReS rainwater management tool was developed as a prototype web application to integrate sustainable, plant-based rainwater management systems into BIM-(Building Information Modeling)-based construction projects. It provides up-to-date design for the wider public and specific planning guidelines. In synthesis with the present and upcoming findings of these projects, a parameter-based and BIM-compatible GBI-design management tool is foreseen to better and sustainably integrate GBI systems into construction projects, and to consider the resource question.

Keywords: Green-blue infrastructure, case study, street trees, vertical green shading, Circular Soil
1. Introduction

The global building sector and the building construction industry significantly impact global climate, as they account for 38% of total global energy-related CO2 emissions [1]. However, climate-related harm is not only due to emissions but also result from the over-exaggerated destruction and use of land and healthy soil, minimising plant cover and creating hard, sealed and impervious surfaces and structures instead. In general, urban surfaces heat up and reflect global radiation, which significantly impacts the urban energy balance [1,2]. The energy balance over grey infrastructure is highly dominated by thermal energy resulting in sensible heat, whereas water saturated landscape and green-blue infrastructure (GBI) contribute to higher latent heat proportions, as energy is stored in the water vapour.

Urban grey infrastructure, as it generally consists of monofunctional, hard, sealed, impervious, heating up and reflecting surfaces, has led to a series of serious challenges such as urban heat stresses, loss of biodiversity, flood risks and natural hazards, and decreasing urban resilience. Ongoing construction activities further result in irreversible soil consumption and loss of its numerous and vital functions [4]. However, a common understanding has been evolving that the establishment of GBI compensate functional losses, as they are multifunctional, integrative and provide pervious, soft, absorbent, shading and non-heating up surfaces. Building greenery, for example, has been proved to reduce thermal effects on wall and facades [5,6]. Consequently, thermal transport through the building envelope is considered to be decreased, resulting in lowered energy demand for cooling and heating. Green retrofit and design are thus promising to make a sustainable and resource-saving contribution to EU climate goals [7] by reducing energy consumption and costs, and to improve the well-being of building users.

In our understanding, the green retrofit does not only address building green but even more requires the transition from material and resource use towards reuse and adapted handling and management concepts. This involves management of soils and (urban) rainwater likewise, and a rethinking of designs of urban structures and open spaces. We further postulate that the establishment of GBI can only be considered sustainable when resource use respects the planetary boundaries [8] and urban activities are not permanently challenging these boundaries [9]. Therefore, the demand for urban infrastructure should not any longer affect natural resources. Future urban and GBI designs need to consider circularity to meet the requirements of sustainability and resource-saving.

This paper presents preliminary results and a synthesis from four research projects on advancing GBI designs for re-establishing ecosystem functions and diverse habitats in urban areas. We present a concept that specifically addresses the resource question by linking novel GBI design advances with improved management for implementation. Our mixed methods research supports constructional design for transforming grey into green infrastructure and addresses specifically urban landscape construction and building greenery.

2. GBI case studies and advancements in the built environment

2.1. A Circular Soil concept for sustainable soil management

While the ongoing construction boom generates a growing stock of used materials, the valuable soil resources get lost as does their ability to provide ecosystem services [4,9,10]. Soil, as well as sand and gravel, ends up at landfills, while sand for construction becomes rarer [11,12]. Excavated soil is classified as waste, which added up in over 530 million tons on EU level in 2018 [13]. This is not in line with the EU-Soil Strategy for 2030 [14], as most excavated soils are sound and suitable for reuse.

Within the course of 2 large-scale building projects in Vienna (Austria) this matter was addressed to minimise disposal related mass transport. A field study was started in order to produce engineered soils for onsite-reuse and installation of green infrastructure. The research focused 1) the assessment of plant growth performance on engineered soils produced from the excavated materials and (2) the establishment of a systematic onsite production procedure for deducing a Circular Soil concept.
Circular Soils are intended to be applied as horticultural soils for landscape construction and installing building greenery, saving scarce soil resources while generating large scale vegetated areas for climate change adaptation.

The underlying idea evolved from the production of engineered soils [15] and covered the optimisation of the production and installation process. Plant growth performance test using standard seed mix allowed for the assessment of differences in reference and optimised soil alternatives. The trial included an IBC (Intermediate Bulk Containers) replicate setting with three replicates for two alternatives [16]. A vegetation monitoring was conducted over two vegetation periods to assess vitality, projective cover ratio and grass-herb ratio. The study revealed that optimised engineered soils were applicable and feasible for sufficient plant growth performance and complied with regulations regarding the grain-size distribution of the individual GI types. Hence, the optimisation processes could be established based on the results of the field study.

As presented in Minixhofer et al. [16], the Circular Soil concept follows a stepwise approach for landscape construction. First, the quality of the excavated materials has to be analysed (Step 1). It has to be determined if the chemical, physical and geotechnical parameters are within limits of the standardised (national) regulations and norms. Then, the landscaping purposes have to be defined (Step 2), focusing on the creation of GI, soil and biodiversity protection. On the basis of these target designs, the volume and mass balances can be calculated (Step 3). Soil amendments can be added as needed and help to optimise the mixing ratios (Step 4) for the on- or off-site production of the optimised engineered soil alternatives (Step 5). Finally, the installation of the engineered soils comes last (Step 6), following a standardised procedure that has to comply with regulated quality assurance.

The Circular Soil concept has promising potential for strategic sustainable soil management and supports circularity in urban construction projects. The current limitations lie in missing logistical guidelines. For a successful establishment of new routines and regulations further research requires including parameters for rainwater management (e.g. infiltration rates) as well as ecological and financial benefits (e.g. Life Cycle Assessment) for the whole process.

2.2. StreetTREE-design for improved urban street trees' living conditions

Trees in particular are considered the most efficient and cost-effective solution for climate regulation, as tree canopies and foliage provide cooling through transpiration, shading and reduction of radiation transfer [17,18]. These benefits strongly depend on specific plant physiological traits: Leaf area density (LAD) or leaf area index (LAI), arrangement of leaves relative to each other and angle to the sun, light intensity and frequencies, reflectance, absorbance, and transmissivity [19]. Moreover, tree age and size, crown vitality and overall state of health are crucial in order to exploit these ecosystem services.

However, state-of-the-art tree plantations do not meet the requirements for establishing vital and healthy trees with a long lifespan, and even less under urban and changing climatic conditions. In most urban applications tree pits are of too small dimensions for adequate root penetration, substrates are compacted with little pore volume and inappropriate drainage and water holding capacities [20]. Recent approaches such as structural soils [21] and the Stockholm System [22] have opened up new vistas and proved satisfying for providing more suitable conditions. Conflicts with street infrastructure elements are nevertheless remaining [23]. Currently, there is no vegetation-technical solution available, that complies with the requirements of both street infrastructure and the trees.

The StreetTREE hypothesis addresses the optimisation of tree planters in combination with substrate volume, qualities and rooting space as an integral component of a sustainable rainwater management and harvesting system. The research interest lies in the advancement of a design to cost-efficiently install urban trees in a given street infrastructure, and, at the same time, extending the trees lifespan and the microclimatic performance.

StreetTREE seeks to answer how evapotranspiration can be adjusted in order to estimate the planter’s water requirement and water budget. The aim is to synchronise the surface runoff with the water storage capacity of the StreetTREE system and the tree-specific water demand.
The StreetTREE design is developed as a modular system covering a water retention basin with an integrated planter allowing root penetration through to the underground substrate, including high performance filtration substrate, an autonomous irrigation system and variable surface designs (e.g., shrubs, perennials, plaster, wooden decks). Applications are thought to be variable and compatible in diverse urban settings such as streets, squares, parking lots (Figure 1).

**Figure 1.** Simplified scheme of the StreetTREE concept [© Andreas Berger 2021]: the planter (brown) integrates irrigation, drainage and underlying pump sump. Overflow is directed into the canalisation (blue). The system is applicable at any given urban pipeline infrastructure (green, yellow, pink).

Currently, the StreetTree design is tested as a prototype, and substrates and their geotechnical and hydraulic functional approval are lab tested [15]. The scientific approach covers an extensive, sensor-based performance monitoring at three demo sites, regarding plant growth, microclimate regulation, water balance and purification and technical functionality. For evapotranspiration calculation and water balance estimation, the Landscape Coefficient Method [24] will be applied. This will provide novel data related to microclimatic performance and targeted control of rainwater harvest for irrigation. A life cycle analysis will compare the resource demand and selected benefits from ecosystem services (water and climate regulation) compared to conventional solutions with and without tree components.

The StreetTREE design faces a series of technical risks relating to the different components (the above-ground planter, the tree substrate, the water retention basin and sealing, irrigation pump) and the interfaces to be developed between them. Planter requirements cover UV-resistance, lightweight and easy transportability, environmental compatibility, and aesthetic value. In addition, the system design must be able to support high static and dynamic weight loads, including optional temporary removal due to construction activities.

StreetTREE substrates must provide long-lasting high hydraulic performance, water storage capacity, pore volume, and capillarity with assured surface inflow cleaning performance. The root-
resistant and waterproof foil of the water retention basin must withstand high pressures where perforations may occur.

Despite the challenges to be overcome the innovative StreetTREE-design promises to enable large scale and area-wide re-establishing of trees for green retrofitting of the built urban stocks. In synergy with existing and important street infrastructure elements it ensures vital tree growth and thus essential climate regulation services. To compensate for restricted rooting space, rain water and nutrients will be harvested from sealed surfaces for irrigation. This novel approach of the StreetTREE-design further supports decentralised and sustainable rainwater management and is a valuable component in pluvial flood prevention.

2.3. GLASGrün-designing: deciduous green shading for microclimatic improvement behind glass facades

In industrialised countries, energy consumption for indoor comfort occupies a 40% share of the total energy consumption, and a significant amount of energy could be saved through innovative “energy conscious” construction, thermal renovation [25] and retrofitting of building insulation. The green retrofit is a serious contribution as building greenery has significant effects on the urban energy and water balance [26] and direct benefits for mitigating urban heat islands and on outdoor and indoor thermal comfort [27,28]. Simulations clearly indicate strong differences between greening scenarios and conventional architecture, and also between minimum and optimum GBI fitting [29].

While, to some extent, green roofing and walling has reached a certain status of standard application, buildings with larger proportions of glass elements have not yet been considered seriously in green retrofitting. In contemporary architecture, glass is one of the most popular building materials and is consistently used in various forms. Glass elements provide translucency and natural light, reducing daytime electricity consumption [30], especially in commercial and office buildings. Despite their advantages, glass facades have a significant impact on the microclimate, both inside and outside the building. The high concentration of solar radiation has a negative impact on the energy balance of the building. Continuous technical improvements of multifunctional glazing (e.g. multiple or vacuum insulating glass) promise higher thermal comfort through high-performance thermal insulation. However, there is evidence for still high transmission values of insulating glass [31], contrasting European standards for room climate and thermal comfort [32]. Such guidelines and workplace ordinances no longer justify the obsessive use of glass in modern architecture, as it is difficult to regulate the indoor climate and increases energy consumption and costs for heating, cooling and ventilation [33].

As it is technically approved that thermal comfort is enhanced by the reduction of sunlight exposure, vertical green (VG), (e.g. green façades, green walls [34,35]) bear the potential to counter-act the problem of high solar radiation input through an external shading layer, as they act as a natural solar filter. Green retrofit can significantly reduce the absorption of thermal radiation on the building surface, which also regulates surface temperatures [5,36]. Recently, there has emerged raising evidence of thermal resistance and the energy saving potential of VG [6,37,38].

The success of thermal effects depends both on structural arrangements of the green “curtain” and on specific plant physiological traits: Leaf area density (LAD) or leaf area index (LAI), arrangement of leaves relative to each other and angle to the sun, light intensity and frequencies, reflectance, absorbance, and transmissivity [39]. Although the topic has basically been known for a long time [40], specific plant characteristics, especially those related to solar radiation, and how to pointedly apply them in building design, have not yet been widely researched [39].

Globally, VG retrofitting on existing buildings with glazed facades has not yet been investigated. Currently, there are no standard applications for vertical greening and insulation of glass facades. Regular VG standards are not applicable, as “direct” solutions with self-adhesive climbers attaching to the exterior surface with roots or pads (e.g. Hedera helix, Parthenocissus quinquefolia) are not compatible with glass facades because plants do not find a foothold on smooth surfaces. Further, glazed areas need to remain accessible for maintenance and structural control. In “double-skin” VG alternatives, plants need technical support structures (modular trellises, stainless steel cables, or stainless
steel/HDPE\(^1\) mesh) to assist the upward growth of a wider variety of climbing plants. This form of greening can be implemented on almost all building facades if the structural requirements are met. For glass facades, climbing aids need specific adjustments for application at or with distance, and static challenges need to be overcome for subsequent installation.

The GLASGrün research focuses on solving both plant-specific and structural challenges and on deducing transferable standard designs. Research questions address identifying and designing suitable greening systems and technologies and structural adaptations needed for avoiding the connection of plants and climbing aids with the glass elements, and static limits and feasible options. GLASGrün therefore implements a greening retrofit of existing heat stressed buildings with glass exposure and will evaluate scaffolding and suspended modules as supportive structure and for load transfer for ground or planter-based greening alternatives [34]. In order to identify shading and regulating effects, a continuous sensor-based logging allows for monitoring radiation, thermal input and the indoor energy balance. Plant traits (volume, leaf coverage, LAI, plant vitality etc.) will be related to thermal building physics, and indoor and outdoor microclimatic effects will be observed. Beyond that, potential limitations or impacts of glass area to plant vitality will be identified.

GLASGrün demonstration objects are installed in June 2022 and will hence provide novel data and insights in temperature regulation, thermal comfort, solar gains and losses, in the potential of reducing solar input and of energy consumption for indoor air conditioning in relation with green shading. The transferability and scalability of the GLASGrün-designs to a great variety of objects are paramount and are defined as a target outcome of the currently running study. A concept for rain water harvesting will be included on basis of an integrated supply- and demand-oriented irrigation management.

2.4. **BIM-compatible designing of GBI for urban structures and open spaces: The INReS rainwater-management-toolbox**

Urban regions are particularly affected by stormwater events and pluvial flooding, as a large part of the precipitation has to be drained through the sewage system due to extensive land sealing and related problems as described above. This can result in enormous costs for municipalities. Sustainable, integrative rainwater management provides a remedy and according efforts and policies have been established in various areas and nations [41,42]. Urban hydrological cycle rehabilitation covers in particular four strategies: rainwater harvest, infiltration, storage and pipe drainage [43]. A ‘green stormwater resource base’ is assessed beneficial to urban communities as it provides direct ecosystem service value [44].

Recently, combination with and integration of GBI have been acknowledged and enhanced in various ways [45–47]. This includes wetlands, ponds and swales as well as bio-retention, raingardens and building green (green roofs and walls). Retention systems or cisterns can buffer rainfall, making valuable water sources available for urban flora and fauna in times of irregular wet and dry periods.

The planning, execution and operation of such GBI-based systems have not yet reached day-to-day operation status and pose major problems for those concerned due to the complexity and abundance of system solutions. Neither new construction nor renovation projects fully exploit the potential of retention.

In a recently finished exploratory study (INReS [48]) the aim was to prepare and test the applicability of an interactive web application for recommending suitable measures for dealing with rainwater in the built environment, which (1) allows BIM(Building Information Modeling [49]) compatibility for object-related implementation and (2) enables a simplified application in the form of a management toolbox. The basis for a web application was tested in a proof of concept, which considered identifying essential parameters and interfaces, clarifying internal processes of web applications and analyzing legal framework conditions. The internal processes of the web application and the database were developed and reviewed. Finally, the potential for BIM application was verified in a feasibility check and proved employable [49].

\(^1\) High-density polyethylene nets
INReS developed and provided a prototype-rainwater-management-toolbox, which according to a previously conducted market survey and analyses is not yet available. The toolbox is an online decision support based on fact sheets for sustainable and updated designs of green roofing, vertical greening and plant-based infiltration providing the state of knowledge beyond the state-of-the-art. The toolbox offers quick and straightforward decision support for identifying appropriate rain water management actions, requiring no expert’s knowledge. The web application integrates characteristic parameters and values for spatial localization, local climatic and soil conditions, the building object (building envelope, static, surface ratios) and potential measures (water retention, specific weights, infiltration and discharge coefficients). The prototype-toolbox is a rainwater-management-web-aid and is currently publicly available (no login required) as a German Version [50].

3. Synthesis of singular approaches to a comprehensive, BIM-compatible GBI design management and planning tool

The above introduced projects and designs are hitherto stand-alone-projects, which is indicative for many initiatives and activities on public and authority level. INReS and the StreetTREE concept won the first, respectively the third price of the 2020 co-creation LAB “Rainwater in the City” of the Viennese Business Agency Wirtschaftsagentur Wien [51]. Such creation labs indicate the need for novel and smart solutions, that can be brought to a comprehensive and sustainable management of interacting challenges related to climate change [52].

We suggest here a novel GBI design management approach that strategically syntheseses island solutions to advance GBI designs for urban open spaces and to offer concrete long-term solutions that are embedded in research and development strategies of city administrations with research units and innovative start-ups. Urban landscapes are complex and three-dimensional. This comprises issues of urban energy and water balance, temperature regulation, soil protection, soil resource regulation, and many more. To comply with the complexity of three-dimensional urban landscapes the integration of multi-layered and multi-dimensional solutions is required, and urban rooftop and façade landscapes, soil and ground landscapes and horizontal surfaces need to be addressed equally and at the same time.

Therefore, our GBI design management approach builds established approaches complying with GI and municipality rainwater management strategies such as the Green Stormwater Infrastructure approach [53], the Sponge City idea [54, 21] or the Stockholm System [22] and merges this with innovative up-to-date approaches as the Circular Soil [16] and the GLASGrün concepts to create multi-layered and multi-functional buffer and compensation areas.

Based on the INReS results and in synthesis with the projects presented beforehand, a parameter-based and BIM-compatible GBI-design management tool is currently post-processed to integrate sustainable GBI systems into construction projects and considering the resource question. The GBI-designs should cover (I) basic and advanced systems for temperature and urban heat regulation, as the GLASGrün-designs currently under development; (II) the reuse and repurpose of excavated construction material for engineered soils and GBI establishment (according the Circular Soil principle); and (III) rainwater management with focus on harvesting and reuse for irrigation purposes (as the StreetTREE planter will provide). The aim is a comprehensive BIM-compatible planning tool to provide more advanced guidance for GBI principles, technical design, regulations, and to be available to the wider public, landscape planners and building contractors. The interested public can thus access an ever-expanding portfolio of solutions and products and obtain information on their suitability for their own use via compactly formulated fact sheets. Experts benefit from an expansion of the product portfolio by having a higher number of BIM elements available for their planning.
Figure 2. Concept for an integrated and advanced GBI design management tool for sustainable and resource-saving urban open spaces: Schematic illustration of the interconnected spheres of sustainable and resource-saving applications for BIM-compatible planning: (I) microclimatic regulation by advanced GBI systems, (II) Circular Soil use for GBI installation, and (III) rainwater management and harvesting.

4. Conclusion

Based on the advances and preliminary results of the recently presented Circular Soil Concept and the ongoing projects GLASGrün, StreetTREE and INReS we connect the question of GBI design with resource saving management. We address three essential spheres: (I) microclimatic regulation by advanced GBI systems, (II) Circular Soil use for GBI installation, and (III) rainwater management and harvesting. Our concept is based on a holistic approach: The thoughtful and clever interconnection of these basically stand-alone approaches is promising and decisive for ensuring sustainable success, for meeting the sustainability requirements and for initiating a responsible and circular handling of limited resources. The concept for a BIM-compatible GBI-design management tool is based on a theory of parameters, but is equally applicable to a data basis. However, as currently data are still being gained from the projects presented above, these will be shared in a follow-up paper.

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