Technische Universität München
TUM School of Engineering and Design

BLAU-GRÜNE ARCHITEKTUR

Integriertes Entwerfen mit Wasser und Vegetation

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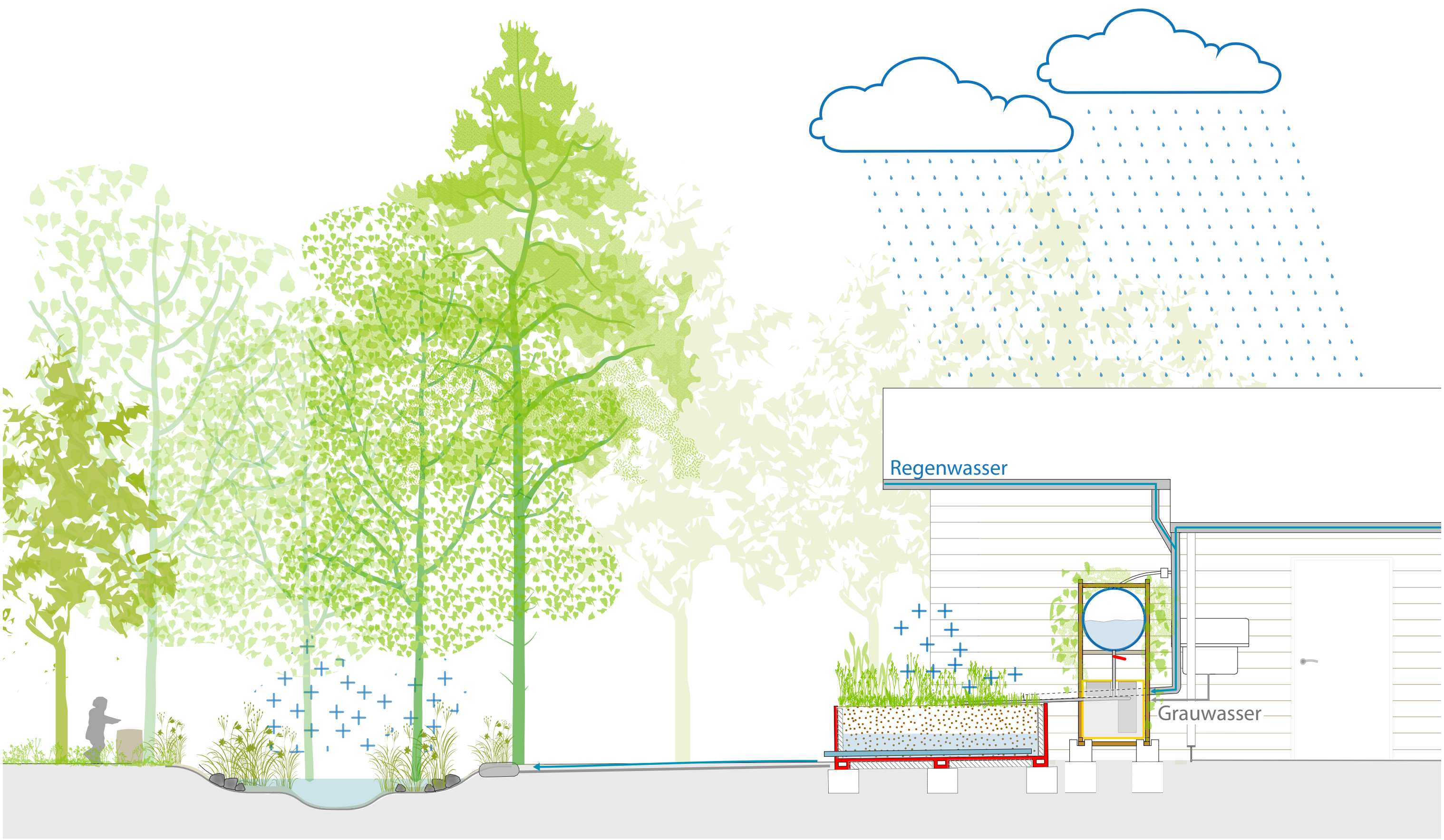


Epirrhema

Müsset im Naturbetrachten
Immer eins wie alles achten;
Nichts ist drinnen, nichts ist draußen;
Denn was innen, das ist außen.
So ergreifet ohne Säumnis
Heilig öffentlich Geheimnis.

Freuet euch des wahren Scheins,
Euch des ernsten Spieles;
Kein Lebendiges ist ein Eins,
Immer ist's ein Vieles.

Johann Wolfgang von Goethe

KURZFASSUNG

Die vorliegende Arbeit untersucht, wie das Konzept der integrierten Planung mit Wasser und Vegetation auf den architektonischen Entwurfsprozess übertragen werden kann. Das Ziel ist, eine Vorgehensweise für Architekt:innen und interdisziplinäre Planungsteams zu entwickeln, die nicht nur den funktionalen, sondern auch den gestalterischen Mehrwert einer dem Klimawandel angepassten Bauweise erhöht. In diesem Zusammenhang führt diese Arbeit in Anlehnung an die bereits geläufige blau-grüne Infrastruktur (BGI) den Begriff der blau-grünen Architektur (BGA) ein. Gemeint sind damit intensiv begrünte und wassersensibel geplante Gebäude, die bis jetzt in der Praxis immer noch die Ausnahme sind. Die Ergebnisse entstanden in einem wechselseitigen Prozess aus theoretischer Erarbeitung, praktischer Anwendung und wissenschaftlicher Reflexion. Dafür sind ergänzend zu der kumulativ angelegten Dissertation zwei kleine Umsetzungsprojekte in interdisziplinärer Zusammenarbeit entstanden.

Die vorgestellte Entwurfsstrategie für BGA soll als Anstoß für einen veränderten Umgang mit Wasser und Vegetation am und im Gebäude dienen. BGA bezeichnet Gebäude und umgebende Freiflächen, die naturnahe und technische Systeme der Vegetation (grün) und des städtischen Wassermanagements (blau) integrieren. Durch die frühzeitige Berücksichtigung dieser Parameter im architektonischen Entwurf entstehen multifunktionale Systeme, die auf Extremwetterereignisse wie Überhitzung und Starkregen reagieren und negative Folgen abmildern können. BGA trägt damit zur Klimaanpassung bebauter Gebiete bei und hat positive Auswirkungen auf das Mikroklima und den urbanen Wasserhaushalt. Die Planung blau-grüner Projekte findet im interdisziplinären Team mit der Siedlungswasserwirtschaft (blau) und Landschaftsarchitektur (grün) statt.

In der vorliegenden kumulativen Dissertation wird anhand von drei bereits veröffentlichten Publikationen gezeigt, wie integrierte Entwurfs- und Planungsprozesse für BGA gestaltet werden können, um die synergetische Wirkung von Wasser und Vegetation zu erhöhen. Dafür werden im ersten Paper vier exemplarische, bereits gebaute Projekte auf die Gewichtung der blauen und grünen Komponenten hin grafisch analysiert, sowohl im planerischen Herangehen als auch in der Umsetzung. Die Fallstudien zeigen, dass Gebäude einerseits viele mögliche Schnittstellen für blau-grüne Systeme bieten, dass aber andererseits sinnvolle Verbindungen und mögliche Synergien bei der Planung oft übersehen werden. Es besteht ein Bedarf an methodischen Lösungsansätzen für BGA-Projekte, die imstande sind, die Schnittstellen zu optimieren und blaue und grüne Systeme effektiv zu koppeln.

Das zweite Paper der Arbeit behandelt das Impulsprojekt in Stuttgart, das als Teil des BMBF-finanzierten Forschungsprojekts INTERESS-I realisiert wurde. Es handelt sich dabei um eine mobile, temporäre Architektur, die Regenwasser und aufbereitetes Grauwasser zur Bewässerung von Vertikalbegrünung

verwendet. Der interdisziplinäre Planungsprozess wird mittels *Research by Design* detailliert beschrieben, methodisch ausgewertet und in drei Phasen unterteilt: *Pre-Design* (Definition der Ziele), *Design* (Entwurf und Umsetzung) und *Post-Design* (Überprüfung und Reflexion).

Die aus der entwurfsbasierten Vorgehensweise gewonnenen Erkenntnisse werden anschließend in eine Entwurfsstrategie übertragen, die im dritten Paper der Arbeit auf ein Praxisprojekt angewendet und evaluiert wird. Dabei handelt es sich um eine blau-grüne Architektur für einen Schulgarten, die im Rahmen einer interdisziplinären Lehrveranstaltung an der Technischen Universität München entworfen und umgesetzt wurde. Studierende der Architektur und der Landschaftsarchitektur arbeiteten gemeinsam daran und verteilten zunächst die Rollen und Verantwortlichkeiten (blau/grün/Integration) im Planungsteam. Der Entwurf des naturnahen Systems wurde anschließend eigenhändig mit Unterstützung der Schülerinnen und Schüler in die Praxis umgesetzt. Das Grauwasser aus der Schulgartenküche wird in einer Pflanzenkläranlage behandelt und zusammen mit Regenwasser in einen neu angelegten Teich geleitet. Auf kleinem Raum wurden eine Vielzahl von Aspekten miteinander vernetzt: Ästhetische Gestaltung, didaktischer Anspruch, Grauwasseraufbereitung, Anforderungen des Umweltschutzes und Erhöhung der Artenvielfalt. Auch hier wurden die Ergebnisse ausgewertet und Ansatzpunkte zur Weiterentwicklung der Entwurfsstrategie für BGA ermittelt.

Es konnte gezeigt werden, dass Gebäude und gebäudenahe Freiflächen ein hohes Potenzial haben, durch die Integration von blau-grünen Lösungen zur Klimaanpassung beizutragen. Dass dieses Potenzial in der Praxis zu einem großen Teil nicht ausgeschöpft wird, ist insbesondere auf die traditionelle Arbeitsteilung innerhalb der planend-gestaltenden Professionen zurückzuführen. Blau-grüne Infrastrukturen werden bislang eher in der Landschaftsarchitektur, Landschaftsplanung und Stadtplanung gefordert und umgesetzt. Diese Arbeit versucht, zur stärkeren Verankerung dieser Konzepte in der Architektur beizutragen. Die konzeptionellen und methodischen Fragestellungen und Lösungsansätze verstehen sich als Handreichungen, die Architekt:innen helfen sollen, weitere Projekte im Sinne der BGA integriert umzusetzen.

ABSTRACT

This doctoral thesis explores how the concept of integrated design with water and vegetation can be applied to the architectural design process. The aim is to develop an approach for architects and interdisciplinary planning teams, that increases not only the functional, but also the aesthetic value of climate change adapted design. In this context, this work introduces the term blue-green architecture (BGA) in reference to the already common blue-green infrastructure (BGI). This refers to intensively greened and water-sensitive buildings, which are still the exception in practice. The results were developed in a reciprocal process of theoretical elaboration, practical application and scientific reflection. In addition to the cumulative dissertation, two small implementation projects were developed in interdisciplinary cooperation.

The presented design strategy for BGA is intended to serve as an impetus for a change in approach to water and vegetation on and in buildings. BGA refers to both buildings and surrounding open spaces that integrate semi-natural and technical systems of vegetation (green) and urban water management (blue). By taking these parameters into account at an early stage in the architectural design, multifunctional systems are created that can respond to extreme weather events such as overheating and heavy rainfall and mitigate negative consequences. Thus, BGA contributes to climate adaptation of built-up areas, which has positive effects on the microclimate and the urban water balance. The planning of blue-green projects takes place in an interdisciplinary team with urban water management (blue) and landscape architecture (green).

In this cumulative dissertation, three papers are used to show how integrated design and planning processes for BGA can be implemented to increase the synergetic effect of water and vegetation. In the first paper, four exemplary, already completed projects are graphically analysed with regard to the weighting of blue and green components, both in the planning approach and implementation. The case studies show that, on the one hand, buildings offer many possible interfaces for blue-green systems, but conversely, practical connections and possible synergies are often overlooked during planning. This highlighted that there is a need for systematic approaches for BGA projects, that are able to optimise the interfaces and effectively couple blue and green systems.

The second paper of the thesis deals with the Impulse Project in Stuttgart, which originated from the BMBF-funded INTERESS-I research project. It is a mobile, temporary architecture that uses rainwater and treated greywater to irrigate vertical greenery. The interdisciplinary planning process is described in detail via Research by Design, analysed and structured according to three phases: Pre-Design (definition of objectives), Design (design and implementation) and Post-Design (review and reflection).

The insights gained from the design-based approach are then transferred into a design strategy,

which is applied to a practical project and evaluated in the third paper of the thesis. This involves a blue-green architecture project for a school garden, which was designed and implemented as part of an interdisciplinary course at the Technical University of Munich. Students of architecture and landscape architecture worked collectively, first distributing the roles and responsibilities (blue/green/integration) in the planning team. The design of the semi-natural system was then put into practice by the students with support from the school pupils. The grey water from the school garden's kitchen is treated in a constructed wetland and fed together with rainwater into a redesigned pond. A large number of aspects were interlinked in a small space: aesthetic design, didactic requirements, grey water treatment, environmental protection requirements and increasing biodiversity. The results were evaluated and key points for further development of the design strategy for BGAs were identified.

In summary, this illustrates that buildings and open spaces in their vicinity have a high potential to contribute to climate adaptation by integrating blue-green solutions. The fact that this potential is not fully exploited in practice is largely due to the traditional division of work within the disciplines in the field of planning and design. Blue-green infrastructures have so far been requested and implemented more frequently in landscape architecture, landscape planning and urban planning. This thesis seeks to contribute to the stronger anchoring of these concepts in architecture. The conceptual and methodological questions and approaches are intended as guidelines for architects, to aid in the implementation of further projects in an integrated manner according to BGA.

VORBEMERKUNGEN

Den Bezeichnungen „blau“ und „grün“ kommt in dieser Arbeit besondere Bedeutung zu. Sie beziehen sich dabei nicht auf die farblichen Attribute, sondern bezeichnen wasser- und vegetationsspezifische Aspekte im architektonischen und landschaftsarchitektonischen Kontext. Teilweise werden auch die am interdisziplinären Planungsprozess beteiligten Fachplanungen als blaue und grüne Seite bezeichnet. Damit sind die jeweiligen Disziplinen der Siedlungswasserwirtschaft, bzw. Landschaftsarchitektur und ihre fachspezifischen Herangehensweisen gemeint, die entweder aus dem Blickwinkel des Umgangs mit Wasser (blau) bzw. aus dem der Vegetation (grün) erfolgt.

Der Hauptteil der vorliegenden Arbeit (Kapitel 3) basiert auf drei in begutachteten Fachzeitschriften veröffentlichten Artikeln, die auf Englisch erschienen sind. Die rahmengebenden Kapitel (1, 2 und 4) sind auf Deutsch verfasst, um die zentralen Ergebnisse einem breiteren Fachpublikum auch außerhalb der Wissenschaft zugänglich zu machen. Vereinzelt werden Fachbegriffe genannt, für die es keine deutsche Übersetzung gibt, oder die in der englischen Version geläufiger sind. Diese sind kursiv gesetzt. Einige Grafiken, die wichtige Ergebnisse illustrieren, wurden aus den Originalveröffentlichungen in die rahmengebenden Kapitel übernommen. Zur besseren Verständlichkeit wurden bis auf wenige Ausnahmen die englischen Beschriftungen ins Deutsche übersetzt.

PUBLIKATIONSLISTE

Diese Arbeit basiert auf drei Einzelpublikationen, die jeweils in internationalen Fachzeitschriften mit Peer-Review-Verfahren erstveröffentlicht wurden. Die Artikel sind in Originalform im Kapitel 3 abgedruckt. Im Folgenden finden sich Zusammenfassungen der Paper und eine Aufstellung der Eigenanteile der Erstautorin.

Paper 1: Well, F. & Ludwig, F. (2020) „Blue–green architecture: A case study analysis considering the synergetic effects of water and vegetation", Frontiers of Architectural Research, Vol. 9, No. 1, S. 191–202. DOI: 10.1016/j.foar.2019.11.001.

Paper 2: Well, F. & Ludwig, F. (2021) „Development of an Integrated Design Strategy for Blue-Green Architecture", Sustainability, Vol. 13, No. 14, S. 7944. DOI: 10.3390/su13147944.

Paper 3: Well, F. & Ludwig, F. (2022) „Integrated Planning and Implementation of a Blue-Green Architecture Project by Applying a Design-Build Teaching Approach", Land, Vol. 11, No. 5, S. 762. DOI: 10.3390/land11050762.

Paper 1: Blue–green architecture: A case study analysis considering the synergetic effects of water and vegetation

Blue-green infrastructure is a network of natural and near-natural areas that has a positive effect on the quality of urban environment. This multifunctional planning approach addresses different issues and objectives depending on whether the focus is on the blue (water) or the green (vegetation) elements. Green-motivated projects aim to densify urban vegetation and include the growing sector of building greening. A good climatic effect of vegetation can be achieved by sufficient irrigation. In many cases, this approach results in additional water requirements. Blue-motivated projects consider water accumulation in cities (e.g., by heavy rainfall) as a waste product and look for solutions for local drainage and evaporation. These planning approaches offer only one-sided solutions and create no sufficient interfaces between water availability and water demand. Based on four case studies, this work examines the extent to which blue-green projects take advantage of the possibilities for the synergetic use of resources. The projects are analyzed graphically by applying the daily tools of architects as a scientific method. A graphic presentation of the blue and green components makes existing solutions and missing links visible. Analytical results show that buildings can be considered to be an interface for blue-green systems. Moreover, the possible synergies are often overlooked during the planning process. This fact highlights the need for a new planning approach that interlinks blue and green aspects that are already in the early planning stages.

Author’s contribution:

conceptualisation, F.W. and F.L.
methodology, F.W. and F.L.
investigation, F.W.
writing (original draft preparation), F.W.
writing (review and editing), F.W. and F.L.
visualisation, F.W.
supervision, F.L.
project administration, F.L.
funding acquisition, F.L. and F.W.

Paper 2: Development of an Integrated Design Strategy for Blue-Green Architecture

Blue-green architecture entails buildings that contribute to improving the urban climate through the synergetic combination of water management and vegetation. They are part of an urban blue-green infrastructure network that combines ecosystem services in a multifunctional way. Projects implemented in an interdisciplinary manner create synergies with regard to the combination of waterrelated and vegetation-related objectives. However, applicable design strategies for this approach are currently lacking in practice. This paper investigates the approach of a blue-green architectural project in Stuttgart (the so called "Impulse Project") and derives insights for an integrated design strategy. The analysis and transfer of the research is carried out by using the research by design methodology. For this purpose, the interdisciplinary design process is divided into three phases (pre-design, design, post-design) and described in detail. Reflection on the documented design reveals the knowledge gained and enables the transfer of the findings to future projects by means of the integrated design strategy for blue-green architecture.

Author's contribution:

conceptualisation, F.W. and F.L.
methodology, F.W.
investigation, F.W.
resources, F.W.
data curation, F.W.
writing (original draft preparation), F.W.
writing (review and editing), F.W. and F.L.
visualisation, F.W.
supervision, F.L.
project administration, F.L.
funding acquisition, F.L.

Paper 3: Integrated Planning and Implementation of a Blue-Green Architecture Project by Applying a Design-Build Teaching Approach

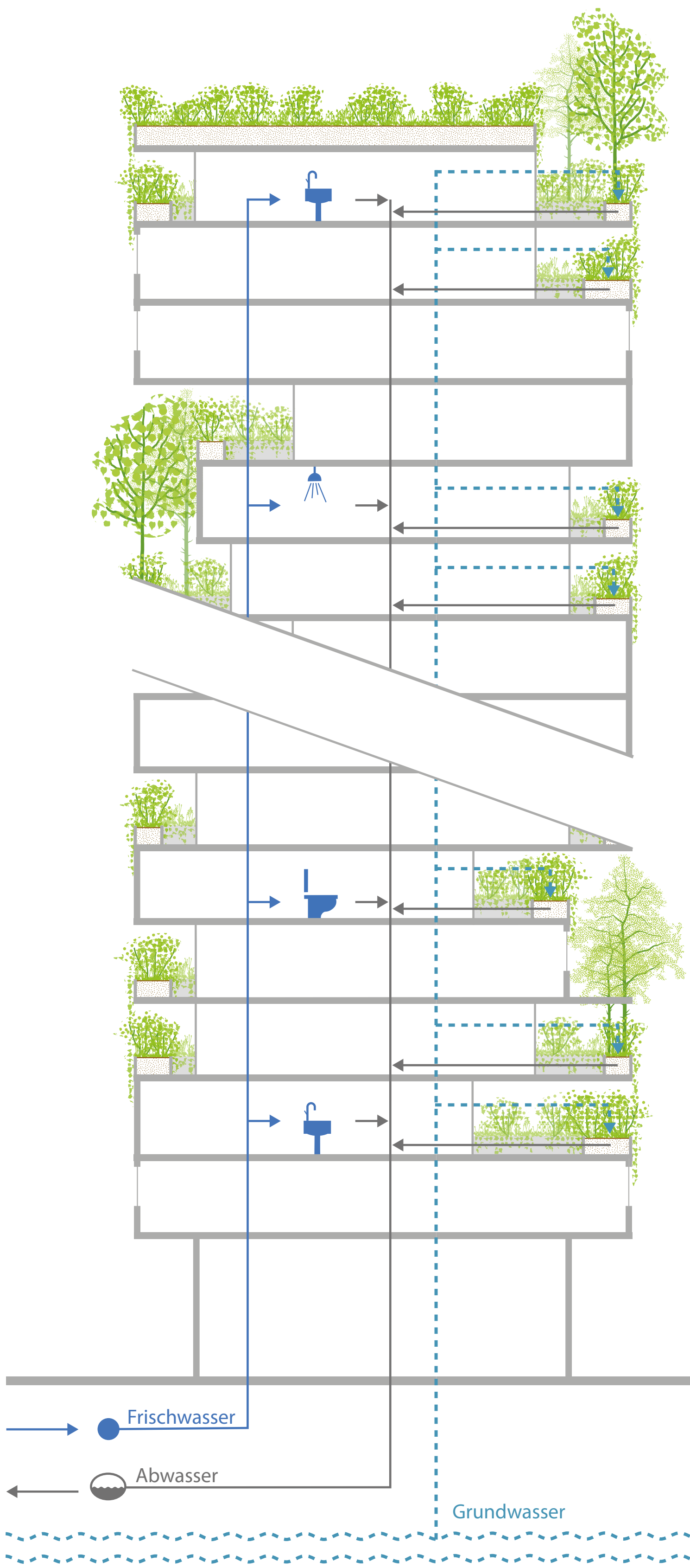
Blue-green architecture (BGA) describes buildings and open spaces that combine naturebased and technical systems of vegetation and urban water management. This creates positive effects on the urban climate, public health, biodiversity, and water balance. In this study, a design strategy for BGA is applied and evaluated on a practical project. The project consists of an interdisciplinary course in which students of architecture and landscape architecture designed and implemented a BGA for a school garden in Munich, Germany. The students worked in an interdisciplinary planning team in which they took on different roles and responsibilities (blue/green/integration). As a result, the design was put into practice by their own hands and a nature-based system was built. The greywater from the school garden is now treated in a constructed wetland and, in combination with rainwater, feeds into a redesigned pond. Biodiversity was increased and a contribution to the environmental education of the pupils was made. The students demonstrated high learning success. Finally, the design strategy for BGA was positively evaluated using a design-based research approach and additional points were added for future applications.

Author's contribution:

conceptualisation (study design), F.W. and F.L.
conceptualisation (university course) and teaching, F.W.
methodology, F.W.
investigation, F.W.
writing (original draft preparation), F.W.
writing (review and editing), F.W. and F.L.
visualisation, F.W.
supervision, F.L.
project administration, F.W. and F.L.
funding acquisition, F.W.

ABB. 1
URBAN GARDENING BEWÄSSERUNG, MÜNCHEN. FOTO: F. WELL

INHALTSVERZEICHNIS


Frischwasser
Abwasser
Grundwasser

1. EINLEITUNG

ABB. 2 (LINKS)
Bosco Verticale, Mailand, als Beispiel für eine blau-grüne Architektur. Eigene Darstellung [64]

Die veränderten Anforderungen an Stadt und Architektur verändern auch die Art des Planens und Entwerfens. Infrastruktur, Gebäude und Freiräume müssen auf immer engerem Raum einem immer höheren Anspruch an Multifunktionalität gerecht werden, um den Klimawandel nicht weiter zu verstärken, sondern ihm entgegen zu wirken [1]. Die Auswirkungen des Klimawandels in Form von Extremwetterereignissen verlangen darüber hinaus nach flexiblen Netzwerken in der gebauten Umwelt, die Sicherheit, Gesundheit und Wohlbefinden für die Bevölkerung gewährleisten [2].

Der Begriff der integrierten Planung (manchmal auch integrale Planung) beschreibt in den Ingenieurwissenschaften die frühzeitige Einbeziehung relevanter Faktoren in die Planung und Umsetzung, um die Wirkungsweise möglichst genau vorhersagen zu können [3]. Besonders wichtig ist dabei die interdisziplinäre Zusammenarbeit mit Fachplaner:innen [4]. Im Bereich der Energie- und Haustechnik gibt es bereits Beschreibungen dazu, wie sich die integrierte Vorgehensweise im Vergleich zum konventionellen Planungsprozess gestaltet [5]. Im Sinne der Klimaanpassung ist es von zentraler Bedeutung, die Integration um die Aspekte Wasser und Vegetation am und im Gebäude zu erweitern.

Konventionell geplante und gebaute Architektur führt zu einer hohen Flächenversiegelung, die sich im Fall von Extremwetterereignissen negativ auswirkt: Im Starkregenfall kommt es zu einem hohen Oberflächenabfluss, was zu lokalen Überflutungen führen kann [6]. Im Falle lang anhaltender Hitze und Trockenheit steigt die Lufttemperatur in versiegelten Gebieten noch zusätzlich an, da es wenig Verdunstungskühlung durch Vegetationsflächen gibt [7]. Diesem Umstand kann durch gezielte Einbindung von klimawirksamen Grünsystemen und wassersensibler Planung entgegengewirkt werden [8, 9]. Gebäude können dabei sowohl singulär als auch innerhalb blaugrüner Netzwerke einen wichtigen Beitrag leisten [10, 11].

In der vorliegenden Arbeit wird untersucht, wie das Konzept der integrierten Planung mit Wasser und Vegetation systematisch beschrieben und im architektonischen Entwurfsprozess angewendet werden kann. Das Ziel ist, eine Vorgehensweise für Architekt:innen und interdisziplinäre Planungsteams zu entwickeln, die nicht nur den funktionalen, sondern auch den gestalterischen Mehrwert einer klimawandelangepassten Bauweise fördert. In diesem Zusammenhang verwendet diese Arbeit den Begriff der blau-grünen Architektur (BGA). Gemeint sind damit intensiv begrünte und wassersensibel geplante Gebäude und gebäudebezogene Freiräume, die bis jetzt in der Praxis immer noch die Ausnahme sind (vgl. Abb. 2). In der Architektur fehlt es bisher an dem notwendigen Fachwissen und dem Verständnis für blau-grüne Systeme. Die hier vorgestellte Entwurfsstrategie für BGA soll daher als Anstoß für einen veränderten Umgang mit Wasser und Vegetation am und im Gebäude dienen. Die Erkenntnisse über die systematische Vorgehensweise in der integrierten Planung sind wiederum auf großmaßstäblichere Projekte übertragbar, die über das einzelne Gebäude hinaus gehen.

Um dieses Ziel zu erreichen, wurde die wissenschaftliche Erarbeitung des Themas eng mit kleinen Umsetzungsprojekten in der Forschung und Lehre verknüpft (Abb. 3). Die Entwurfs- und Planungsprozesse für BGA wurden angestoßen, begleitet und evaluiert,

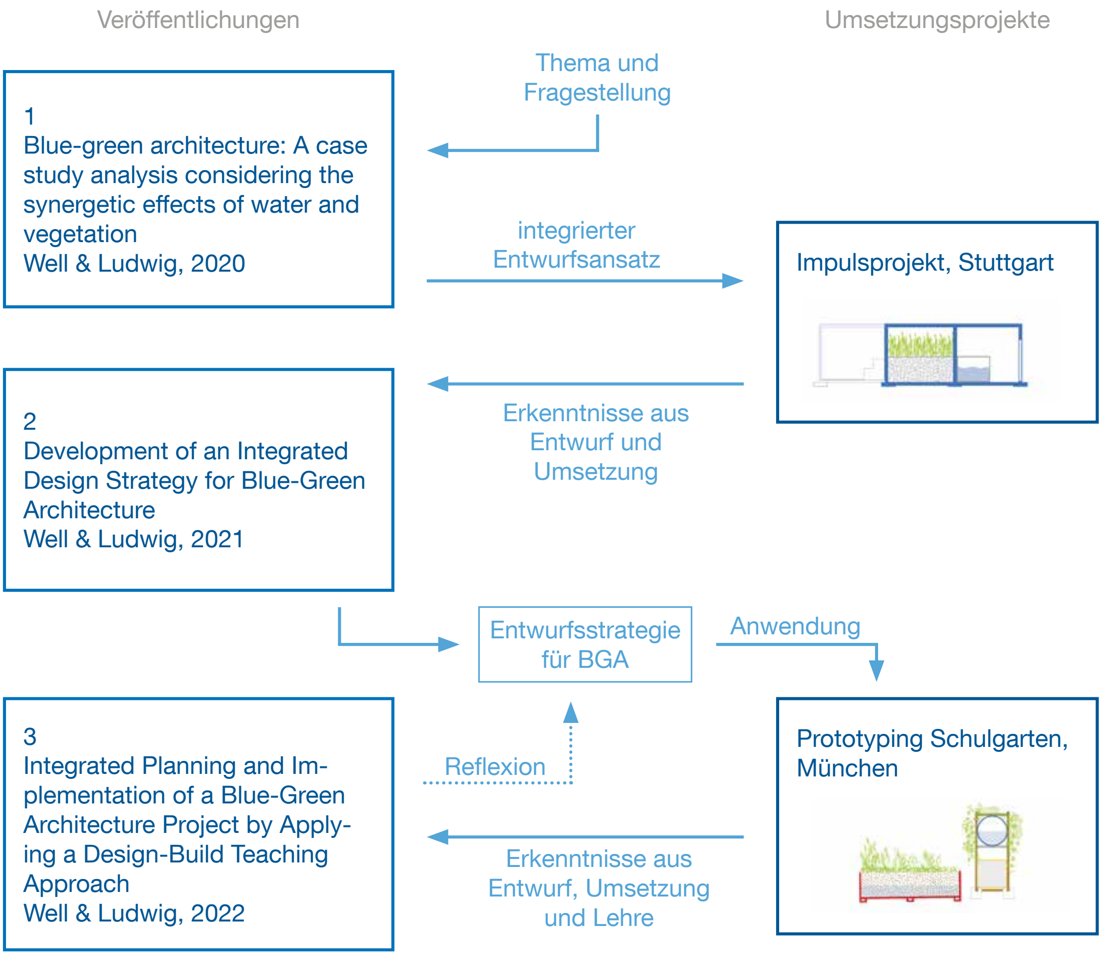


ABB. 3
Aufbau der vorliegenden Arbeit, die im wechselseitigen Prozess aus Veröffentlichungen und Umsetzungsprojekten entstand. Eigene Darstellung.

um daraus Erkenntnisse über die interdisziplinäre Zusammenarbeit und zentrale Stellschrauben im Entwurf abzuleiten. Die vorveröffentlichten Einzelpublikationen, die den Hauptteil der Arbeit bilden (Kapitel 3), sind in internationalen Fachzeitschriften mit Peer-Review-Verfahren erschienen.

Im ersten Paper wurde anhand von vier Fallbeispielen der Stand der Praxis in Bezug auf BGA erörtert. Die unterschiedlichen Herangehensweisen und Wirkungen wurden grafisch analysiert. Der integrierte Entwurfsansatz, der in dem Artikel entwickelt wurde (vgl. Abb. 17), kam im Impulsprojekt zur Anwendung. Dieses wurde im Rahmen des Forschungsprojekts INTERESS-I (Integrierte Strategien zur Stärkung blaugrüner Infrastrukturen) in Stuttgart umgesetzt. Beim Impulsprojekt handelt es sich um eine mobile, temporäre Architektur, die aufzeigt, wie die Kombination aus Regenwasser und aufbereitetem Abwasser aus Duschen und Handwaschbecken, sogenanntes Grauwasser, zur Bewässerung von Vertikalbegrünung verwendet werden kann. Der Entwurfs- und Planungsprozess des Umsetzungsprojekts wurde dokumentiert und reflektiert. Diese entwurfsbasierte Vorgehensweise lieferte Erkenntnisse, über deren systematische Auswertung eine Entwurfsstrategie für BGA entwickelt wurde. Die Entwurfsstrategie wurde in einem weiteren Umsetzungsprojekt auf Anwendbarkeit erprobt. Dafür wurde im Rahmen einer Lehrveranstaltung ein BGA-Projekt in einem Münchner Schulgarten realisiert. Die Erkenntnisse wurden wiederum publiziert und zeigten Ansatzpunkte zur Weiterentwicklung der Entwurfsstrategie auf.

Die Arbeit entstand im wechselseitigen Prozess aus theoretischer Erarbeitung, praktischer Anwendung und wissenschaftlicher Reflexion. Sie ist daher als Verbindung explorativer und analytischer Forschungsmethoden zu lesen.

ABB. 4 (OBEN)
Impulsprojekt Stuttgart. Foto: F. Well

ABB. 5 (UNTEN)
Prototyping-Projekt im Schulgarten. Foto: F. Well

ABB. 6 (OBEN)
Starkregenereignis mit Hagel.
Foto: F. Well

ABB. 7 (UNTEN)
Lang anhaltende Dürre belastet die urbane Vegetation. Foto: F. Well

1.1 - AUSWIRKUNGEN DES KLIMAWANDELS UND LÖSUNGSANSÄTZE FÜR DIE GEBAUTE UMWELT

Der Klimawandel ist kein Phänomen abstrakter Modellrechnungen mehr. Die Folgen der Erderwärmung sind auch in Deutschland längst Realität geworden [12]. Von 1881 bis 2021 stieg die Lufttemperatur im Jahresmittel um 1,6 °C an. Auch die Zahl der sogenannten heißen Tage mit Temperaturen über 30 °C nahm stetig zu. In den 1950er Jahren waren es durchschnittlich noch drei Tage pro Jahr; inzwischen liegt der bundesweite Durchschnitt bei neun heißen Tagen pro Jahr [13].

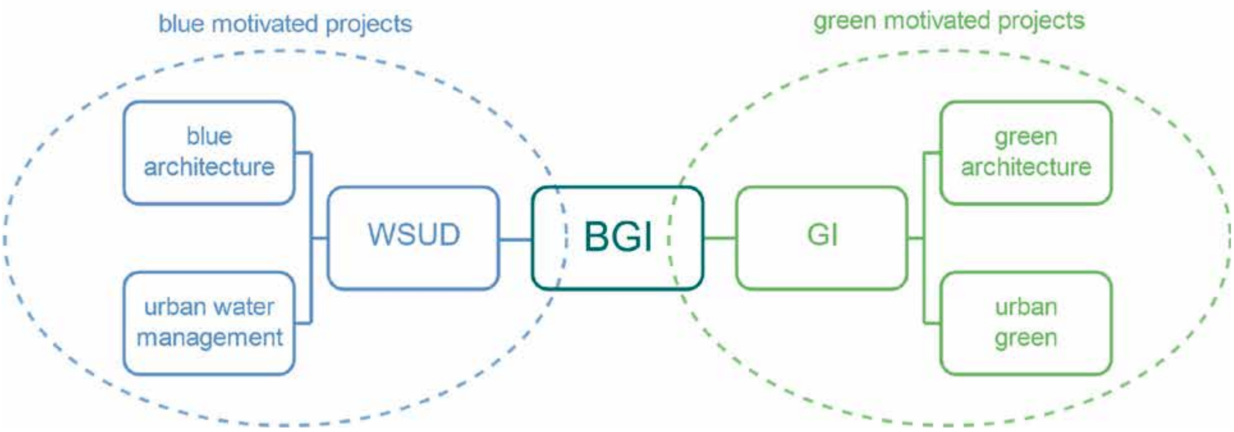
Ähnlich dramatische Veränderungen sind beim Niederschlag zu verzeichnen [14]. Die Winter sind feuchter geworden und es kommt zu mehr Niederschlägen, während die Sommer tendenziell trockener werden [13]. In der warmen Jahreshälfte verteilt sich der Regen weniger gleichmäßig, was dazu führt, dass es vermehrt zu Starkregenereignissen (Abb. 6) kommt, die sich mit langen Trockenphasen (Abb. 7) abwechseln [15].

Sturzfluten, die nur kurz andauern, aber sehr heftige Niederschläge mit sich bringen, richten hohe Schäden an [16]. Die Vereinten Nationen haben im World Water Development Report 2020 aufgeführt, dass in den vergangenen 20 Jahren durch wasserbezogene Katastrophen wie Überschwemmungen und Dürren weltweit 166.000 Menschen ums Leben gekommen und ökonomische Schäden von knapp 700 Milliarden US-Dollar entstanden sind [17]. Aus dem globalen Dürre-Index der Vereinten Nationen geht hervor, dass auch Mitteleuropa von starker Trockenheit betroffen ist. Die städtische Abwasserentsorgung europäischer Städte basiert meistens auf Mischwasserkanälen, die seit dem 19. Jahrhundert angelegt wurden, um Abwasser möglichst hygienisch und effektiv zu entsorgen [18]. Die Systeme sind nicht auf die hohen Mengen im Starkregenfall ausgelegt und schwemmen daher beim Überlauf unbehandeltes Abwasser in Oberflächengewässer [6, 19]. Sie sind nicht mehr zeitgemäß, nicht zuletzt auch deshalb, weil der hohe Anteil an abgeleitetem Niederschlagswasser zur Versorgung der städtischen Begrünung fehlt [20].

Für bebaute Gebiete sind die Klimawandelfolgen besonders dramatisch, weil der hohe Grad an versiegelten Oberflächen den Effekt der Überhitzung und das Überflutungsrisiko verstärkt [21]. Unbebaute Gebiete, wie beispielsweise landwirtschaftlich genutzte Flächen, leiden ebenfalls unter den Folgen von Extremwetterereignissen [22]. Insgesamt sind sie jedoch resilienter als städtische Gebiete, da der Boden im Starkregenfall mehr Wasser aufnehmen und an Hitzetagen über Verdunstung wieder abgeben kann [23–25]. Die hohe Versiegelung trägt auch zum sogenannten Hitzeinseleffekt (*Urban Heat Island*, bzw. UHI) bei, der die Temperaturdifferenz von Städten zum umgebenden Umland bezeichnet [26]. Die Lufttemperatur in Innenstädten kann dabei bis zu 11 °C höher liegen [27]. Der Effekt wird durch Verstädterung, Klimawandel und steigende Energieverbräuche perspektivisch verstärkt [28, 29] und stellt damit eine Gesundheitsgefahr für die Bevölkerung dar [30].

Die dichte Konzentration von Bewohner:innen und Infrastruktur macht Städte besonders vulnerabel im Fall von Extremwetterereignissen [31]. Daher spielen Klimaschutz (*mitigation*) und Klimaanpassung (*adaptation*) eine wichtige Rolle in der Stadtpolitik [32–35].

Es gibt zahlreiche internationale, europäische und nationale Bemühungen und Strategien, um gesundes Leben in Zeiten veränderter klimatischer



Bedingungen zu gewährleisten. Im Jahr 2015 wurden die *Sustainable Development Goals* (SDGs) von den Vereinten Nationen beschlossen [36]. Diese 17 Ziele der 193 Mitgliedsstaaten beinhalten unter Punkt 11 „Nachhaltige Städte und Gemeinden" und schließen in der detaillierten Ausführung ausdrücklich die Senkung von Umweltbelastungen, den Schutz vor Wasserkatastrophen und den allgemeinen Zugang zu hochwertigen Grünflächen mit ein [37]. Die Bundesregierung hat die SDGs in der 2021 neu aufgelegten Nachhaltigkeitsstrategie aufgegriffen [38]. Auf europäischer Ebene fördert das New European Bauhaus unter dem Motto „beautiful – sustainable – together" die nachhaltige Transformation der gebauten Umwelt im Sinne des European Green Deals [39].

Die angestrebte Neuausrichtung der gebauten Umwelt vereint eine große Zahl an Akteur:innen, Disziplinen, Zielsetzungen und Lösungsansätzen. Entsprechend vielfältig sind die Konzepte und Technologien, die in diesem Zusammenhang in den vergangenen Jahrzehnten angestoßen, entwickelt und erprobt wurden. Die hohe Aktualität und die Notwendigkeit einer schnellen Umsetzung verhilft dabei zu einer großen Bandbreite an Innovationen in Forschung, Wirtschaft und kommunaler Praxis.

Im Bereich der Klimaanpassung existieren eine Vielzahl an Strategien und Konzepten, die teilweise hohe Überschneidungen aufweisen. Dazu gehören insbesondere naturbasierte Lösungen (*nature-based solutions*, bzw. NBS) [40–42], das in den USA und Kanada verbreitete *Low Impact Development* [43, 44], das insbesondere in China etablierte Prinzip der Schwammstadt [45, 46], der kreislauforientierte Ansatz *Cradle to Cradle* [47, 48] und das damit verwandte *Regenerative Design* [49]. Kopp et al. (2021) [50] haben auf Basis von 27 Studien im Bereich BGI eine ausführliche Analyse und Unterscheidung der diversen Ansätze vorgenommen. Fletcher et al. (2015) [43] beschreiben Unterschiede in der Terminologie von Planungskonzepten der nachhaltigen Siedlungswasserwirtschaft.

In dieser Arbeit liegt der Fokus auf blau-grüner Infrastruktur (BGI) und blau-grüner Architektur (BGA). Beide Konzepte werden in den folgenden Kapiteln näher beschrieben und definiert.

ABB. 8
Blau und grün motivierte Planungsansätze im städtischen Maßstab sowie auf Gebäudeebene werden in der BGI zusammengeführt. WSUD = Water Sensitive Urban Design, GI = Green Infrastructure. Eigene Darstellung [64]

1.2 - BLAU-GRÜNE INFRASTRUKTUR (BGI) ALS KLIMAANPASSUNGSSTRATEGIE

BGI ist ein Konzept der Stadt- und Landschaftsplanung, das seit einigen Jahren zunehmend an Bedeutung und Beachtung gewinnt [51]. Die Stärkung der urbanen Resilienz gegenüber Extremwetterereignissen ist dabei ein treibender Faktor [10, 52]. Die Definitionen für BGI sind in der Literatur nicht einheitlich und von grüner Infrastruktur (GI) nicht klar abzugrenzen. Um die Verwendung des Begriffs in der vorliegenden Arbeit zu erläutern, erfolgt hier eine Einordnung im Kontext aktueller Literatur. Sehr verbreitet ist die Definition der Europäischen Kommission aus dem Jahr 2013. Sie beschreibt GI als ein „strategisch geplantes Netzwerk natürlicher und semi-natürlicher Flächen [...], das eine breite Anzahl an Ökosystemleistungen erbringt." [53]

Diese Basis-Definition wurde in den vergangenen Jahren teilweise erweitert und präzisiert [54]. So schreibt beispielsweise Dover (2015): „Grüne Infrastruktur ist die Gesamtheit der ökologischen Ressourcen eines Gebiets, einschließlich Einzelkomponenten und strategisch geplanten und umgesetzten Netzwerken aus hochwertigen Grünflächen und anderen Umweltelementen, einschließlich Oberflächen wie Gehwege, Parkplätze, Zufahrten, Straßen und Gebäude (außen und innen), die zur biologischen Vielfalt beitragen und Ökosystemleistungen fördern." [55]

Das Londoner Ingenieurbüro Arup definiert GI als „das System von Freiflächen, natürlichen Flächen, städtischen Wäldern und Parks; begrünten Straßen, Plätzen und öffentlichen Freiräumen; Flüssen und Flussläufen; sowie kleinmaßstäblichen Interventionen wie Gründächer und begrünte Fassaden – welche alle Teil des physischen Netzwerks von Städten und ihrer direkten Umgebung sind und wichtige Ökosystemleistungen übernehmen" [56] (S. 107) und bezieht damit Elemente der blauen Infrastruktur mit ein (vgl. Abb. 9).

Pötz & Bleuzé (2012) setzen GI und BGI gleich, indem sie schreiben „Grüne Infrastruktur oder blaugrüne Infrastruktur ist ein Netzwerk, das durch Bauen mit der Natur die ‚Zutaten' für die Lösungen städtischer und klimatischer Herausforderungen bereithält." [57]

Bei der Analyse von Beschreibungen und Definitionen der BGI treten Unterschiede in der Auffassung über den Umfang und die Funktionen der blauen Infrastruktur auf [58–60]. Die Einbeziehung von technischer Wasserinfrastruktur (Leitungen, Rohre, Kanäle) im Gegensatz zu aquatischen Elementen (Bäche, Flüsse, Teiche, Wasserspiele) ist in den Definitionen der BGI nicht einheitlich beschrieben. Der Forschungsverbund netWORKS ordnet diese Aspekte beispielsweise der grauen Infrastruktur zu [61] und fokussiert blau-grün-graue Lösungen. Andere Definitionen sehen BGI in der Abgrenzung zu grauer Infrastruktur, die zurück- bzw. umgebaut werden soll [62, 63]. Der Forschungsverbund INTERESS-I, dessen Ergebnisse eng mit dieser Arbeit verknüpft sind, hat den Begriff der blauen Infrastruktur um die technischen Elemente der Wasserinfrastruktur erweitert [58]. Dadurch wird sichergestellt, dass Kombinationen aus natürlicher und technischer Infrastruktur in die Lösungsfindung einbezogen werden, was insbesondere im dicht bebauten städtischen Raum erforderlich ist, um auf die hohen Anforderungen an Multifunktionalität planerisch bestmöglich und flexibel reagieren zu können.

Eine klare Zuordnung von Planungselementen zur blauen oder grünen Infrastruktur ist deshalb schwierig, weil die Grenzen fließend sind. Vereinfacht könnte

ABB. 9
Urbane BGI dient der Naherholung und übernimmt zahlreiche Ökosystemdienstleistungen in der Stadt. Rosengarten, München. Foto: F. Well

man beispielsweise sagen, dass Vegetation immer als blau-grünes Element verstanden werden kann, da jede Pflanze Wasser aufnimmt und verdunstet. Auch die auf dem Markt verfügbaren Produkte wie beispielsweise Retentions-Gründächer, können in ihrer Funktion nicht eindeutig der blauen oder grünen Seite des Systems zugerechnet werden. Das dieser Arbeit zugrunde liegende Verständnis von BGI bezieht sich daher weniger auf blaue und grüne Komponenten, die zu dem Gesamtnetz beitragen, als vielmehr auf die Verbindung blauer und grüner Planungsansätze miteinander (vgl. Abb. 8).

Dieser Ansatz ist in ausführlicher Form in der Publikation Well und Ludwig (2020) [64] beschrieben. Kurz zusammengefasst bedeutet die Herangehensweise, dass über die Zusammenführung der blauen und grünen Zielsetzungen synergetisch wirksame blau-grüne Systeme geschaffen werden. Die angesprochenen Zielsetzungen sind maßgeblich für den Umgang mit Wasser und Vegetation. Bei einer einseitigen Betrachtung der zugrunde liegenden Fragestellung können sie dazu führen, dass das eine dem anderen untergeordnet wird. Das würde bedeuten, dass Vegetation genutzt wird, um den urbanen Wasserkreislauf zu verbessern, bzw. Wasser genutzt wird, um ein gestalterisch aufwendiges Vegetationskonzept zu bewässern.

BGI berücksichtigt Konzepte des urbanen Wassermanagements ebenso wie urbane Grünsysteme und erhöht damit die Wirksamkeit der realisierten Maßnahmen [65]. Wasserverfügbarkeiten und Wasserbedarfe werden bestmöglich aufeinander abgestimmt. Dieser Ansatz wird von Dreiseitl und Wanschura (2016) ähnlich beschrieben [62] (S. 42). Er beruht auf der Annahme, dass sich die positiven Effekte vervielfachen, wenn Wasser und Vegetation gemeinsam gedacht werden und in einem System zusammenwirken.

ABB. 10 (OBEN)
Intensive Dachbegrünung, wagnisART, München. Foto: F. Well

ABB. 11 (UNTEN)
Impulsprojekt und Urban Gardening, Stuttgart. Foto: F. Well

1.3 - BLAU-GRÜNE ARCHITEKTUR: DAS GEBÄUDE ALS SCHNITTSTELLE VON WASSER UND VEGETATION

In dieser Arbeit liegt der Fokus auf dem Gebäude und die blau-grüne Fragestellung wird aus dem Blickwinkel der Architektur betrachtet. Die Planungs- und Gestaltungsprinzipien der BGI werden auf einer kleineren Maßstabsebene betrachtet und angewendet [64, 66, 67]. Dafür wird hier der Begriff der blau-grünen Architektur (BGA) eingeführt.

BGA beschreibt gebäude- und freiraumbezogene, intensive Grünsysteme in Kopplung mit einem Wassermanagement, das Schwankungen in Qualität und Verfügbarkeit berücksichtigt. Die Grünsysteme können sowohl im Bereich der Gebäudehülle als auch im umgebenden Freiraum verortet sein. Das Wassermanagement bezieht sämtliche Wasserströme am und im Gebäude, auf dem Grundstück und in der näheren Umgebung mit ein. Dabei werden insbesondere alternative Wasserressourcen ausfindig gemacht, die Brauchwasserqualität haben und zur Bewässerung eingesetzt werden können. Passende Speicher- und Aufbereitungsmöglichkeiten tragen dazu bei, dieses Wasser nicht über die Kanalisation entsorgen zu müssen, sondern für die Bewässerung zu erschließen [68]. Die ausreichende Versorgung der Vegetation mit Wasser verbessert die Vitalität und die Verdunstungsleistung [69]. Diese Erbringung von Ökosystemdienstleistungen ist ein wesentliches Merkmal blau-grüner Lösungen [51, 70, 71]. Dazu gehören u.a. auch die Verbesserung des Mikroklimas und der Luftqualität, die Verbesserung der lokalen Wasserqualität, die Verringerung des Oberflächenablaufs, die Erhöhung der Biodiversität durch Habitate und ein gesundheitlicher, kultureller und ökonomischer Mehrwert für die Bevölkerung [72–74]. BGA erschließt diese Qualitäten in kleinmaßstäblicher Ebene und wirkt damit den negativen Umweltauswirkungen der dichten städtischen Bebauung entgegen [75].

Der Betrachtungsrahmen für BGA umfasst einzelne Gebäude, bzw. Gebäudekomplexe und die umgebenden Freiflächen bis hin zur Grundstücksgrenze. Dabei ist diese Grenze als durchlässige Schnittstelle zu sehen, um die Einbettung der BGA in ein größeres blau-grünes Netzwerk zu ermöglichen. Gebäude haben durch die Integration von naturbasierten Lösungen ein hohes Potenzial, zur Klimaanpassung beizutragen [28, 76, 77]. Dieses Potenzial wird in der Praxis zu einem großen Teil nicht ausgeschöpft, was insbesondere auf die traditionelle Arbeitsteilung innerhalb der planend-gestaltenden Professionen zurückzuführen ist [78].

In der Architekturausbildung wird in der Regel nur Basiswissen über den Umgang mit Wasser und Vegetation vermittelt. In der Regel enthält das Grundstudium einzelne Module zur Landschaftsarchitektur und Stadtplanung, jedoch fehlt die Lehre im Bereich der gestalterischen Einbindung in den architektonischen Entwurf. Diese fachliche Trennung setzt sich in der Planungspraxis fort und führt dazu, dass naturbasierte Lösungen und blau-grüne Infrastrukturen eher in der Landschaftsarchitektur, Landschaftsplanung und Stadtplanung gefordert und umgesetzt werden.

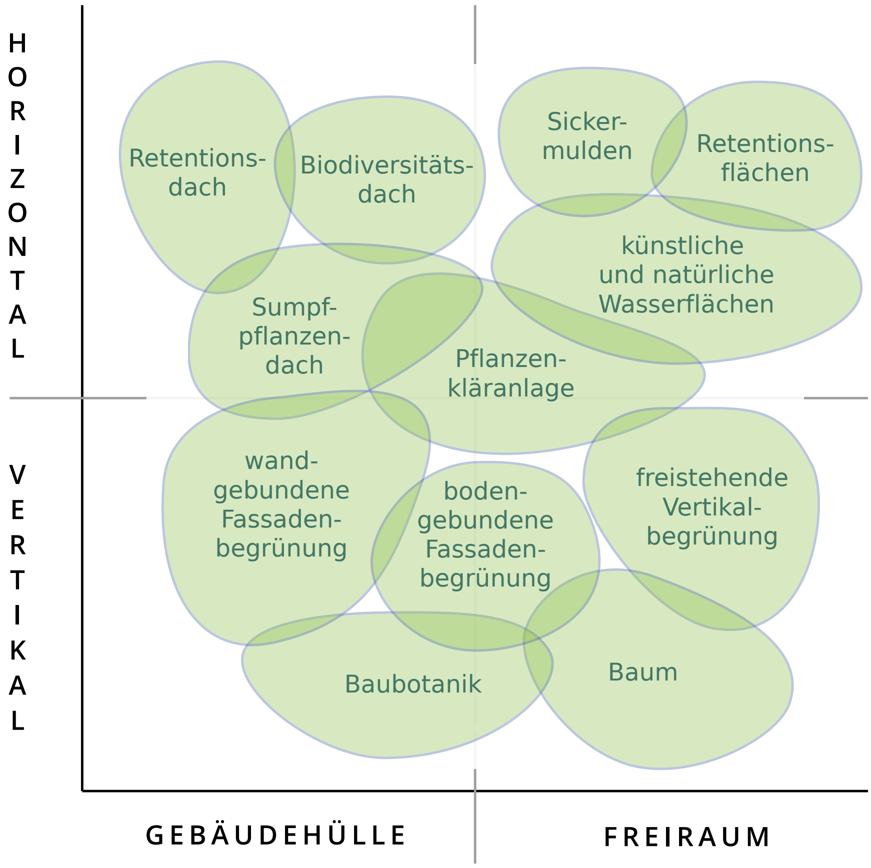
Das übergeordnete Netzwerk der BGI schließt Gebäude prinzipiell mit ein, jedoch bleiben konzeptionelle und methodische Fragestellungen in diesem Kontext ungeklärt [79]. Es fehlt an Strategien und Handreichungen für Architekt:innen, um Projekte im Sinne der BGA integriert umzusetzen.

Wie auch bei der BGI ist die integrierte Herangehensweise an den Entwurf und die Planung

die wichtigste Voraussetzung für BGA. Gleichwohl gibt es einzelne Bausteine, die in dem blau-grünen System zur Anwendung kommen können. Dazu gehören beispielsweise Dach- und Fassadenbegrünung, Zisternen und Pflanzenkläranlagen. Oftmals stehen aber auch individuelle Einzellösungen im Fokus, die aus dem jeweiligen Projekt heraus entstehen. Im „Leitfaden für integrierte Planung blau-grüner Infrastrukturen“ [58] (S. 28-31) wurden Tabellen mit blauen und grünen Komponenten zusammengestellt, die auch im Entwurf von BGA herangezogen werden können. Darüber hinaus zeigt Abbildung 16 ein Cluster naturbasierter Lösungen für BGA. Dabei wird deutlich, dass die Abgrenzung der einzelnen Komponenten nicht immer eindeutig möglich ist. Es kommt zu Überschneidungen an der Grenze von Gebäudehülle und Freiraum, sowie zwischen horizontal und vertikal angelegten Systemen. Auch die Systeme untereinander weisen in ihren Funktionen und Anwendungsmöglichkeiten teilweise Überschneidungen auf. So kann beispielsweise ein Sumpfpflanzendach als horizontal angelegte Pflanzenkläranlage in der Gebäudehülle betrachtet werden. Konzepte wie die Baubotanik vereinen Merkmale wie die einer boden- und wandgebundenen Fassadenbegrünung mit den Qualitäten freistehender Bäume.

Nicht in Abbildung 16 enthalten sind Bestandteile der technischen (Wasser-)Infrastruktur. Dabei kann es sich beispielsweise um unterirdische Wasserspeicher oder mechanische Aufbereitungssysteme handeln. Es zählen dazu auch Bewässerungstechnik, Brauchwassernetze und smarte Lösungen, die auf Wettervorhersagen reagieren und das Wassermanagement auf Starkregen oder Trockenheit anpassen können.

Die Gebäudehülle so zu aktivieren, dass sie Ökosystemdienstleistungen erbringt, ist ein Ansatz, der zwar bekannt, aber wenig verbreitet ist [80].



Innovative Grünsysteme für Dach und Fassade erhöhen die Wirksamkeit positiver Umwelteffekte, indem sie gestalterisch und funktional die Aufenthaltsqualität für Nutzer:innen und Bewohner:innen erhöhen. Hinzu kommt, dass Gebäude als Knotenpunkte der Wasserversorgung und Abwasserentsorgung betrachtet werden können und daher in Kombination mit Regenwassermanagement unterschiedliche alternative Wasserressourcen bereithalten und auch direkt wieder nutzen können [81]. Es ist daher dringend erforderlich, dass sich die Integration von Wasser und Vegetation in die urbane Infrastruktur nicht ausschließlich auf den Freiraum beschränkt. In integrierten Entwurfsprozessen kann das notwendige Wissen aus den Fachdisziplinen in BGA-Projekte einfließen. Nur so gelingt es, die Flächen, die funktionalen Möglichkeiten und das gestalterische Potenzial, das Gebäude in dieser Hinsicht bieten, voll auszuschöpfen [82]. Eine spätere Einbindung der Fachplanungen birgt die Gefahr rein additiver Lösungen und könnte damit den erwünschten Synergien entgegenstehen. Voraussetzung für erfolgreiche BGA-Projekte ist daher an erster Stelle das Bewusstsein für integrierte blau-grüne Planung in der Architektur. Darüber hinaus ist die inter- und transdisziplinäre Zusammenarbeit mit der Stadtplanung, Siedlungswasserwirtschaft, Gebäudetechnik und Landschaftsarchitektur erforderlich.

ABB. 12 - 15 (LINKS)
Obere Reihe: BGA im Schulgarten mit Teich und bepflanztem Bodenfilter. Fotos: K. Pujkilovic (links, Abb. 12) und F. Well (rechts, Abb. 13)
Untere Reihe: Impulsprojekt mit Fassadenbegrünung und Grauwasserbeschickung des Bodenfilters. Fotos: J. Rettig

ABB. 16 (OBEN)
Cluster naturbasierter Lösungen für BGA. Eigene Darstellung

1.4 - FORSCHUNGSFRAGEN UND ZIELSETZUNGEN: INTEGRIERTER ANSATZ IM BGA-ENTWURF

Der Ausgangspunkt dieser Arbeit ist die Fragestellung, wie wasserbezogene und vegetationsspezifische Zielsetzungen und Parameter frühzeitig in den architektonischen Entwurf einfließen können, um die Klimaanpassung von Gebäuden und gebäudenahen Freiräumen zu erhöhen. Dabei sollen blaue und grüne Aspekte gleichwertig berücksichtigt und die Synergien an den blau-grünen Schnittstellen erhöht werden.

Den drei Artikeln, die den Hauptteil der Arbeit bilden, liegen wiederum eigene Teil-Fragestellungen zugrunde. Diese sind im Folgenden zusammengefasst.

Im ersten Artikel werden vier gebaute Fallbeispiele, die der BGA und BGI zugeordnet werden können, grafisch analysiert (Methodik siehe Kapitel 2.2). Die grafische Analyse basiert dabei auf folgenden Forschungsfragen: Was war die Motivation für das Projekt? Auf welchem Konzept basierten die blauen und grünen Bestandteile? Welche Art von Bepflanzung wurde eingesetzt? Welche Wasserströme gibt es im Rahmen des Projekts und in der unmittelbaren Umgebung? Inwieweit besteht eine synergetische Verbindung zwischen Wasserversorgung und Begrünung?

Ziel der ersten Studie war es, die Herangehensweise bei bestehenden Projekten besser zu verstehen und blaue und grüne Motivationen zu identifizieren. Darüber hinaus wird die Notwendigkeit für eine integrierte Vorgehensweise im Entwurf konkretisiert.

Der zweite Artikel beschreibt einen integrierten blau-grünen Entwurfsprozess, dessen Vorgehensweise systematisch analysiert wird. Anschließend werden die Erkenntnisse abstrahiert und in eine Entwurfsstrategie überführt. Der Studie liegen daher zwei Abfolgen von Forschungsfragen zugrunde.

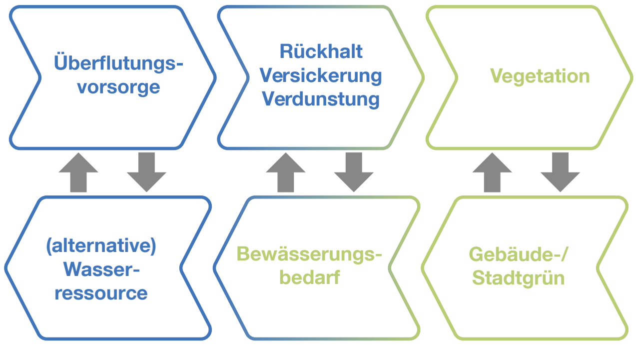
Erstens: Wie sieht der integrierte blau-grüne Entwurfsprozess in der Anwendung aus? In welchen Schritten verläuft der Prozess? Wie gestaltet sich das Zusammenspiel im interdisziplinären Team und welche unvorhergesehenen Schwierigkeiten treten auf? Wie laufen die Entscheidungsprozesse ab und welche positiven Ergebnisse werden durch den integrierten Ansatz erzielt?

Zweitens: Welche allgemeinen Erkenntnisse lassen sich für die integrierte blau-grüne Planung ableiten? Wie lassen sie sich auf weitere Projekte übertragen? Welche Strategien müssen für eine erfolgreiche Umsetzung von blau-grünen Architekturprojekten entwickelt werden?

Das Ziel der zweiten, entwurfsbasierten Studie war die Entwicklung einer Entwurfsstrategie, die bei Folgeprojekten zum Einsatz kommen kann.

Der dritte Artikel beinhaltet die Anwendung der Entwurfsstrategie für BGA im Rahmen einer Lehrveranstaltung. Fragestellungen und Zielsetzungen unterliegen in diesem Fall wiederum einer Dreiteilung. Die Forschungsfragen sind:

1. Kann die Designstrategie für BGA dazu verwendet werden, ein funktionales und ästhetisches



System zu schaffen, das den Anforderungen der Nutzer entspricht?

2. Erleben die Studierenden einen Lernerfolg durch die forschungsbasierte und praxisnahe Lehrmethode?

3. Welche Schlussfolgerungen können aus dem Entwurfs- und Planungsprozess gezogen werden, um die Entwurfsstrategie für BGA zu verbessern?

Die drei Zielsetzungen der dritten Studie waren dementsprechend: Eine BGA als gebautes Ergebnis, ein erkennbarer Lernerfolg bei den Studierenden und eine Evaluation der Entwurfsstrategie auf Stärken und Schwächen.

Alle in den Artikeln betrachteten Projekte (Case Studies und Umsetzungsprojekte) befinden sich in gemäßigten Klimazonen. Die Erkenntnisse der integrierten Vorgehensweise für BGA sind teilweise auf andere klimatische Umgebungen übertragbar, jedoch sollten dabei auch die Planungskultur und die ortsspezifischen Anforderungen und Zielsetzungen für blau-grüne Projekte berücksichtigt werden.

Die Projektteams, an welche die vorgestellte Entwurfsstrategie gerichtet ist, sollten interdisziplinär besetzt sein und alle für das Projekt relevanten blauen und grünen Kompetenzen repräsentieren. Die Verantwortung für die entwerferisch-gestaltende Integration kann sowohl von Architekt:innen als auch von Landschaftsarchitekt:innen übernommen werden. Die Entscheidung darüber sollte je nach Art des Projekts getroffen werden. Eine enge interdisziplinäre Zusammenarbeit ist in jedem Fall erforderlich.

Das Ziel der Arbeit ist eine Entwurfsstrategie für Architekt:innen und Entwurfsteams, die die integrierte Herangehensweise für BGA abbildet und als Orientierungshilfe für die interdisziplinäre Zusammenarbeit herangezogen werden kann. Diese Entwurfsstrategie kann als Schritt-für-Schritt-Anleitung gelesen werden, sie soll aber insbesondere das Bewusstsein dafür stärken, dass die synergetisch wirksame Integration von blau-grünen Strukturen in den Gebäudeentwurf einen mikroklimatischen, ökologischen und ästhetischen Mehrwert bildet.

ABB. 17
Integrierter Planungsansatz für BGA und BGI. Eigene Darstllung [64]

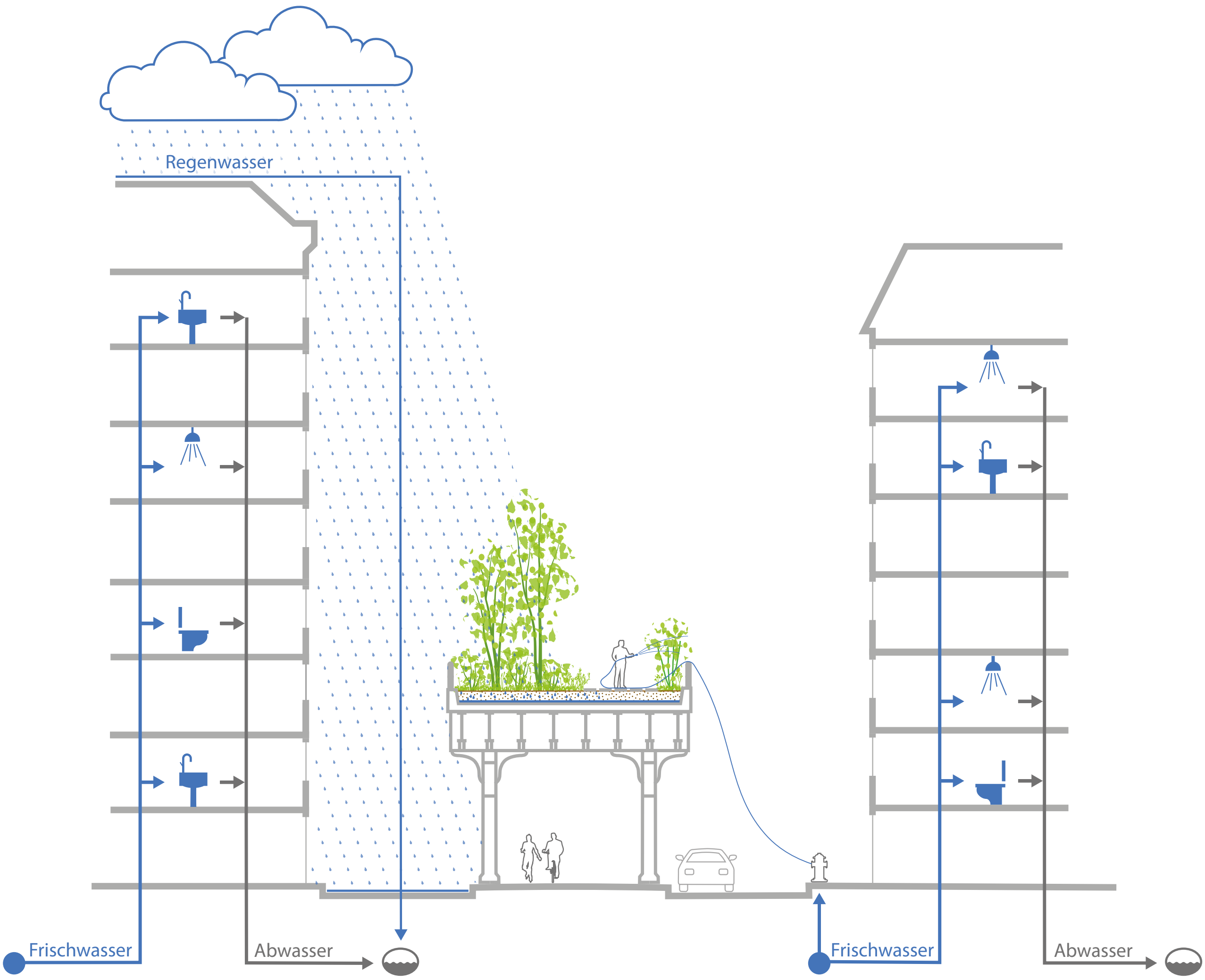


ABB. 18
The High Line, New York City, grafisch analysiert in Hinsicht auf blau-grüne Synergien. Eigene Darstellung [64]

2. ZUSAMMENSTELLUNG UND REFLEXION DER GEWÄHLTEN METHODEN

Die vorliegende Arbeit ist in der Fachrichtung Architektur (mit Schnittstellen zur Landschaftsarchitektur) verwurzelt und eng mit architektonischen Entwürfen und kleinen Umsetzungsprojekten verknüpft. Daher folgen auch die ausgewählten Methoden einem entwurfsbasierten Prinzip und bilden in ihrer Gänze eine qualitative Herangehensweise [83]. Die Frage danach, wie blau-grüne Entwurfsprozesse zu gestalten sind, wurde beantwortet, indem eine Abfolge aus ebendiesen durchlaufen wurde. Die Erkenntnisse wurden reflektiert und schriftlich festgehalten. Im Folgenden wird dieser methodische Ansatz in seiner Bedeutung für die Forschungsfragen eingeordnet und um eine kurze Beschreibung der Methoden ergänzt, die in den drei Einzelveröffentlichungen zur Anwendung kamen.

2.1 - QUALITATIVER FORSCHUNGSANSATZ

Die adressierten Forschungsfragen (vgl. Kapitel 1.4) verlangen eine intensive Auseinandersetzung mit dem architektonischen Entwurfsprozess. Die Frage danach, wie blaue und grüne Zielsetzungen und Komponenten in den Entwurf einfließen und synergetisch wirken können, ist dabei über alle drei Einzelpublikationen hinweg entscheidend. Es werden besonders diejenigen Aspekte im Prozess genauer untersucht, die nur bedingt quantifizierbar sind. Dazu gehört beispielsweise die zugrunde liegende Motivation für ein Projekt, aber auch das implizite Wissen im Entwurf. Wölfel (2012) hat Designwissen detailliert erörtert und beschrieben und in diesem Zusammenhang die relevanten Begrifflichkeiten und Definitionen zusammengestellt [84]. Beim Entwerfen bezieht er sich u. a. auf Hatchuel und Weil (2003) und übersetzt deren Definition folgendermaßen: „Entwerfen ist ein Prozess, durch den etwas Unbekanntes absichtsvoll aus Bekanntem entstehen kann.“ [84]

Die Methodenkombination der vorliegenden Arbeit reicht vom Forschen über Design bis hin zum Forschen durch Design [85]. Es handelt sich damit in der Gesamtheit um eine qualitative, explorative Vorgehensweise. „Durch die Anwendung qualitativer Methoden erhalten Forscher einen Einblick in die Motivation, Wertvorstellungen, Verhaltensnormen, Erwartungen und den sozialen Kontext bestimmter Gruppen. Die große Stärke qualitativer Forschung liegt in der ausführlichen Beschreibung des Forschungsthemas, oft in Bezugnahme auf individuelle Aussagen von Einzelpersonen.“ [85]

Die theoretische Grundlage für den integrierten Planungsansatz wurde durch die Analyse gebauter Projekte gelegt (1. Paper, Forschung über Design). Anschließend wurde die Entwurfsstrategie für BGA in

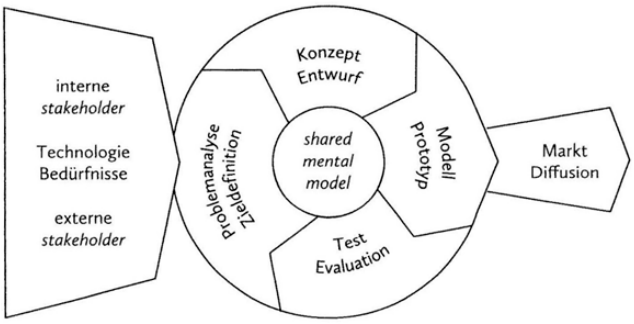


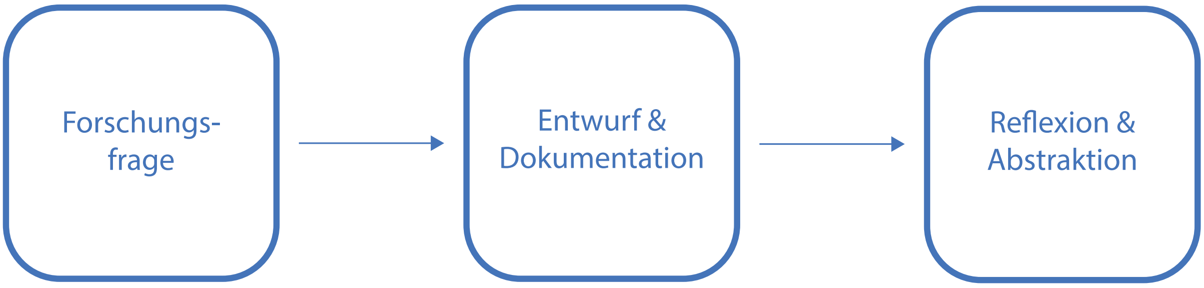
ABB. 19 (LINKS)
Innovationsprozess nach Wölfel [84]

ABB. 20 (RECHTS)
Entwurfsbasierte Vorgehensweise des 2. und 3. Papers. Eigene Darstellung [66]

einem entwurfsbasierten Prozess entwickelt, angewendet und evaluiert (2. und 3. Paper, Forschung durch Design, Abb. 20). Diese Vorgehensweise ist mit dem von Wölfel (2012) beschriebenen Innovationsprozess (Abb. 19) vergleichbar. Cortesão et al. (2019) haben beschrieben, wie die bewusste Kombination mehrerer entwurfsbasierter Methoden dazu beitragen kann, anwendbares Wissen für die städtische Planung zu generieren [86]. Dabei werden insbesondere auch Designexperimente, replizierbare Entwurfsleitlinien und Überprüfungsmethoden genannt, die es in einer angemessenen Reihenfolge anzuwenden gilt [86]. Die vorliegende Arbeit beginnt mit einer grafischen Analyse von Fallbeispielen (*Case Studies*). Im zweiten Artikel wird ein *Research-by-Design*-Prozess durchlaufen. In der dritten Veröffentlichung kommt eine praxisbasierte Forschungsmethode zur Anwendung. Die vorherigen Erkenntnisse werden dabei angewendet und evaluiert. Alle drei methodischen Ansätze werden in den folgenden Unterkapiteln näher beschrieben.

Ein wesentlicher Bestandteil der gesamten Arbeit war die Dokumentation und Reflexion der Erfahrungen aus dem Forschungsprojekt INTERESS-I und dem Schulgarten-Projekt, das als kleine Umsetzungsmaßnahme folgte. Die aus INTERESS-I gewonnenen Erkenntnisse umfassten zum einen das in der zweiten Veröffentlichung beschriebene Impulsprojekt. Zum anderen floss auch das Wissen aus der im Projekt bearbeiteten Pilotgebiete in die Arbeit ein [58] (S. 55- 71). Die Entstehung und Weiterentwicklung der Entwurfsstrategie war daher sehr von diesen Erfahrungen geprägt. Die kontinuierliche Protokollierung der Erkenntnisse und offenen Fragen ist vergleichbar mit der von Kumar (2012) beschriebenen Methodik des *Reflective Journal Log* [87].

Die Kombination der verschiedenen systematisch analysierenden und entwurfsbasierten Methoden ermöglichte eine ergebnisoffene Entwicklung der Entwurfsstrategie für BGA unter Einbeziehung des interdisziplinären Fachwissens der Projektpartner:innen. Die Diskussion und Anwendung der Entwurfsstrategie trug anschließend zur Weiterentwicklung bei. In Bezug auf die mikroklimatische Wirksamkeit und andere Umweltwirkungen sind ihm Rahmen der vorliegenden Arbeit keine quantitativen Daten erhoben worden. Die Annahmen über die ökologischen und stadtklimatischen Effekte beziehen sich auf Literaturstudien, welche die positiven Umweltwirkungen von naturbasierten Lösungen und blau-grünen Systemen durch Simulationen und Messungen quantifizieren. Im Bereich der ökologischen Stadtentwicklung besteht eine Lücke zwischen vorhandenem Wissen, bzw. theoretischen Konzepten und innovativen Projekten, die dieses Wissen anwenden [88–90]. Daher soll diese Arbeit einen Beitrag dazu leisten, einen Paradigmenwechsel in der architektonischen Planung hin zu klimaangepassten Gebäuden anzustoßen, die als Teile blau-grüner



Netzwerke wirken.

Die Kopplung des integrierten Entwerfens von BGA mit interdisziplinären Lehrveranstaltungen trug dazu bei, den Ansatz bereits in der Ausbildung von Architekt:innen und Landschaftsarchitekt:innen zu verankern. Zu den Lehrveranstaltungen, die alle an der Technischen Universität München stattfanden, gehörten das Seminar Green Typologies im Wintersemester 2020/21 (vgl. Kapitel 2.2), das Interdisziplinäre Projekt des Master-Studiengangs „Ressourceneffizientes und nachhaltiges Bauen“ im Sommersemester 2021 und das Seminar „Prototyping blue-green systems“, ebenfalls im Sommersemester 2021, das in den Kapiteln 2.4 und 3.3 beschrieben ist.

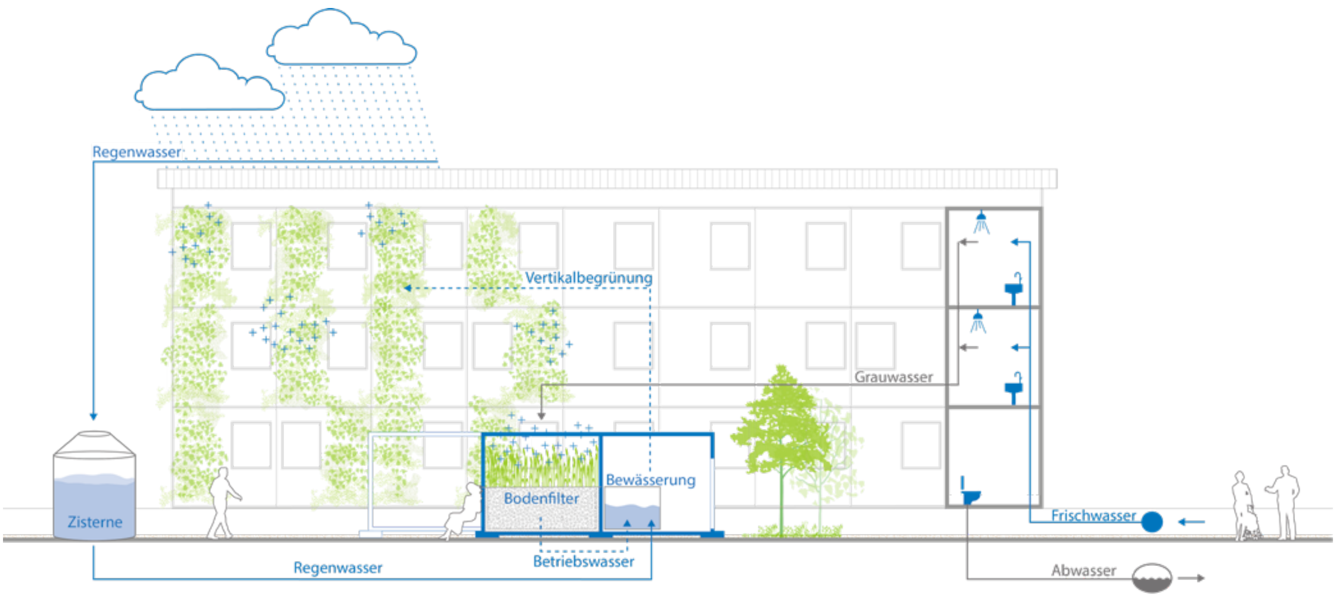
2.2 - CASE STUDY UND GRAFISCHE ANALYSE

Zu Beginn der Arbeit stand eine Analyse von Fallbeispielen, um den Stand der Praxis im Bereich blau-grüner Projekte zu ermitteln. Eine breit angelegte Literatur- und Internetrecherche nach existierenden Planungskonzepten und gebauten Beispielen von BGI und BGA zeigte deutliche Unterschiede in den Herangehensweisen. Vier Projekte wurden exemplarisch herausgegriffen und grafisch untersucht [64]. Im Zeichenprozess wurde erkennbar, welche blauen und grünen Bestandteile das jeweilige Projekt und die nähere Umgebung aufweisen und welche Synergien durch blau-grüne Kopplungen entstehen.

Case Studies sind eine gebräuchliche Methode in der Landschaftsarchitektur, um komplexe Phänomene zu untersuchen [91]. Die Analyse mehrerer Fallbeispiele wird, im Gegensatz zum *within-case*, als *cross-case*-Vergleich bezeichnet [91].

Bei den vorliegenden Fallbeispielen handelt es sich jeweils um zwei Projekte im städtebaulichen Maßstab und zwei auf Gebäudeebene. Die Projekte unterscheiden sich außerdem in der Ausgangsmotivation in der Planung. Zwei davon sind grün motiviert, d. h. die Gestaltung mit Vegetation und die damit verbundenen positiven Wirkungen steht im Vordergrund. Die beiden anderen folgen einem blauen Ansatz. Sie sind aus den Fragestellungen des nachhaltigen Wassermanagements heraus motiviert, auch bekannt als *Water Sensitive Urban Design* (WSUD). Alle vier Projekte weisen sowohl blaue als auch grüne Anteile in der Umsetzung auf. Jedoch ist jeweils eine der beiden Seiten stärker gewichtet, während die andere funktional nachfolgt. Wertvolle Möglichkeiten für synergetische Schnittstellen von Wasser und Vegetation gehen dadurch verloren.

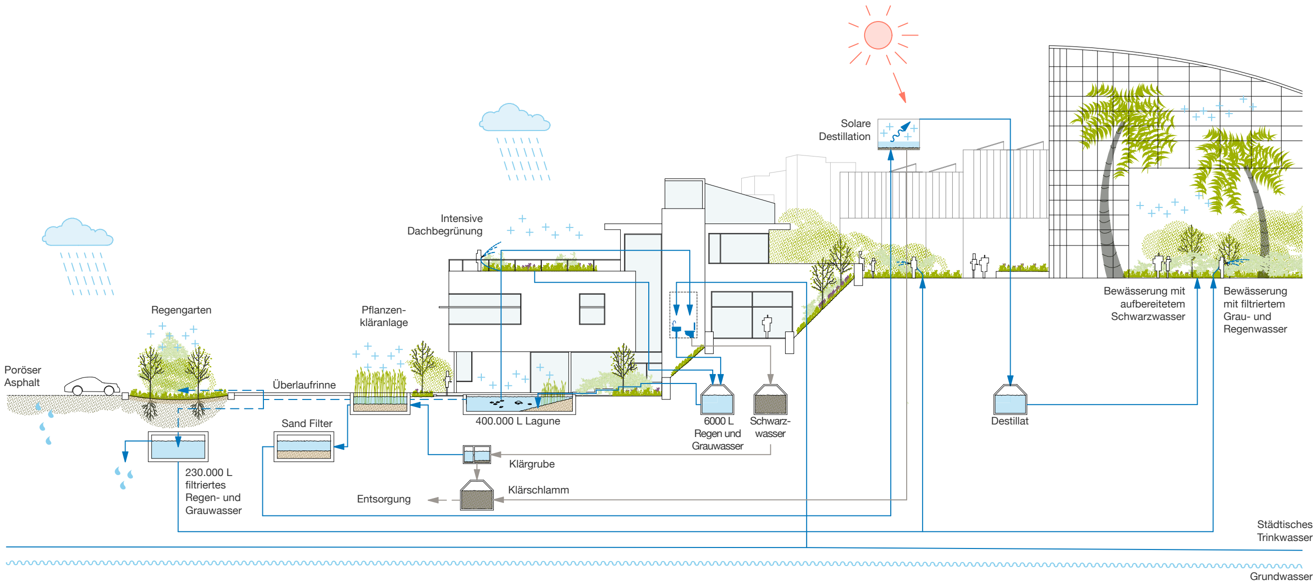
Die vier Fallstudien demonstrieren daher die bestehende Forschungslücke für eine integrierte Herangehensweise, in welcher blaue und grüne Zielsetzungen gleichermaßen berücksichtigt werden.



Für die grafische Analyse wurden alle Projekte als Schnittansichten gezeichnet. Die detaillierte Darstellung aller Wasserströme und Grünstrukturen der Projekte und in der näheren Umgebung offenbarte, wo Verbindungen zwischen diesen bestanden, bzw. wo diese in der Planung nicht hergestellt wurden. Die architektonische Zeichnung wurde gekoppelt mit einer systemischen Darstellung der blauen und grünen Elemente. Diese Mischform in der Grafik ermöglichte eine bessere Nachvollziehbarkeit der blau-grünen Funktionsweise verbunden mit einer räumlich-ästhetischen Einordnung in die bauliche Struktur.

Die angefertigten grafischen Analysen dienen als Kommunikationsmittel, um räumliche und funktionale Zusammenhänge für die Leser:innen nachvollziehbar zu machen. Der darstellerischen Kommunikation von Projektbeispielen kommt in der Architektur und Landschaftsarchitektur besondere Bedeutung zu [92, 93]. In Fachbüchern und Fachzeitschriften mit Praxis-Bezug werden in der Regel Fotos und – je nach Zielgruppe – auch Planzeichnungen gebauter Projekte abgebildet. Im interdisziplinären Kontext kommen immer häufiger nichtmaßstäbliche Systemdiagramme zum Einsatz, um technische und konzeptionelle Zusammenhänge zu vermitteln. Der Fokus liegt dabei für gewöhnlich auf den „Erfolgsfaktoren“ der Projekte und nicht auf einer objektiven Analyse von Vor- und Nachteilen. Die grafische Analyse, wie sie hier durchgeführt wurde, erfolgt aus einem neutralen Blickwinkel. Sie ermöglicht dadurch die Erfassung von räumlichen und systemischen Zusammenhängen, die in Fotos, Planzeichnungen und Diagrammen nicht sichtbar werden. Die Betrachter:innen bekommen beispielsweise einen Eindruck von den Dimensionen, die technische Wasserspeicher wie unterirdische Zisternen erfordern. Der Vergleich der Fallbeispiele offenbarte außerdem Unterschiede in den Freiraumqualitäten der umgesetzten Grünsysteme. Sukzessive tauchten im Zeichenprozess spezifische Fragestellungen hinsichtlich der blauen und grünen Bestandteile auf, die durch weitere Recherche gelöst werden konnten.

Der Mehrwert dieser Methodik liegt daher insbesondere in der stetigen Weiterentwicklung der Darstellung. Sie schafft ein tieferes Verständnis für die abgebildeten Projekte sowie für die blau-grünen Lösungen, als es üblicherweise über Literaturrecherchen erreicht wird. Es ist charakteristisch für die Analyse von Fallbeispielen, dass die Daten auf unterschiedliche Art und Weise ermittelt werden [87]. Auch bei den hier vorgestellten Analysen war die Datengrundlage sehr



unterschiedlich und abhängig davon, wie breit das Projekt dokumentiert und publiziert wurde. Daher mussten auch alle Ergebnisse genauestens auf Objektivität und Verlässlichkeit hin untersucht werden.

Nach ihrer Veröffentlichung stießen die grafischen Analysen auf großes Interesse, was den Anstoß dazu gab, die Methodik weiterzuentwickeln. In einer Lehrveranstaltung im Wintersemester 2020/21 fertigten Studierende eigene grafische Analysen von blau-grünen Projekten an (vgl. Abb. 22). Dabei wurde die Darstellungsart teilweise um weitere Stoffströme wie beispielsweise Abfall und Schwarzwasser ergänzt. Auch Aspekte der Energie wurden aufgegriffen, wenn diese im Zusammenhang mit dem blau-grünen Konzept standen. Die Analysen erfolgten aus einem kritischen Blickwinkel, um Schwachstellen aufzuzeigen. Dazu gehörte u.a. die maßstabsgetreue Abbildung von Wasserspeichern, um deren Verhältnismäßigkeit (Über-/Unterdimensionierung) erkennbar zu machen.

Die Darstellungsart wurde auch in weiteren Forschungsprojekten und Lehrveranstaltungen adaptiert. Vom Stuttgarter Impulsprojekt wurde ebenfalls eine grafische Analyse angefertigt, um die Funktionsweise an die Fachöffentlichkeit zu vermitteln (Abb. 21) [94, 95]. Auch für die Publikation des Schulgarten-Projekts wurde eine entsprechende Zeichnung erstellt [67]. In diesen Fällen war der analysierende Aspekt der Zeichnung zweitrangig und es stand die Vermittlung des Zusammenspiels aus räumlich-ästhetischer Qualität und Funktion im Vordergrund.

ABB. 21 (LINKS)
Impulsprojekt Stuttgart.
Die Grafik wurde insbesondere zur Vermittlung der Funktionsweise verwendet. Eigene Darstellung [94]

ABB. 22 (OBEN)
Grafische Analyse des Phipps Center for Sustainable Landscapes, USA, als Beispiel einer studentischen Arbeit.
Grafik: E. N. Hotz

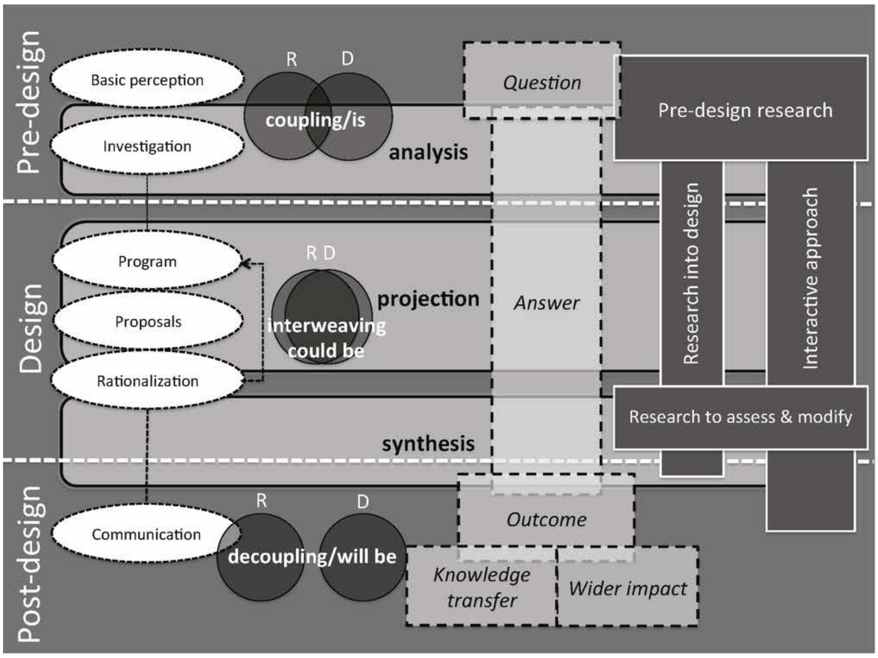


ABB. 23 (OBEN)
Research by Design als dreiphasige Methodik nach Roggema [96].
Die Definition von RbD beruht auf einer Literaturstudie und Analyse der diversen Methodenbeschreibungen.

ABB. 24 (UNTEN)
Planungsbesprechung am Bauplatz des Impulsprojekts im interdisziplinären Team. Foto: F. Well

2.3 - RESEARCH BY DESIGN

Die zweite Veröffentlichung baut methodisch auf *Research by Design* (RbD) nach Roggema (2017) auf [96]. RbD ist in der Literatur auch unter *research through design* bekannt. Es gibt zahlreiche Studien, die diese entwurfsbasierte Forschungsmethode beschreiben. Roggema (2017) gründet die von ihm vorgeschlagene Definition für RbD auf einer breiten Literaturstudie und zeigt auf, inwiefern es eine übergreifende Systematik hinsichtlich der durchlaufenen Phasen gibt (Abb. 23):

„*Research by Design* ist eine Methode, die Entwerfen nutzt, um räumliche Lösungen für ein bestimmtes Gebiet zu erforschen, und dabei einen Gestaltungsprozess vorsieht, der aus einer Vorentwurfsphase (*Pre-Design Phase*), einer Entwurfsphase (*Design Phase*) und einer Nachentwurfsphase (*Post-Design Phase*) besteht. Damit wird eine theoretische und normative Grundlage für den Gestaltungsprozess geschaffen, die es ermöglicht, die Qualitäten und Probleme des Ortes zu untersuchen und seine (räumlichen) Potenziale zu erforschen, während gleichzeitig die Freiheit geschaffen wird, sich mit den Vorschlägen auf unbekanntem Terrain zu bewegen und neue Erkenntnisse und Wissen zu produzieren, die für ein breites Publikum interessant und nützlich sind.“ [96]

Das bedeutet im Fall der vorliegenden Arbeit, dass der Planungs- und Entwurfsprozess für ein kleines Umsetzungsprojekt Gegenstand der Forschung wird. Das Impulsprojekt in Stuttgart wurde im Rahmen des BMBF-geförderten Forschungsprojekts INTERESS-I realisiert und demonstriert blau-grüne Infrastruktur als mobile Architektur im städtischen Kontext [97]. Der Entwurf entstand in Zusammenarbeit mit dem Architekturbüro Daniel Schönle. Die Professur für Green Technologies in Landscape Architecture (TUM), an der auch die vorliegende Arbeit verortet ist, übernahm die Koordination und Kommunikation im Projektteam und mit den beteiligten Fachplanungen (vgl. Abb. 24), sowie die wissenschaftliche Begleitung des gesamten Prozesses. Diese Rolle ermöglichte mir eine enge Einbindung in den entwerferischen Prozess und gleichzeitig eine gewisse Distanz für die Abstraktion und Reflexion der Erkenntnisse.

Der in der vorausgehenden Publikation beschriebene integrierte blau-grüne Ansatz kam in diesem Projekt zur Anwendung. Der gesamte Prozess spiegelt die drei von Roggema (2017) beschriebenen Phasen wider: Um die gleichwertige Gewichtung der blauen und grünen Seite zu gewährleisten, wurden die Rahmenbedingungen und Zielsetzungen vor Beginn der architektonischen Planung umfassend analysiert und die notwendigen räumlichen Anforderungen daraus abgeleitet (*Pre-Design Phase*). Insgesamt 16 Entwurfsvarianten führten schließlich zu einer blau-grün integrierten Architektur, die entsprechend umgesetzt und im Juni 2020 in Betrieb genommen wurde (*Design Phase*).

Die Ergebnisse der begleitenden Forschung zum Entwurfs- und Planungsprozess wurden im darauffolgenden Jahr in dem interdisziplinären Journal Sustainability publiziert [66]. Im Sinne von RbD wurden die gewonnenen Erkenntnisse dokumentiert, reflektiert und in abstrahierter Form in eine Entwurfsstrategie für BGA übersetzt, die auf Folgeprojekte übertragbar ist (*Post-Design Phase*). Zentrale Schritte im integrierten blau-grünen Entwurfsprozess wurden definiert, um damit sicherzustellen, dass blaue und

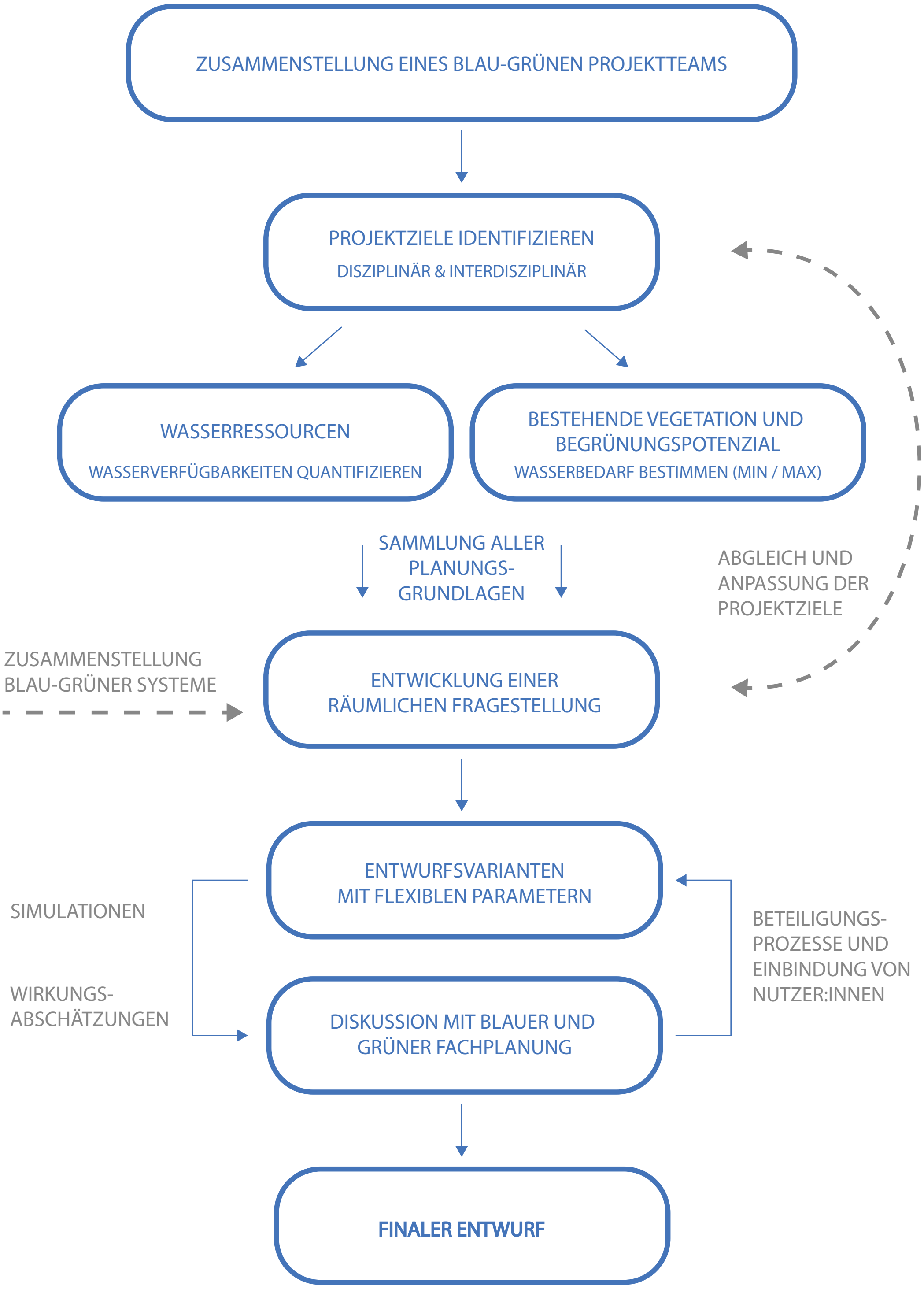

ZUSAMMENSTELLUNG EINES BLAU-GRÜNEN PROJEKTTEAMS
PROJEKTZIELE IDENTIFIZIEREN
DISZIPLINÄR & INTERDISZIPLINÄR
WASSERRESSOURCEN
WASSERVERFÜGBARKEITEN QUANTIFIZIEREN
BESTEHENDE VEGETATION UND BEGRÜNUNGSPOTENZIAL
WASSERBEDARF BESTIMMEN (MIN / MAX)
SAMMLUNG ALLER PLANUNGS-GRUNDLAGEN
ABGLEICH UND ANPASSUNG DER PROJEKTZIELE
ZUSAMMENSTELLUNG BLAU-GRÜNER SYSTEME
ENTWICKLUNG EINER RÄUMLICHEN FRAGESTELLUNG
SIMULATIONEN
WIRKUNGS-ABSCHÄTZUNGEN
ENTWURFSVARIANTEN MIT FLEXIBLEN PARAMETERN
DISKUSSION MIT BLAUER UND GRÜNER FACHPLANUNG
BETEILIGUNGS-PROZESSE UND EINBINDUNG VON NUTZER:INNEN
FINALER ENTWURF

ABB. 25 (LINKS)
Integrierte Entwurfsstrategie für BGA (blau) mit Ansatzpunkten für die Weiterentwicklung (grau). Eigene Darstellung basierend auf [67]

ABB. 26 (UNTEN)
Interdisziplinäre Lehrveranstaltung (Design-build) mit Umsetzung eines BGA-Projekts, Prototyping Schulgarten. Foto: F. Well

grüne Faktoren gleichermaßen in die Entwicklung der räumlichen Lösung einfließen und synergetisch zur Klimaanpassung beitragen.

Der explorative, nicht-lineare Ansatz, der der gewählten Methode zugrunde liegt, hat sich in der beschriebenen Studie als zielführend erwiesen. Der architektonische Entwurfsprozess ist durch die vielen Einflussfaktoren ein komplexes System, in dem implizites Wissen eine wichtige Funktion einnimmt. RbD ermöglicht eine ergebnisoffene Herangehensweise an die Forschungsfragen.

2.4 - DESIGN-BUILD UND PRACTICE-BASED DESIGN RESEARCH

Im dritten Paper wird der Entwurf und die Umsetzung einer BGA im Rahmen einer Lehrveranstaltung beschrieben. Die zugrunde liegende Methodik ist eng mit der des vorhergehenden Papers verwandt. Die Besonderheit lag in diesem Fall in der Dreiteilung der Forschungsfragen, die sich auch in der Zusammenstellung der Methoden widerspiegelte. Die Entwurfsstrategie für BGA bildete die methodische Grundlage im Entwurf, an der sich das Projektteam aus Studierenden orientierte. Die zweite Forschungsfrage bezog sich auf den Lernerfolg der Studierenden und wurde durch die Auswertung von Bauprotokollen evaluiert, in welchen die Studierenden ihre eigene Planung reflektierten. Die Lehr- und Forschungsmethode, in der Studierende der Entwurfsdiziplinen ihre eigenen Entwürfe praktisch umsetzen (vgl. Abb 26), wird als *Design-build* bezeichnet [98–100]. In diesem Fall wurde der Lernerfolg durch die interdisziplinäre Zusammenstellung des Teams aus Studierenden der Architektur und der Landschaftsarchitektur noch zusätzlich gesteigert [101].

In Zusammenhang mit der dritten Forschungsfrage diente das Umsetzungsprojekt dazu, die Entwurfsstrategie für BGA erstmals anzuwenden und in Hinsicht auf Stärken und potenzielle Schwächen zu evaluieren. Methodisch orientiert war das Vorgehen dabei an *Practice-based Design Research* [102]. Auch in diesem Fall ist die Reflexion des eigenen Tuns die Basis für qualitative Forschungsergebnisse [103, 104]. Die experimentelle Umsetzung, wie sie beim Schulgarten-Projekt erfolgte, spielt bei dieser Methodik eine besondere Rolle [105]. Im Vergleich zum Impulsprojekt war dieses Mal die Forschung enger mit der entwerferischen Tätigkeit verknüpft und fand weniger aus der begleitenden Distanz statt. Auf Basis dieser Vorgehensweise wurde die Entwurfsstrategie mit Vorschlägen für eine Weiterentwicklung versehen (Abb. 25).

3. EINZELPUBLIKATIONEN

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Research Article

Blue—green architecture: A case study analysis considering the synergetic effects of water and vegetation

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KEYWORDS
Blue-green infrastructure;
Urban water management;
Building greening;
Urban microclimate

Abstract Blue—green infrastructure is a network of natural and near-natural areas that has a positive effect on the quality of urban environment. This multifunctional planning approach addresses different issues and objectives depending on whether the focus is on the blue (water) or the green (vegetation) elements. Green-motivated projects aim to densify urban vegetation and include the growing sector of building greening. A good climatic effect of vegetation can be achieved by sufficient irrigation. In many cases, this approach results in additional water requirements. Blue-motivated projects consider water accumulation in cities (e.g., by heavy rainfall) as a waste product and look for solutions for local drainage and evaporation. These planning approaches offer only one-sided solutions and create no sufficient interfaces between water availability and water demand. Based on four case studies, this work examines the extent to which blue—green projects take advantage of the possibilities for the synergetic use of resources. The projects are analyzed graphically by applying the daily tools of architects as a scientific method. A graphic presentation of the blue and green components makes existing solutions and missing links visible. Analytical results show that buildings can be considered to be an interface for blue—green systems. Moreover, the possible synergies are often overlooked during the planning process. This fact highlights the need for a new planning approach that interlinks blue and green aspects that are already in the early planning stages.
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1. Introduction

The demands placed on urban environments are constantly increasing. Social and ecological challenges lead to a worldwide densification of inner-city areas. Furthermore, the competition for space leads to a functional overlapping and strong sealing. Urbanized areas have a higher air and surface temperature and a lower insurability compared with natural ones. The annual average air temperatures in cities are 1–3 °C higher than that in surrounding landscapes (Fryd et al., 2011). This temperature difference is also known as the urban heat island (UHI) effect, which has several causes. Sealed grounds prevent the infiltration of precipitation, which results in low surface evaporation. Apart from this aspect is the waste heat generated by energy consumption. UHI consequences include increasing energy demand, air conditioning costs, air pollution, heat-related illness, and mortality (ARUP, 2014). This effect is expected to be intensified by climate change (Kenward et al., 2014).

One circumstance that will in any case be aggravated by climate change is the rise in extreme weather events, such as heavy rainfall and long drought (Hassol et al., 2016). In July 2011, during a cloudburst in Copenhagen, over 150 mm of rain fell within 2 h, resulting in extensive flooding. Copenhagen City decided to initiate the development of a city transformation plan that would optimize water retention in the city by integrating blue–green elements (American Society of Landscape Architects, 2016). Other cities must also revise their water management schemes due to heavy rain and floods (Stokman et al., 2015). Other meteorological changes place cities under stress. Persistent periods of heat and drought have a negative impact on energy consumption and health. The heatwave that hit Europe in 2003 is estimated to have caused over 30,000 deaths (Mann, 2018). Dryness leads to an imbalance between water availability and water demand. The need for plant irrigation increases in dry phases, whereas water supplies simultaneously decrease (Schoenberg et al., 2014).

The integration of natural elements into cities is an effective method to counteract the effects of UHI and the consequences of extreme weather events (Gunawardena et al., 2017). Urban green provides water retention and slow evaporation, which in turn has a positive impact on the microclimate. The term "blue–green infrastructure" (BGI) refers to the combination of blue (water) and green (vegetation) components in distinction to gray infrastructure, such as roads, settlements, and canals. The concept was developed at the level of infrastructure and landscape. This concept has already been successfully applied on that scale. Architecture and buildings can be an integral component of BGI if they embody the inherent principles and objectives and thus become part of the network.

1.1. Definitions and functions of BGI

The concept of BGI has yet to be generally understood. The term "green infrastructure" (GI), also known as "urban green infrastructure" (UGI), is common. In the case of GI, the definitions in the literature also vary, especially with regard to the integration of "blue" components. A commonly cited definition of GI comes from the European Commission. "Green infrastructure can be defined as a strategically planned network of valuable natural and semi-natural areas with further environmental elements, which is designed and managed in such a way that a broad spectrum of ecosystem services is guaranteed in both urban and rural areas and biological diversity is protected" (European Commission, 2014).

A good overview of the spectrum and possibilities of BGI results from projects that have already been successfully implemented. For this reason, the definitions of the planning and execution of engineering offices are also relevant. The engineering company, Arup, which has implemented numerous notable projects in this field, defines GI as follows: "the system of open spaces, natural areas, urban woodland and parks; green streets, squares and public realm; rivers and waterways; and smaller scale interventions such as green roofs, walls and façades – all of which lie within the physical networks of cities themselves and their immediate hinterlands, and perform essential ecosystem services" (ARUP, 2014). The following subcategories are listed in the "Green Infrastructure Cards" developed by Arup: demographics, urbanization, water, climate change, waste, energy, and food (Rabe, 2015). The integration of water is an optional component but not mandatory. This list also illustrates the area of tension in which the projects operate in a great variety of requirements.

Ramboll, a company that implements climate adaptation and flood risk management projects worldwide, provides another definition for BGI in which the interaction of green and blue becomes the key feature: "BGI combines hydrological functions with urban nature, landscaping and urban planning. Blue (water) and green (nature, squares and parks) serve to protect against floods and other impacts of climate change." (Ramboll, 2018). This description shows the interdisciplinary approach of BGI, but it remains at the conceptual level on a large scale. Small interventions are not considered.

In the following, BGI is used as an umbrella term for projects of all scales in the urban environment, where blue and green elements are combined and have a multifunctional impact in urban space. Under this definition, a wide range of issues and solutions is addressed. In addition, BGI cannot be assigned to one profession. The perspective on the topic also changes depending on the discipline.

The combination of blue and green elements depends on location, scale, season, and weather; moreover, it can provide various functions regarding social, ecological, and design aspects and make cities resilient to climate change (Fryd et al., 2011; Hansen et al., 2017; Klemm et al., 2017). The resulting multifunctionality is a mandatory component of BGI (Brears, 2018, p. 10). Some core functions are the improvement of microclimate, air quality, and public health (Klemm et al., 2017). On an urban scale, the positive effects of BGI include sound insulation, air cleaning, fine dust binding, rain water retention, and aesthetic aspects (Pfoser et al., 2014). These blue–green functions regarding supply, regulation, and culture can also be summarized as ecosystem services. Such functions enable urban nature and biodiversity that have a considerable value for society (Kowarik et al., 2017).

1.2. Application of BGI in architecture

The use of blue—green systems at the building level is less common than in landscape planning. Rather, many individual components can be part of a blue—green network. Sustainable water management in buildings includes, for example, the collection and reuse of rainwater as service water for irrigation or cooling. When rainwater runoff seeps into the ground, resulting in the enrichment of groundwater, the aim is often to compensate for the negative effects of the ground being sealed by the building. The separate collection of gray water remains an absolute exception. The internal treatment of gray water in buildings remains to be a cost-intensive specialized solution even though it is amortized over the life cycle by saving drinking water (König, 2013a).

Building greening is an important component of BGI. Green roofs and façades appear in many different variations. Green roofs are usually classified in accordance with their established categories (extensive/intensive). Nevertheless, extended concepts, such as marsh plant and retention roofs, have been developed over time.

The systematic installation of roof and façade greening and the plantation of trees and green spaces near a building can positively affect the direct and indirect energy consumption of buildings. Heating and cooling energy can be saved through shading (trees and facade greening), cooling by evapotranspiration (all green elements), and insulation (green roofs) (Fryd et al., 2011; Pfoser et al., 2014).

2. BGI-related planning concepts

BGI bundles planning concepts that deal with the blue (water) and green (vegetation) aspects. The differences of the subcategories lie in motivation and approach. Blue-motivated projects mostly result from urban water management, flood protection, and decentralized rainwater management. By contrast, green-motivated projects aim for the densification and optimization of urban vegetation. For this reason, blue-driven projects can be grouped under water sensitive urban design (WSUD) and green-driven projects under GI. Fig. 1 shows the classification through which BGI is based by breaking down the contained planning concepts into blue and green approaches. All concepts can include blue and green components. The differences do not lie in the applied elements but in the questions from which the projects are motivated. The interconnection of these objectives comes together in BGI.

2.1. WSUD—blue-motivated projects

The WSUD concept is a further development of conventional water management and integrates the disciplines of urban and landscape planning. WSUD allows all aspects of the urban water cycle to be considered and to approach the natural water cycle (Hoyer et al., 2011, p. 18). The implementation of WSUD includes the following solutions: rainwater use, wastewater treatment, detention and infiltration, conveyance (e.g., open stormwater channels), and evapotranspiration (Hoyer et al., 2011, p. 21). These elements partly use plants and urban green, whether in biotopes, green roofs, or rain gardens. The application of WSUD occurs at different scale levels (Wong, 2006). With regard to buildings, this concept includes not only the retention of precipitation to reduce runoff but also the resource-efficient treatment and reuse of waste water on site. This concept has no term in the current literature. We describe the approach here as "blue architecture" (Fig. 1).

In general, disposal problems with water are present in cities. Wastewater is produced in varying qualities and at different times and must be disposed by a central system. The amount of domestic wastewater only slightly varies. A major problem is the acute overload of the system due to cloudbursts. WSUD also considers this issue and provides various solutions for flood prevention and stormwater management (Brears, 2018, p. 10). Enlarging the canal system and adapting it to new conditions is not an economical solution (Deister et al., 2016, p. 12). Instead, various vegetated and nonvegetated solutions exist to reduce surface runoff (Perini, 2017; Sabbion, 2017). Mechanisms that absorb water and return it to the natural water cycle or enable intermediate storage are implemented to relieve the sewerage system and prevent local flooding in the event of heavy rainfall (Deister et al., 2016).

Fig. 2 shows the planning procedure for blue-motivated projects on an urban scale. Heavy rainfall events lead to a massive increase in the amount of water, which overloads the sewer system, at certain points. Flood protection requires local opportunities for water reuse, retention, and

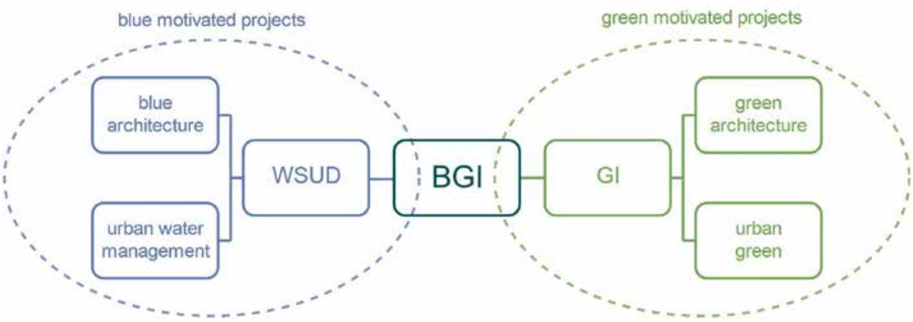

Fig. 1 Blue—green infrastructure: subordinate and related planning concepts according to blue and green motivated approaches.

Fig. 2 Planning approach of blue-motivated projects.

transpiration. The connection with vegetation is a logical consequence, resulting in blue—green solutions.

Vegetated systems include rain gardens and wetland ponds. The dimensioning of this blue—green retention mechanisms that are approached from the "blue" side is based on the amount of water that is expected as precipitation. In some cases, the buffered water is used for irrigation during dry periods. The design of green elements is not the goal of greening, as in the case of GI, but it is a medium for water retention. The positive effects of greening can also be observed here to a certain extent. However, the design options are limited.

For this reason, projects that arise from the "urban water management" or "blue architecture" point of view are covered by the umbrella term, BGI. However, the motivation clearly comes from water handling and disposal and uses vegetation as an instrument.

2.2. GI—green-motivated projects

The green components of BGI originate mainly from GI and consequently combines two elements, namely, urban green and green architecture. The initial idea here, as previously described, is to solve climatic, ecological, and social problems by integrating vegetation into cities (Pötz and Bleuzé, 2012). The design quality for the urban environment is also an important goal. In addition to urban green, such as parks, green squares, urban forests, and renaturalized river landscapes, green architecture is gaining importance. The advantages of green roofs and façades have been extensively researched and proven (Pfoser et al., 2014). An increasing number of cities is prescribing the greening of flat roofs. A pioneer in this field is Hamburg City, which passed a "green roof strategy" in 2014 (Bürgerschaft der Freien und Hansestadt Hamburg, 2014). A major development is currently happening in the field of vertical greening. The French botanist and artist, Patrick Blanc, is receiving great attention in the field of façade greening because of his vertical gardens. These systems have a positive effect on the urban climate and are of aesthetic quality (Blanc et al., 2009). However, vertical gardens also receive justified criticism because fragile systems require a permanent water supply and are often supplied with drinking water (CNN, 2009).

The relatively new concept of "Baubotanik" develops the interweaving of buildings and plants even further. Instead of merely adding green systems to architecture, the plant itself becomes an elementary component here. The growth behavior and seasonal cycle of the vegetation are integrated into the design concept of the building structure (Ludwig et al., 2012). Urban green and green architecture have something in common, that is, vegetation, as an ecological and creative functional carrier, forms the starting point. An adequate water supply must be ensured to keep vegetation alive.

Many facilities, such as parks and city green areas, that are part of GI require no artificial irrigation and only need to be watered in exceptional cases during long drought periods. In the case of building greenery, in particular with intensive green roofs and wall-bound vegetation, irrigation is often mandatory and integrated into the overall concept. Plants have a specific water requirement that depends on many factors and cannot be precisely quantified. However, plants, as flexible systems, can also buffer fluctuations in water supply and adapt their requirements accordingly (Köhler, 2012, p. 145). Water consumption of plants results from the difference between potential evapotranspiration and effective precipitate in relation to change in soil moisture (Frenken and Gillet, 2012). Therefore, plants with a high evaporation capacity have a high water requirement. This notion indicates that even green systems that normally require no irrigation can tolerate and evaporate a specific excess of water. This effect is particularly favorable to the microclimate and can be used in a manner by which excess water can be brought out onto green areas that are unnecessarily dependent on irrigation. For example, green roofs are suitable for this purpose.

Several possible solutions are available to ensure an adequate water supply. On the one hand, plants with a high drought resistance can be chosen. This approach keeps the need for (additional) irrigation low. On the other hand, water concepts that are fed from a sustainable source can be developed. The classical approach at this point is to store rainwater in cisterns. However, a connection to the local water network for extreme cases is often unavoidable. The resulting water concepts mostly include rainwater or other alternative water sources. However, these concepts are based on the connection to the local water network for good measure. In particular, the projects are planned in accordance with demand. This notion implies that the required amount of irrigation water is determined and then made available. Fig. 3 describes this procedure.

Climate change increases the causes of drought stress for trees and also leads to an increasing need for artificial irrigation (Roloff, 2004, p. 190; Schoenberg et al., 2014). The use of locally generated water is an ecologically, economically, and resource-efficient solution to cover this water demand. Different water sources can be considered. The use of rainwater is convenient in many ways. Rainwater is often of good and constant quality. Large contamination is rare. However, the availability strongly fluctuates. By contrast, groundwater is a constantly available water source and has a high quality because it is naturally filtered and purified. Nevertheless, groundwater cannot be used as irrigation water at all sites. Access to groundwater is expensive and strictly regulated to maintain the ecological balance (Pötz and Bleuzé, 2012).

Fig. 3 Planning approach of green-motivated projects.

3. Blue—green architecture and integrated systems

The combination of blue and green approaches into one planning strategy enables the coordination of water demand and water availability. This coordination ensures a balanced use of resources, contributes to microclimatic improvement, and makes a remarkable contribution to resilient adaptation to climate change. Fig. 4 explains the two-sided procedure for BGI. The objectives of GI and WSUD are combined into an integrated system that includes blue and green elements according to local conditions. This notion means that different types of wastewater occurring in the city are directly managed on site and linked with high-quality vegetation elements in terms of design and microclimate. Only a synergetic consideration of the green and blue approaches guarantees an effective, flexible, and adaptable solution. If the question of water supply is considered in close connection with water management, then suitable interfaces can be developed.

As described in the Introduction section, the implementation of this strategy concerns all areas of urban design. This study is conducted from an architectural point of view; the focus is on buildings and their immediate surroundings. According to the definition of Köhler (2012, p. 14), this concept also includes technical structures, such as bridges, because any type of building can be greened. Buildings have a high potential to form green and blue interfaces. First, buildings take up a large amount of space in the city. Thus, buildings should be prioritized in the consideration. Second, buildings always have a certain amount of water flow. Buildings are connected to the water supply and sewage system. Third, buildings benefit from greening in many ways. Fourth, the implementation options are flexible and various. Buildings can greatly vary depending on the local conditions, and solutions for existing and new buildings are available.

This work investigates the extent to which a two-sided approach in the planning of blue—green projects of different dimensions can strengthen synergies and thus achieve a good climatic impact and high resource efficiency. The following case studies present an analysis of the existing projects to determine the extent to which a synergetic approach is already established, and at which points development potential remains. This work uses a graphical analysis of projects as a core method to map out the role of blue and green elements in the analyzed case studies. The theses, questions, and strategies of this work relate to the Central European region. Locations with a different climate must be considered and evaluated differently.

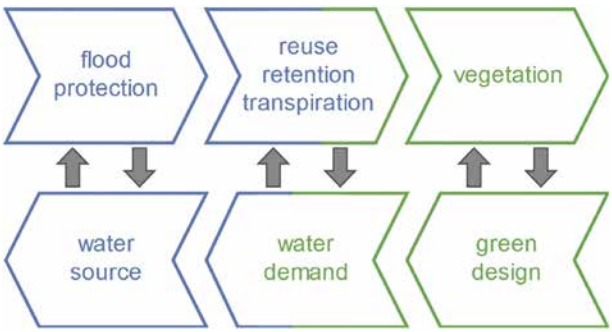

Fig. 4 BGI: Combining blue and green motivated planning approaches into one integrated strategy. The procedure is already established on the urban and landscape scale but not on the building scale.

4. Case studies

In this section, four case studies, which are examples of BGI, are presented. The projects were selected to represent a broad spectrum of approaches and implementation from an architectural point of view. These studies illustrate the current planning practice and highlight the strengths and weaknesses of blue—green planning and implementation. The analysis focused on the synergetic combination of green and blue elements. For this purpose, the existing vegetation and water flows in the project and the surrounding area were examined to identify possible interfaces and optimization potential.

The four case studies were selected in accordance with the following criteria: The High Line in New York City and the Potsdamer Platz in Berlin were planned on an urban scale. Both projects are located in large cities and respond to local conditions. Nevertheless, these projects have different questions. The High Line is a classic green project that focuses on an aesthetically pleasing effect. With regard to the Potsdamer Platz, a rainwater management concept is developed to ensure a decentralized drainage in a dense inner-city area. Two further projects, namely, Bosco Verticale in Milan and Block 6 in Berlin, operate on a building level and illustrate two complementary design approaches. In Bosco Verticale, the entire building was designed with an objective of extensive façade greening. Block 6 aimed to provide a self-sufficient water management system that also included the recycling of gray water.

The analysis of the four case studies was based on a comprehensive literature research. If no technical literature was available, then the information was supplemented by gray literature. The following questions were highlighted: What was the motivation behind the project? On which concept were the blue and green components based? What type of greening was used? What were the water flows within the project and in the surrounding area? To what extent did a synergetic link between water supply and greening exist?

The results of the analysis were visualized in drawings. These illustrations show the existing vegetation and the amount of water in the surrounding area. Drawing is a classic tool used by architects to illustrate connections and causalities. During the drawing process, open issues became visible. The result also made it possible to illustrate the existing and missing synergies. The drawings aimed to show the actual state neutrally and not to interpret the results. This mapping was initially performed without evaluating the results. The parallel existence of green systems and water flows clarifies the inconsistency of the synergetic connection.

4.1. High Line

The High Line in New York City is a project that illustrates the mechanism by which the existing gray infrastructure can be turned into a green one while considering climatic and social aspects. The park is located on an elevated railway line, which was overgrown with plants after its closure. The transformation into a linear park was based on this appearance and completed in 2014. The idea behind the project was to replant partially the plants that had sown themselves over the years. This task was performed to ensure that the plant selection adapted to the local conditions and provide a visual impression of the wild High Line (Fiehn, 2013). This preselection of vegetation was supplemented by resistant plants that could stand the difficult conditions of the thin soil and the low supply of water and nutrients (Yudina, 2017). The natural occurrence on the east coast of the USA and a high tolerance to drought were considered (Fiehn, 2013). The design shows a new dissolution of boundaries between architecture, nature, and infrastructure (Stokman, 2018). The paving system of the paths could retain up to 90% of the rainwater, making it available to the planting beds for irrigation (Yudina, 2017). Precipitation is insufficient to maintain the green appearance during summertime. In this case, the plants are manually watered (Friends of the High Line, 2018).

On the basis of the reasons described, the High Line is an example of a project developed using the green approach. The design for an attractive green open space was the priority, whereas the accompanying water concept played only a subordinate role. Fig. 5 shows that numerous water strands in the immediate vicinity were not integrated into the project. The surrounding buildings were excluded despite the high density. No connection to the neighboring buildings, which could serve as water sources with rainwater or gray water, was present. The design focus was on aesthetic quality and recreational value and not on the development of a networked concept.

The High Line concept illustrates the events that occur when a project is designed to keep water requirements as low as possible and, if necessary, to cover the demand as sustainable as possible. Although this concept is a resource-saving approach, the low water consumption leads to reduced evapotranspiration, which in turn limits the cooling effect on the urban climate.

4.2. Potsdamer Platz

The Potsdamer Platz in Berlin is an important traffic junction and has a turbulent history. In the early 90s, the square was redesigned. The aim was to achieve zero rainwater runoff despite the high degree of sealing and include water as a design element (Grant, 2012, p. 89; Hahn, 1994, p. 3; Hoyer et al., 2011, p. 100). The project required a combination of different retention mechanisms to achieve this goal (Fig. 6). The 12,000 m^2 of green roofs directly

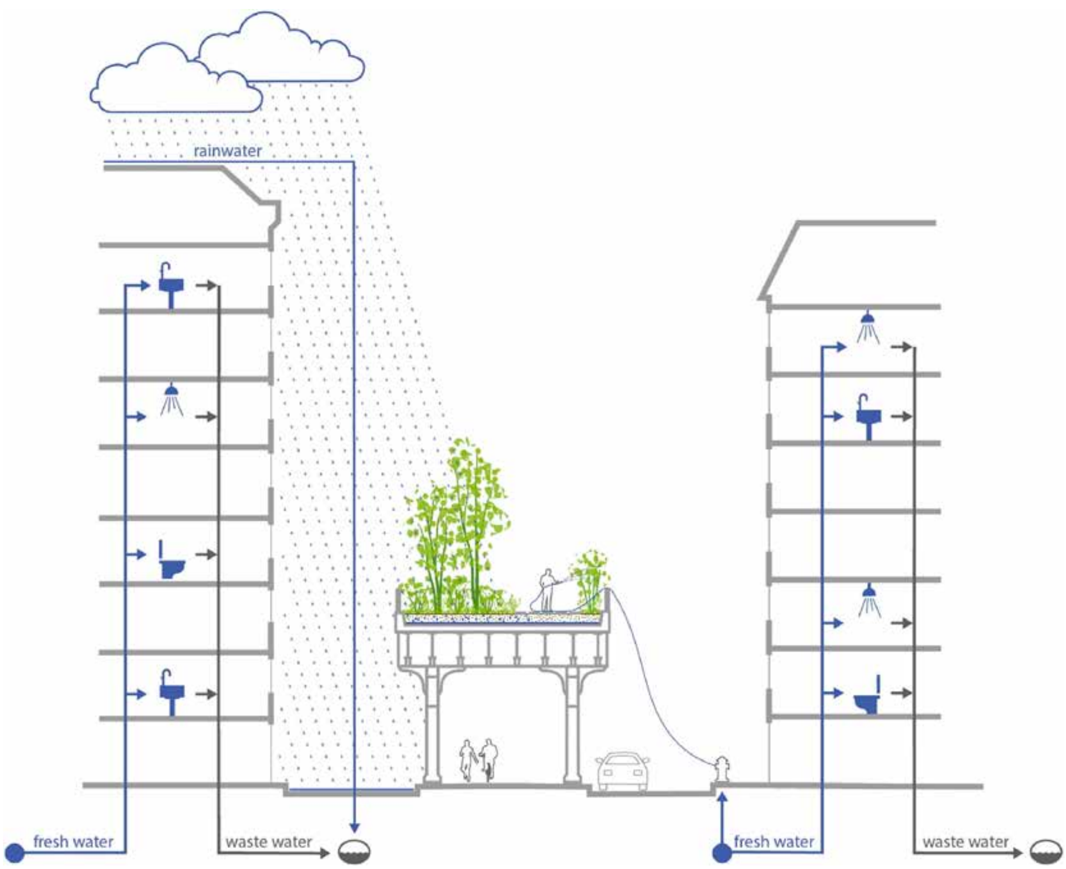

Fig. 5 High Line: The vegetation concept has a low water requirement even though a huge amount of urban water sources are available in the immediate vicinity. The microclimatic effect remains below the possibilities.

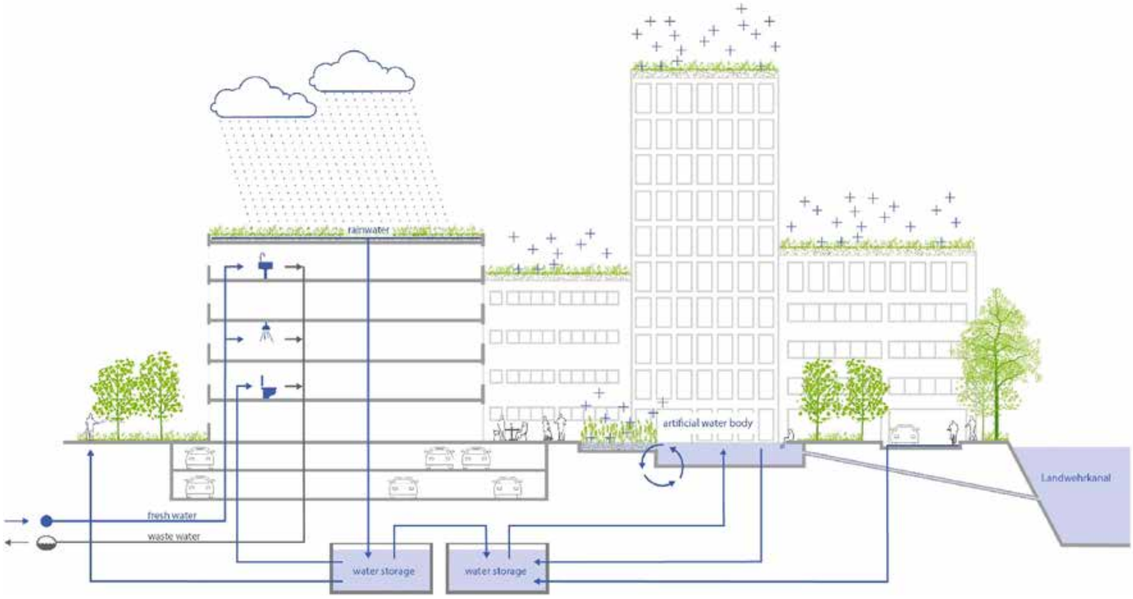

Fig. 6 Potsdamer Platz: The rainwater management system achieves zero runoff by combining different retention options. Green roofs and artificial water bodies collect and evaporate precipitation.

evaporates more than half of the precipitation (Grant, 2012, p. 89; Hoyer et al., 2011, p. 104). The water discharge is led into five cisterns with a total volume of 2600 m^3. An additional storage capacity of 1300 m^3 is provided by the newly created artificial water areas due to fluctuations in the water level (Dreiseitl and Grau, 2006). These reservoirs also take on other functions, especially those in connection with water quality. The vegetated biotopes along the lakes remove particulates and ensure ecological balance (Hoyer et al., 2011; Senatsverwaltung für Stadtentwicklung Berlin, 2017b). The combination of retention mechanisms used here is successful. The possibility of discharging large quantities of surplus water into the nearby Landwehr Canal only becomes effective three times every 10 years. This quantity corresponds to the value of an unsealed site (Dreiseitl and Grau, 2006, p. 48; Pötz and Bleuzé, 2012, p. 183). Approximately 85% of the annual precipitation is retained on roofs and in water surfaces, evaporates, or flows off in a throttled way. The remaining 15% of the annual precipitation can be used for flushing toilets in office buildings and irrigating green areas (Senatsverwaltung für Stadtentwicklung Berlin, 2017b).

The question with regard to blue–green strategies clearly comes from the blue side. The handling of rainwater is progressive and successful. The experience by means of water surfaces also has a great design and integrative quality. Vegetation plays a subordinate role. A room for optimization remains available, especially with regard to building greening. The possibilities for synergetic links are partially exploited either. This fact includes gray water that is not separated and not integrated into the water concept. For the inner-city area, relieving the sewerage system even with a high sealing is a great achievement. This system prevents flooding and its consequential damages. Nevertheless, such a procedure requires high construction costs. The necessary infrastructure with huge water reservoirs and corresponding connections has yet to establish itself as a standard. In such a case, blue–green strategies could combine microclimatic advantages with a reduction in storage volume.

4.3. Bosco Verticale

The Bosco Verticale in Milan was completed in 2015. The project aims to be an example for sustainable housing and contributes to reforestation and naturalization in the city (Stefano Boeri Architetti, 2018). The two towers are covered with dense vegetation of 20,000 plants, of which 700 are trees (Giacomello and Valagussa, 2015). The selected trees must withstand the temperature fluctuations from −1 °C to 31 °C that are common in Milan and cope with the special conditions of height (wind load). The trees were pregrown to ensure that they are prepared for their later location (Stefano Boeri Architetti, 2018). From a design point of view, this task was intended to achieve the optimal possible coverage with greenery. Therefore, this project is clearly green motivated. The water concept was adapted to the greening. The numerous positive effects of vertical greening have been proven. For this reason, the plants of the Bosco Verticale positively contribute to the energy balance of the building. This assumption could not be definitely verified. The data published by Giacomello and Valagussa (2015) were based on simulations and estimations and were not experimentally measured. A simulation of the façade showed that the solar gains and losses from planting are offset on an annual average. The energy savings that can be recorded compared with a flat façade are therefore the same as those that can be achieved by shading a façade with an unplanted balcony alone (Giacomello and Valagussa, 2015, p. 55). No reliable data on the microclimatic effect are also available, but evapotranspiration is assumed to lead to an improvement. Air filtering and fine dust reduction can also be assumed (Giacomello and Valagussa, 2015).

The calculations for water consumption were based on projections. Irrigation automatically occurs through a central system that uses groundwater. The irrigation of the plants with gray water was examined but rejected (König, 2013a). Each tower has a water tank connected to pumps that distribute the water section by section in the building. Sensors control the humidity in the beds, that is, watering is only on demand, resulting in high water efficiency (Giacomello and Valagussa, 2015).

In general, the use of groundwater in buildings is unrecommended. The architects Hildtrud Pötz and Pierre Bleuzé wrote in their handbook on "Blue–green grids" that groundwater resources should be protected and can only be used with permission and under certain circumstances (Pötz and Bleuzé, 2012, p. 179). The situation in Milan justifies an exception. The groundwater level has been rising for years as a result of the decrease in industry. The city council recommends the use of groundwater for new buildings to minimize the consequences, such as flooded garages (König, 2013b; Migge, 2004). A positive side effect of the groundwater pump is that heat pumps are installed to use the groundwater as an energy source for generating hot water (König, 2013a).

The Bosco Verticale represents a classic green-motivated approach at the building level. A building of the highest aesthetic quality has been created and is receiving international attention. The water concept responds to local conditions and meets the requirements of a synergetic and networked approach. The climatic advantages also make the project successful. Nevertheless, the blue–green concept can be critically questioned. This concept contains no integrated rainwater management, and the gray water of the apartments goes unused into the public sewerage system (Fig. 7). Consequently, the backflow of irrigation water further increases the volume of wastewater, and the city's sewerage system is heavily charged. This notion means that the building generates a large amount of waste water instead of reducing the load on the central system.

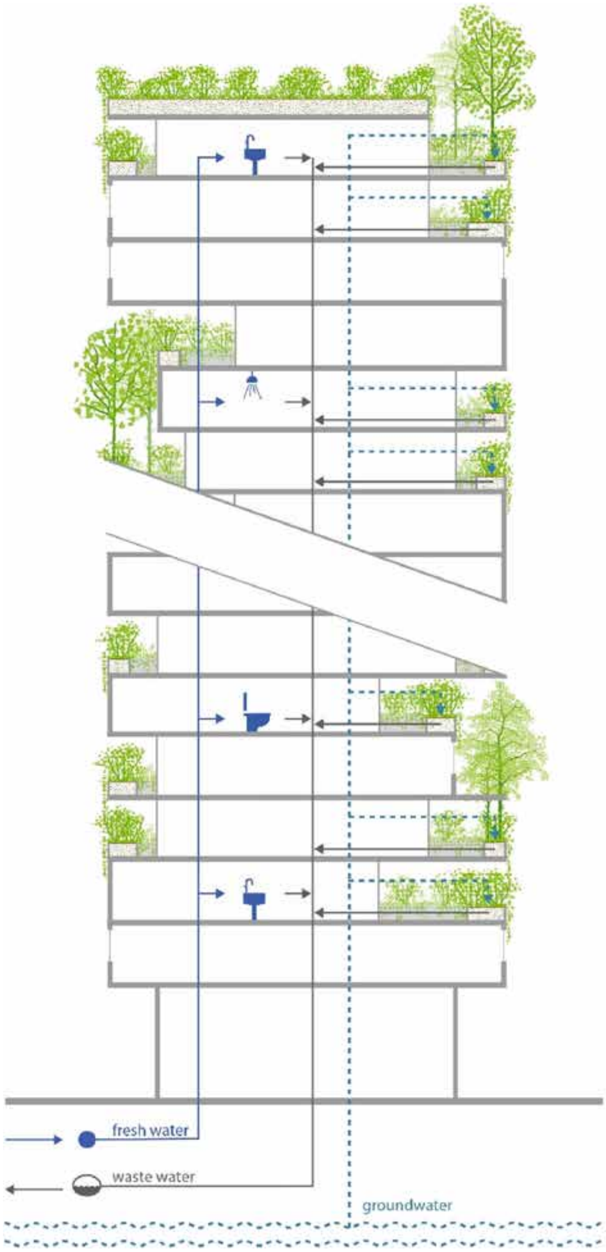

Fig. 7 Bosco Verticale: Groundwater is used for irrigation and loads the sewerage system additionally.

4.4. Block 6

The original design for Block 6 was developed as part of the International Building Exhibition (IBA) 1987. This innovative water concept combines the use of rainwater and graywater (Million et al., 2018, p. 142). The residential complex in Berlin's city center with approximately 250 residents has a separate pipe network for gray and black water, and it is efficient for water saving (Million et al., 2018, p. 22). Fig. 8 shows the original planning that included a constructed wetland to treat the gray water. The generated process water was used for toilet flushing and irrigation. This process resulted in a daily saving of 80 L of freshwater per person (Hahn, 1994). Another discharge from the constructed wetland supplied a groundwater enrichment plant that infiltrated purified gray water. The roof areas were greened to 50% to ensure that they can directly evaporate part of the rainwater.

The excess rainwater was collected in a pond in the inner courtyard, which had such a high water quality that it could be used for bathing. A zero discharge of rainwater into the public sewerage was achieved for the entire property (Hahn, 1994).

The gray water was more polluted than usual due to the water-saving behavior of the tenants. The constructed wetland was unable to cope with this contamination. The wetland was overloaded and did not achieve the required water quality. For this reason, the wetland was shut down in 1993. In 2006, the entire plant was rebuilt (Fig. 9). Since

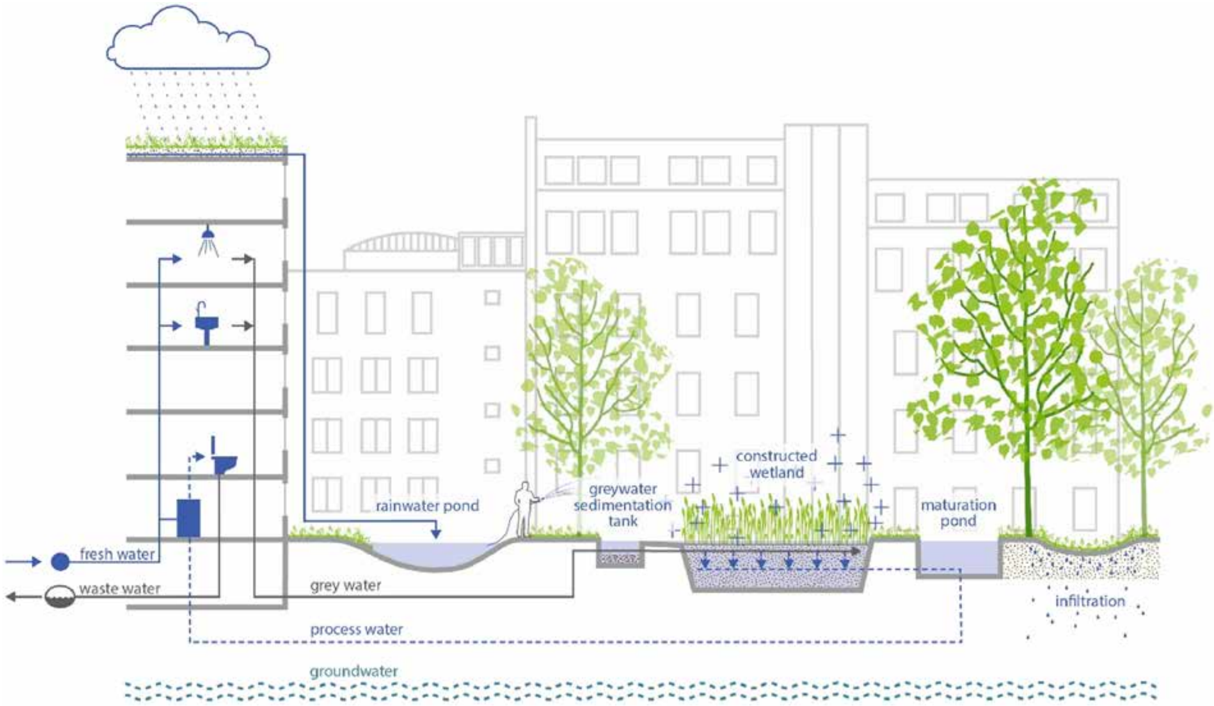

Fig. 8 Block 6 IBA 1987: The original concept included a constructed wetland for gray water treatment and a rainwater pond.

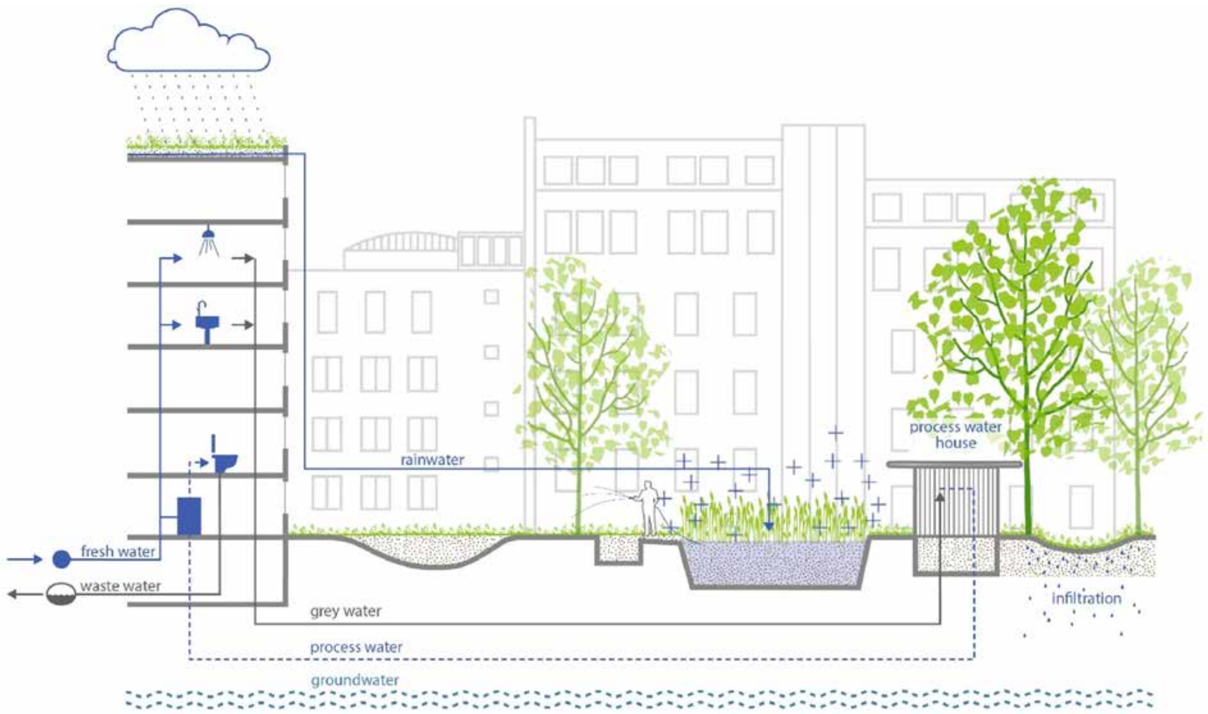

Fig. 9 Block 6 refurbishment 2006: The gray water is now treated in a mechanical—biological system that is located in the newly built process water house. The former constructed wetland contains rainwater.

then, the gray water has been mechanically and biologically cleaned in a process water house. The former constructed wetland now contains the rainwater and can still drain any surplus water for groundwater recharge. The former rainwater pond was filled up (Senatsverwaltung für Stadtentwicklung Berlin, 2017a).

A further component was added to the system in 2013. A greenhouse was installed next to the process water house.

This greenhouse uses the purified gray water for food production (fish and vegetables) and the black water of the apartments for nutrient extraction (Million et al., 2018). This test unit belongs to the research project, Roof Water Farm (RWF), which investigates the use of treated wastewater and nutrients from buildings for urban farming in roof greenhouses. The integration of the test unit into the existing water concept creates further synergies.

The elaborate water concept of Block 6 makes it a blue-motivated project. Overall, this concept is technically and conceptually advanced. Almost all water flows are considered in the system and combined in a useful manner. The compact inner-city plant shows solutions for the decentralized management of various types of wastewater. Green elements, such as green roofs and courtyard greening, are also integrated and improve the microclimate. The partnership with RWF complements the concept with urban farming. However, the project is less developed in terms of building greening and architectural design. A large part of the external areas is required for technical installations. This situation reduces the quality of open space and gives preference to the technical solution.

5. Discussion and conclusion

In the field of BGI, numerous possibilities of approaches and scales for implementation are available. The four case studies examined in this work exemplify the difference of the possible questions and realizations. The focus of the analysis is on the question of the synergetic linking of blue and green approaches. Among the main findings is the unexploited potential of the blue–green projects. A concluding evaluation of the projects is performed through a tabular comparison in Table 1. The following criteria and aspects are included in the evaluation:

- the strength of the blue and green concepts considering the local conditions and the impact and innovation of the blue and green solutions;
- the quality of existing and newly created synergetic effects, which became apparent in the graphical analyses; and
- the architectural design and qualitative aspects of the project based on the international recognition in the professional environment.

The evaluation is performed in three gradations, namely, +, ++, and +++. The following section explains the individual aspects of the evaluation in the four projects.

Table 1 Comparison of case studies.

	Blue concept	Green concept	Synergetic Effect	Design
High Line	+	++	+	+++
Potsdamer Platz	++	+	+	++
Bosco Verticale	+	+++	++	+++
Block 6	+++	+	++	+

The water concept (+) of the High Line is strongly minimized and does not go beyond the discharge of the precipitation on the paths into the beds. Alternative water sources and storage options are not integrated. The green concept (++) is successful, but no synergies (+) are created. Notably, the successful design (+++) of the High Line has received international recognition.

The water concept (++) of the Potsdamer Platz, apart from the gray water, is mature, whereas the potential of the greenery (+) has only been used to a minimal extent. The blue–green synergies (+) remain marginal. A comprehensive greening of the buildings and the open space would also have upgraded the design quality (++).

The Bosco Verticale has a highly developed green concept (+++) and design (+++), whereas the blue concept (+) remains. Nevertheless, the special feature of the rising groundwater levels in Milan creates a synergy (++).

The blue concept of Block 6 (+++) covers all water flows. However, the green concept (+) is purely functional and creates little usable free space. Certain elements, such as the constructed wetland, create blue–green synergies (++), which have no design claim (+).

The comparison shows that all projects have either a good green or blue concept. The projects with a strong green concept are of higher design quality compared with the blue ones. The synergistic effects are partially exploited in any of the four case studies. However, small-scale projects perform well here. The correlation of low synergetic effects and one-sided conception reveals the deficit in the actual planning approaches and therefore calls for a new planning method. Only a systematic approach that includes blue and green objectives guarantees synergetic solutions for blue–green architecture. When transdisciplinary teams develop individual concepts according to local conditions, the resulting projects can create multifunctional and flexible systems. Blue–green projects developed in an integrated approach make cities resilient to climate change. These projects can react to extreme weather events and form active components of adaptation strategies. Comprehensive water management, combined with aesthetically pleasing and microclimatic effective greening, counteracts the consequences of heavy rainfall, persistent drought, and rising temperatures and creates an urban environment worth living in.

Networked approaches, such as blue–green architecture, are regarded as an old invention. This knowledge has been lost in the growing specialization within the professions. In the 1970s, the Austrian artist Friedensreich Hundertwasser came up with the idea of "tree tenants", who can be regarded as forerunners of modern facade greening and plays ecological and aesthetic roles. The artist's idea was to plant trees in apartments, so that they grow out of windows, and tenants can pay their rent with oxygen production, dust and noise absorption, and rainwater cleaning. Hundertwasser also expected health and happiness from the tree tenants (Habarta, 1985).

Although Hunderwasser's designs are no longer up to date, at their core, they contain valuable information on the mechanism by which built environment and nature can interact to create a city worth living in. BGI is a reliable method to improve the adaptability to climate change and the high competition for urban space. The concepts and case studies that have been discussed show the clear need for an enhanced integration of the existing approaches to strengthen their effectiveness.

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Development of an Integrated Design Strategy for Blue-Green Architecture

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Abstract: Blue-green architecture entails buildings that contribute to improving the urban climate through the synergetic combination of water management and vegetation. They are part of an urban blue-green infrastructure network that combines ecosystem services in a multifunctional way. Projects implemented in an interdisciplinary manner create synergies with regard to the combination of water-related and vegetation-related objectives. However, applicable design strategies for this approach are currently lacking in practice. This paper investigates the approach of a blue-green architectural project in Stuttgart (the so called "Impulse Project") and derives insights for an integrated design strategy. The analysis and transfer of the research is carried out by using the research by design methodology. For this purpose, the interdisciplinary design process is divided into three phases (pre-design, design, post-design) and described in detail. Reflection on the documented design reveals the knowledge gained and enables the transfer of the findings to future projects by means of the integrated design strategy for blue-green architecture.

Keywords: blue-green systems; building greening; water management; integrated planning; research by design; design strategy; grey water; climate adaption

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1. Introduction

The concept of blue-green infrastructure (BGI) has been proven to have many positive impacts on the urban environment, the local population and the microclimate [1,2]. Urban development leads to strong interventions in the natural water cycle. The high level of sealing leads to a changed water regime with high runoff, and low retention and evapotranspiration on site [3]. These circumstances have a negative effect on environmental conditions. This also includes the fact that the air and surface temperature in cities tends to be higher than in the surrounding areas (Urban Heat Island Effect). Climate change will further intensify this effect [3]. Projects that are realised according to the principles of BGI provide important ecosystem services in cities, and thus significantly contribute to climate adaptation and resilience strategies. Especially during extreme weather conditions, blue-green systems provide a balancing and mitigating function [4]. Natural and semi-natural spaces, unlike sealed surfaces, can absorb a lot of water in the event of heavy precipitation, and thus prevent against flooding. At the same time, these areas can release stored water in the case of prolonged heat and drought, providing evapotranspiration that improves the microclimate [5]. In addition to the mitigation effect at extreme weather events, BGI contributes to the constant improvement of environmental conditions in cities. This includes, for example, increasing biodiversity, improving hydrological processes such as groundwater recharge through infiltration, recreational value for the population, and establishing a green building culture [1,2].

The term blue-green architecture (BGA) refers to the application of BGI at the building scale [6]. These projects focus on a building and its surrounding open spaces, in contrast to larger urban projects such as parks and river courses. The combination of comprehensive (building) greenery with sustainable water management offers numerous ecological and climatic benefits [7]. A two-sided approach that considers and addresses the aspects of water availability (e.g., the disposal problem during heavy rainfall) and those of water demand (e.g., for irrigation), simultaneously from the start of planning, is necessary to achieve an effective and synergetic design [6]. This requires the expertise of all relevant disciplines to be integrated into a collaborative process. Dreiseitl [8] describes the importance of cross-disciplinary planning for blue-green infrastructure, which is also applicable to blue-green architecture: "Increasing density will help us focus on a more holistic and integrated approach to Blue-Green Infrastructures, with the aim of sharing spaces with different functions. This in turn necessitates that we overcome disciplinary boundaries and better integrate all design and planning processes." [8]

This study describes the interdisciplinary planning process for a blue-green architecture project that combines urban greening aspects with on-site water management. From the findings of the planning and implementation, a design strategy for planners is developed to support the process in future projects and to ensure the greatest possible synergies in regard to the project-specific objectives.

1.1. State of the Art: Architectural Planning Process and Integrated Planning

Commonly, the design process in architecture is linear. The first stage of the project is the spatial programme, on the basis of which the architect designs the building. In the implementation planning phase, the specialist planners become involved and solve any technical issues relevant to the implementation. The essential design aspects are already decided at this stage, and thus set the direction. Accordingly, the decision-making authority lies with the architect. The requirements for building projects have become steadily higher and more complex, not least because of energetic requirements which considerably increase the amount of building services engineering [9]. In this context, the principle of integrated planning has been established [10] (p. 10), meaning the early involvement of specialist planners, particularly engineers. The restructuring of the process makes planning more effective, as problems can be identified earlier and integrated into design solutions. For example, energy requirements have a major impact on building shape, orientation, windows, wall thickness, etc.

The concept of blue-green infrastructure is described in the literature, but still has little application in practice. There is a lack of concrete guidance describing, not only the goals and benefits of blue-green projects, but also the integrated approach to implement vegetation and water management at the building level. Especially in this field, an innovation in planning is needed to meet the complex challenges that come along with climate change. A disciplinary approach cannot adequately cover the areas of concern [6,11]. Within the field of sustainable building, descriptions of interdisciplinary planning processes are found, which refer to the effective integration of energy concepts and technical building equipment. These procedures were, therefore, partly used as references, although they are not fully transferable to blue-green systems.

Heidemann et al. [12] describe the procedure of integral planning of technical building equipment over the entire life cycle (design, planning, construction, operation and use). While these approaches aim to optimise workflows and reduce costs with a focus on energy efficiency, blue-green architecture creates synergy through aspects such as evaporation, urban climate and biodiversity. Despite these differences it can be assumed that blue-green architecture will also benefit from the early involvement of specialised planners, and thereby integrated planning for blue-green architecture offers the possibility to pursue aesthetic, ecological and climatic goals in equal measure.

1.2. Impulse Project and Research Question

This study is based on the planning and implementation of the 'Impulse Project' in Stuttgart, Germany. The temporary architectural structure is part of the research project INTERESS-I (Integrated Strategies for Strengthening Urban Blue-Green Infrastructures), which is funded by the German Federal Ministry of Education and Research. The conditions for the Impulse Project have been specified in the research proposal. The intention was to implement a synergetic blue-green approach on a compact scale and to thereby test out an integrated blue-green design process. Thus, the project serves the research process and the validation of the underlying strategy of integrated planning. In addition, it provides a platform for communication and demonstration of the overall project goals. Later in the project progress, the Impulse Project will also be evaluated for its effectiveness on microclimate, heavy rainfall management and the use of alternative water resources. The quantitative measurements are not part of the present study, which focuses exclusively on the integrated approach and the planning work in the interdisciplinary team, following a qualitative approach according to the method "research by design" (see Section 2).

With regard to the transferability of the findings from the planning process, the following limitations should be mentioned: In terms of the planning team and the planning procedure, the Impulse Project reveals deviations from a conventional construction process. For one, as it is a research initiative, there is no "client" in the classical sense. The planning team defines the framework programme and objectives themselves, and thus becomes its own client. At the same time, the planning team also assumes the role of the users, as the built result serves research and evaluation. For example, various measurements are carried out during the utilisation phase, and system operation is varied in order to detect changes in the effect. These differences to the conventional construction process are considered and described in detail in the discussion, due to their effect on the application of the design strategy in practice.

Two sets of research questions underlie this study:

First: How does the integrated blue-green design process look in application? In which steps does the process take place? How does the interaction in the interdisciplinary team evolve and what unforeseen difficulties arise? How do decision-making processes work and what positive results are achieved by the integrated approach?

Second: What general findings for integrated blue-green planning can be derived? How can they be applied to further projects? Which strategies have to be created for a successful implementation of blue-green architecture projects?

The findings of the analysis are used to develop a strategy for integrated blue-green architectural design. This general approach is a guideline for blue-green projects and describes step by step the application of integrated planning.

2. Materials and Methods

This paper follows a design-based approach. It refers to a procedure in which design is the basis and method of research. The process of designing drives knowledge acquisition. The principles on which design, and thus also architectural research, are founded, are particularly suitable for finding creative solutions to complex problems [13,14]. Designers always work iteratively and seek non-linear possibilities instead of one-dimensional solutions [15] (p. 60 f.). This leads to a knowledge production that can be made visible through reflection. In this sense, it is a qualitative research methodology [16,17] with an inductive research approach [18].

Concerning the Impulse Project, we proceeded as follows: Starting from the research question, the design and the 1:1 implementation were developed together with the project partners. The course of action was documented and the following reflection of such action enabled its abstraction to a wider applicable design strategy (Figure 1).

Figure 1. Design-based approach for the Impulse Project.

The methodological approach shows clear references to research by design, also known as research through design. The definitions for this concept vary in the literature. One reason for this is that it is a broad-based method that is in constant development [19]. In this paper, we refer to the analysis of Roggema [20], in which many findings on design-based research have been incorporated. Based on the analysis of several studies, Roggema has developed a method that divides research by design into three phases. The full definition is as follows:

> "Research by design is a method, which uses design to research spatial solutions for a certain area, accommodating a design process, consisting of a pre-design phase, a design phase and a post-design phase, herewith providing a philosophical and normative basis for the design process, allowing to investigate the qualities and problems of location and test its (spatial) potentials, meanwhile creating the freedom to move with the proposals in uncharted territory, and producing new insights and knowledge interesting and useful for a wide audience." [20]

According to this definition, the three phases of the Impulse Project were identified.

1. Pre-design phase: In this phase the goal of the blue-green project was defined and the question of integrated planning was developed. Particularly important was the initial communication among architects, specialist planners and experts in order to develop a common understanding of the project and the planning task. Introductions to the technical basics (grey water treatment, irrigation technology) expanded the interdisciplinary knowledge of all participants. Additionally, the framework conditions and limiting factors (location, financial scope, users) were identified.
2. Design phase: The second phase consisted of the design process for the Impulse Project. The technical and spatial solutions were evolved in iterative loops by the interdisciplinary team in order to coordinate blue and green aspects synergistically. In accordance with the integrated approach, the architectural design was created in close interaction with the "blue" and "green" representatives. Working together on an implementation project enabled the team to learn from experience. The physical implementation is an elementary part of the research process, because some problems do not arise until the construction phase. During the development of a prototype, it is possible that theoretical considerations cannot be implemented in practice, or, for example, weak points are overlooked. In order to understand the development of the Impulse Project, the process was documented in detail. This included extensive protocols of meetings and discussions, as well as e-mails and notes of telephone calls. This documentation allowed to highlight the questions that arose amongst the planning partners and how they dealt with them. The roles of the participants could thus be identified, and it became clear who contributed to the different parts of the overall process and at which stage.
3. Post-design phase: Investigating the transfer of the insights from the Impulse Project to subsequent projects and outlining the integrated approach form the third phase of the study. According to Roggema's definition, research and design are decoupled in this phase. The critical reflection of the completed project and the analysis of the blue-green integrated design frame the research output on an academic level. The development of a design strategy transposes the findings from the Impulse Project into future blue-green projects.

3. Results

This section describes the results of the entire research by design process following the three phases described above. Planning for the Impulse Project started at the end of 2018 with the first meetings of the project team and intensified in 2019. The implementation followed in autumn 2019 and was delayed due to restrictions caused by the COVID-19 pandemic. Therefore, the commissioning took place belatedly in early summer 2020. The reflection and transfer of the results took place throughout the year 2020.

3.1. Pre-Design Phase: Framework Conditions for Design

3.1.1. Local Situation and Site Search

The site of the Kunstverein Wagenhalle e.V. in Stuttgart, an area with a huge former coach depot used by artists, had already been determined as the location for the Impulse Project before the overall research project started. However, the exact location was not specified. Next to the old coach depot, there are other facilities on the site: The so called Container City hosts several workshops and studios, and was built in direct vicinity of the historic hall in 2016/17. Adjacent to the Container City, the urban gardening project Stadtacker Wagenhallen e.V. is located. This creative environment provides an ideal neighbourhood for the Impulse Project for several reasons. For one, with its temporary architecture, the Container City corresponds to the planned appearance of the Impulse Project. Right from the start, a temporary and mobile solution based on reused overseas containers was envisaged. In addition, there are temporary worker accommodations (residential containers) on the site that had been installed in the context of a tunnel construction site, which belongs to the Stuttgart 21 railway and urban development project. The entire site is part of the future Maker city in the Rosenstein quarter and an integral part of the International Building Exhibition IBA 2027 [21]. The implementation of the Impulse Project, therefore, not only aims to improve a given situation, but seeks to stimulate blue-green urban development in the long term.

The beginning of the pre-design phase was marked by the search for the definite location of the Impulse Project. In a pre-selection, nine possible spots were identified. The immediate neighbours (artists, construction workers, urban gardeners) and their interests were included in the decision, but the decisive factors for the spatial criteria entailed the accessibility, the available space, the structural subsoil, the visual relationship to the existing buildings and the environmental influences. On the basis of this, two positions were shortlisted which had different advantages and disadvantages: a very prominent position at the entrance to the Container City, which was considered the favourite right from the start, and a second, quieter location at the back of the residential containers in proximity to the urban gardening project and a large weeping willow (compare Figure 7). From the very beginning, it was determined that the Impulse Project could only carry out concrete interventions on a small area. Changes (such as the installation of green roofs or the creation of water patches) in the area of the Container City and the urban gardening project were ruled out due to the terms of use and legal framework conditions. Furthermore, solutions that require a major intervention in the ground, such as ponds, underground cisterns or ground-based plantings, were ruled out due to the temporary nature of the project.

3.1.2. Site-Related Pre-Conditions for Water and Vegetation

In the sense of a two-sided blue-green approach, it was necessary at this point to identify the respective problems and framework conditions for the design task. A distinction must be made between overarching and project-specific goals. Overarching goals include, for example, improving the microclimate through intensive greening (evaporation) and contributing to stormwater management through integrated retention. The extent to which the project-specific conditions can offer solutions here remained to be determined by identifying the conditions on site.

In regard to the project-specific goals, the analysis of the surroundings showed that there existed two water flows that could be incorporated into the design on the "blue" side and would have to be taken into account for further considerations. Both water flows are related to the residential containers: the rainwater runoff from the rooftops and the wastewater from the showers and hand basins, so called "grey water". Grey water is defined as slightly polluted wastewater that is free of faeces and can be treated easily to process water [22] (p. 146 f.). The sanitary rooms have exterior installations that can be accessed without major construction effort. This allowed to make the grey water available to the Impulse Project. With its large sheet metal roof, the container housing facility at the same time represents extensive surface sealing that can contribute to overloading the sewer system during storm water events. The storage of rainwater for irrigation purposes is, therefore, also linked to the goal of helping to relieve the burden on the sewer system [6]. In summary, rainwater and grey water both remain unused as a resource and are discharged. Local reuse would contribute to a sustainable water management.

Also on the "green" side, basic potentials for improvement were identified. In the existing vegetation, the large weeping willow and the urban gardening were particularly prominent. The weeping willow seems to cover its water needs independently via deep roots. The urban gardening project, on the other hand, has a high irrigation demand in summer, which is partly covered by rainwater and partly by drinking water. The potential for greening buildings was also identified: both the façade of the residential containers and the roofs of the small surrounding huts were revealed as possible greening surfaces. Also, innovative forms of freestanding vertical greenery to further enhance the site were considered.

The treatment of grey water by a constructed wetland planted with reeds, as well as the irrigation needs of (vertical) greening, could provide opportunities to link blue and green aspects and to create synergies. Although some of these possible interfaces between water and vegetation became visible at that point, no design solution for the planning task was developed. The intention of this was to first interlink the project goals synergetically in order to explore design solutions on this basis.

3.1.3. Planning Team

The interdisciplinary blue-green planning and research team for the Impulse Project in Stuttgart consisted of four parties (Figure 2). All participants belong to the overall INTERESS-I research project and received funding in this context. The coordination of the planning and implementation process, as well as the responsibility for the architectural design and the integration of the blue and green elements into one system, remained with the Technical University of Munich (TUM). The University of Stuttgart (ISWA) took on the task of determining the available water quantities, as well as the storage modelling and control. The Technical University of Kaiserslautern (TUK) was part of the "blue team", but regarding water quality and water treatment. The "green" part was taken over by the horticultural enterprise Helix Pflanzen GmbH (HELIX). This team composition implied that the partners in the research project also took on the role of specialist planners in the integrated planning process for the Impulse Project.

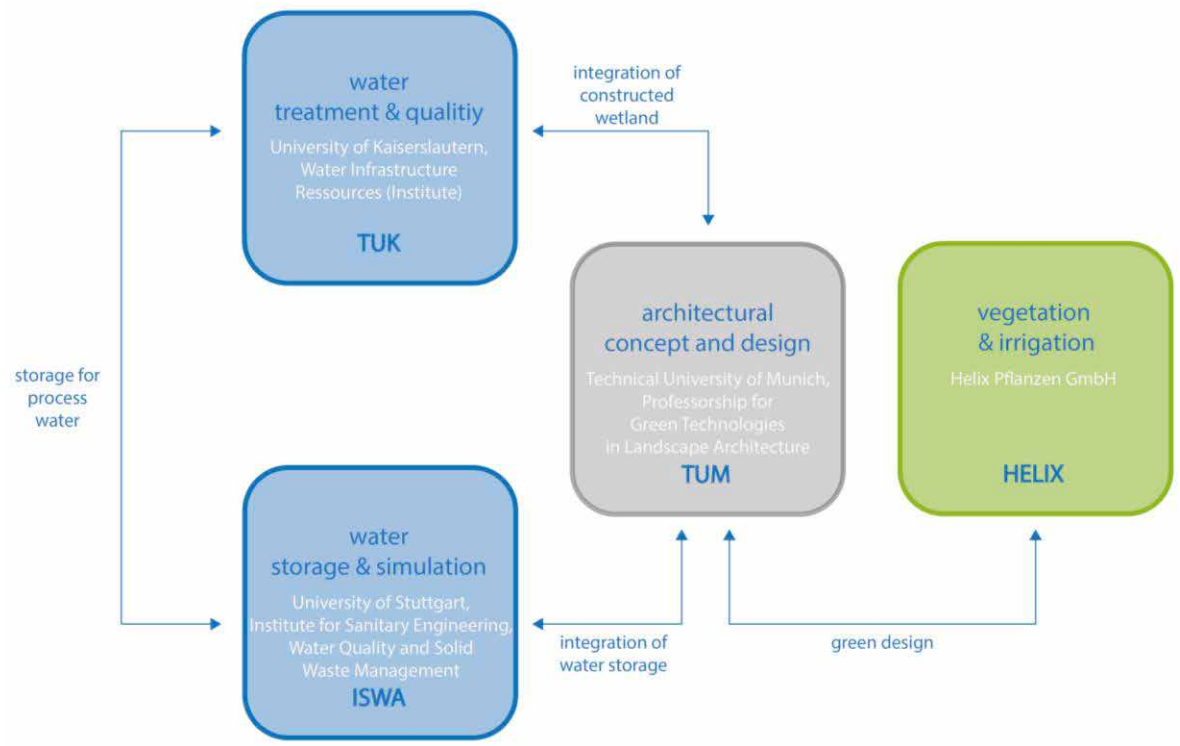

Figure 2. Interdisciplinary planning and research team for the Impulse Project. The interfaces of the design and technical issues are also mapped here.

3.1.4. Specific Objectives, Responsibilities and Contributions of the Project Partners to the Blue-Green System

In an initial meeting, all involved project partners came together and listed their specific goals for the Impulse Project and the related components that they intended to contribute to the blue-green system (Figure 3). The basis for this compilation was, among other things, the approved funds from the research proposal. On behalf of the architectural researchers, the intention was to test the two-sided planning approach as an integrated strategy. The interdisciplinary team's procedure was documented in detail in order to develop it into a design strategy. Even at this early stage, the aim was to use the Impulse Project to positively influence the future development of the neighbouring urban district (Rosenstein quarter). Therefore, publicity was an important aspect too. TUM's area of responsibility included the coordination of the collaboration, as well as the construction site set-up and site management. The planned (overseas) container as a central element (which refers conceptually and design-wise to the Container City) should also be provided by TUM. The researchers from ISWA and TUK are grouped under 'water engineers'. Their objectives relate in particular to the flexibility of the systems, both quantitatively (storage capacity/irrigation with rainwater and grey water, depending on availability) and qualitatively (water treatment). Therefore, the planning and financing of a constructed wetland and all storage tanks (including the cistern) fell within their area of responsibility. This also included water pumps and some control and monitoring components. Helix's main goal was to irrigate vertical greenery with alternative water resources, especially greywater. The horticultural company already has three proven vertical systems on sale, all of which could be used in the Impulse Project. Accordingly, they were responsible for the vegetation, the irrigation technology and, in addition, for the maintenance and upkeep of the greenery.

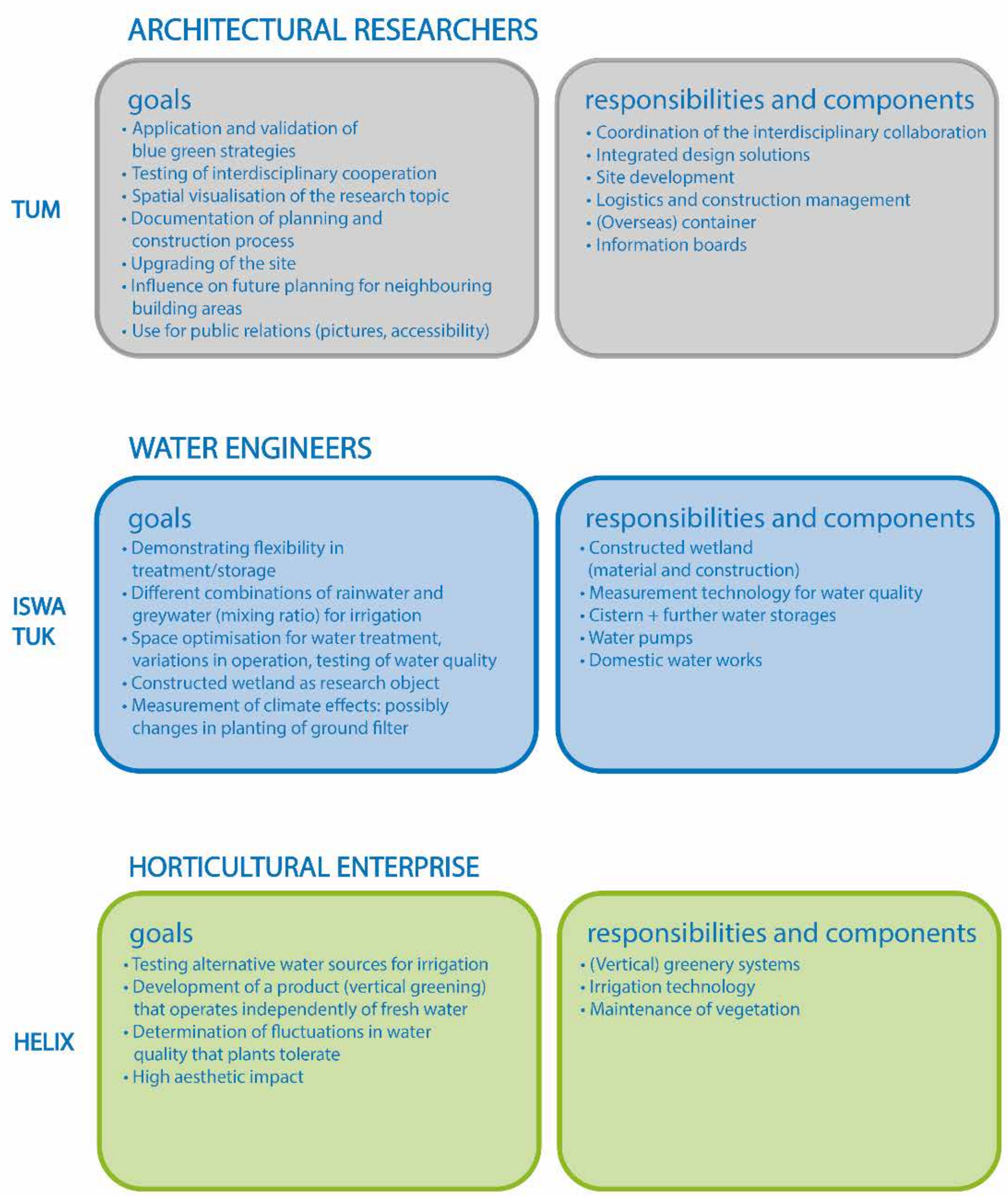

Figure 3. Results of the first interdisciplinary planning meetings: List of specific goals, components and responsibilities of the project partners. Overarching goals that affect the benefits of BGI are not included here.

In this first meeting, the financial framework was also defined. Because the implementation of the Impulse Project was part of a research project, the financial resources were limited by the grants of the funders. At this early stage of planning, the final use of the funds could not be predicted. Therefore, it was not a cost estimate that was made, but a compilation of the available funds. Each project partner contributed a certain budget, which in total made it possible to check the first drafts for feasibility. Some positions were mandatory and fixed, while others contained a margin that should be used to everyone's benefit.

The collection of the components and objectives provided a first overview of the potentials that needed to be developed. In addition, first interfaces and dependencies became visible and conveyed where a precise coordination of the partners would become necessary. The discussions resulted in interrelationships and correlations between the components, which are shown in Figure 4.

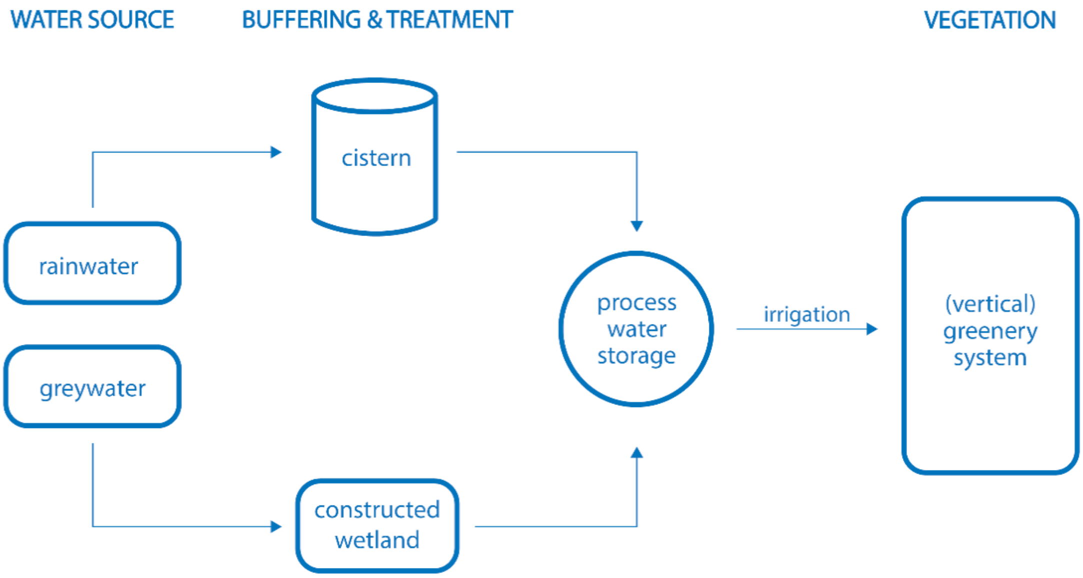

Figure 4. Components at first planning stage of the Impulse Project.

The dimensioning parameters and the conversion into an architectural design were still open at this point in the planning process. Before the spatial issues could be addressed, initial estimations of water availability and water demand were made. A partial roof area of 125 m^2 of the residential containers was available for rainwater collection. Precipitation amounts are subject to strong fluctuations, both spatially and temporally. The estimate was therefore based on an average value of the previous five years. From the data of the Stuttgart Mitte weather station in the years 2014–2018, an average precipitation value of 485 L/m^2 per year results, which leads to a total volume of approx. 61 m^3 per year [23].

The availability of grey water was also based on estimates and not on measured values. Based on the occupancy data of the residential containers provided by the construction company, a constant presence of 24 persons whose grey water would be available can be assumed. A low average value for grey water from showers and hand basins of 20–40 L per person per day was expected. This value is also subject to unpredictable fluctuations, e.g., fewer persons present over public holidays. Nevertheless, calculations showed that a permanent availability of 320–480 L per day (115–175 m^3 per year) can be safely presumed for treatment in the constructed wetland. The excess grey water should be discharged into the sewer.

In the sense of a two-sided planning approach, a similar calculation was made for the vegetation. The rough target here was to green a total area of 100 m^2, preferably with vertical greenery. This quantity was based on the assumption that 100 m^2 would be spatially and financially feasible. Three different vertical greenery systems from the company HELIX were considered, all of which rely on artificial irrigation because they do not root into the ground. The need for irrigation is not constant throughout the year and rises sharply in summer. Comparable measured values of built vertical greenery from HELIX were used as a rule of thumb. On an annual basis, this resulted in a total water requirement of 1 m^3 per 1 m^2 of greenery. This value is also to be considered variable, because depending on the system, a certain drought resistance is given.

This assumption of water availability and water demand was sufficient for further planning. Before the architectural design work began, all fundamentals were collected and contrasted in order to develop a common understanding of the planning task and the disciplines involved: the scientific interests, the specific technical requirements and the desired functions for the users. Subsequently, these points were translated into a spatial problem as a basis for the architectural design. At the same time, the (building) legal conditions had to be evaluated, including liability, accessibility and security.

3.1.5. Description of Conflicting Goals

In the collective planning meetings of all partners, first conflicts of interest became apparent. These were listed without the claim to find an immediate solution. Rather, they served to sharpen the common understanding of the different demands on the project and to underline the need for compromise. The uncertainties and conflicting goals identified at this stage of planning were as follows:

- What criteria are used to select the plants? (Appearance/evaporation performance/robustness).
- The water should be purified, but not too many nutrients that could serve as fertiliser for the plants should be removed from the water.
- The possibilities and chances of irrigation with untreated grey water had been repeatedly considered. However, this was opposed by concerns about the risk to humans and nature as well as technical objections (e.g., algae formation and clogging of the drip irrigation).

3.2. Design Phase: Interdisciplinary Planning and Construction Work

The active design phase started with the handover of the conceptual basis, including all of the complex requirements, to an external architecture office. Parts of the planning activities remained with the architectural researchers of TUM, but the development of the design and the detailed planning were carried out by Daniel Schönle Architecture and Urban Planning. This decision had several reasons: The office of Daniel Schönle is located in Stuttgart and was therefore able to supervise the construction work. Additionally, an architectural office has the necessary equipment and routine for practical building projects. Universities have no infrastructure to manage the execution of construction works. In addition, the office has many years of experience in the design and implementation of green architecture. This transfer of the design to an independent office gave the architectural researchers the opportunity to accompany the process with an external view, and to separate the design components from the academic aspects of integrated blue-green planning. In an iterative process, a total of 16 design variants (V 1–16) were developed, which were repeatedly discussed between the architectural office and the planning participants, as well as the stakeholders involved (inhabitants of the residential containers, artist of the Container City and urban gardening activists). In the following, the emergence and development of the design variants is retraced. The illustration of all design variants would have exceeded the scope of the paper. Therefore, it only contains selected graphics that underline the comprehensibility of the text. The full compilation of all architectural drawings (design variants V 1–16) and further photos can be found in the Supplementary Material (Figures S1–S20).

3.2.1. Design Variants V 1–10

On the basis of the determined framework conditions, the architectural office developed first design variants in the areas around the two shortlisted positions (Figure 5 and Figure S9). The comparison of the versions V 1–5 was discussed to identify advantages and disadvantages. The concept sketches varied between several orientations for the container module and presented a range of spatial and functional options. The type of container module(s) had not yet been decided. The idea of refurbishing an old (overseas) container was considered, as well as the customised production of new modules. Both options have in common that the container frame provides the static structure, while the interior can be designed flexibly.

Figure 5. Design variants V 1–5 (no scale), all consisting of one or two container modules, a constructed wetland and various options for vertical green elements. The architect's initial conceptual considerations show a range of options for the planned location and design of the Impulse Project.

A final decision concerning the position as well as the design had not yet been made at this point, as the opinion and expertise of the specialist planners had to be obtained. The following factors were decisive for the further elaboration: Functions and utilisation, accessibility, integration of water storage tanks, environmental conditions for the constructed wetland, space requirements for installation technology, environmental factors, insulation/frost protection, local conditions for greening (humid/dry) and access to willow (see details below). Based on this a further variant V 6 (Figure S10) was developed.

Further consultations were held with the involved parties and the results were incorporated into the continuing design process, V 7–10 (Figures S11–S14). TUM assumed a mediating role between the architectural office, specialist planners and the local stakeholders. This enabled coordinated communication and deliberation of the different requirements before they were incorporated into the spatial design. For example, the large old willow tree at the intermediate area between urban gardening and the residential containers plays a key role for the location, both spatially and socially. The treetop forms a walk-in space, which is used by different groups for smaller events. At the same time, the willow has a protective function as a boundary to the site road, which should not be interrupted. The integration of the willow in the architectural concept had, therefore, been discussed comprehensively with all stakeholders.

All variants (V 1–10) built on the idea of a two-storey container frame solution, consisting of a technical room at the bottom, on which the constructed wetland was placed (Figure 6). Specific planning for the container module did not exist at this stage. A detailed drawing of the two-storey container module was completed at a later stage of the project and is shown in the Supplementary Material (Figure S17).

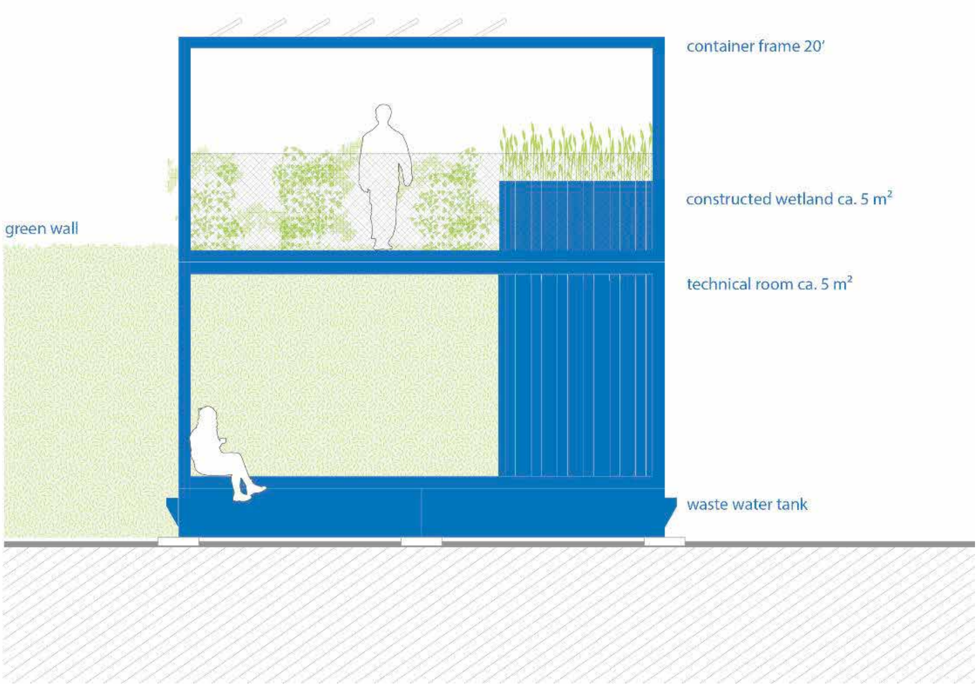

Figure 6. First architectural drawings for a two-storey solution with container frames in the design variants V 1–10 (no scale). The constructed wetland in the second storey would only be accessible with restrictions. The waste water tanks would be integrated into the overall concept as a base.

3.2.2. Design Variants V 11–13

As the planning progressed, the final decision regarding the location of the container frames needed to be made. At a meeting of all project partners, the variants V 11–13 (Figure 8 and Figure S15) were presented for discussion. V 11 once again showed the original favourite: a prominent position at the entrance of the Container City that had a high potential for a large public impact (location ① in Figure 7). In the meantime, however, it had become clear that the dust blown from a neighbouring cement plant could damage the constructed wetland. In addition, the directly adjacent site road with heavy traffic would significantly reduce the sojourn quality. The site was also rather shaded, which did not allow effective cooling by irrigated vegetation; this was in contrast to the aim of the research question. The function of the constructed wetland would also be reduced if the solar radiation was too low. The proposed site was therefore moved to the second shortlisted position, the quieter and sunnier area between the urban gardening and the construction workers' residential containers. In the design variants V 12 and V 13, the Impulse Project was positioned in this area. All partners agreed with this location as the final position (location ② in Figure 7).

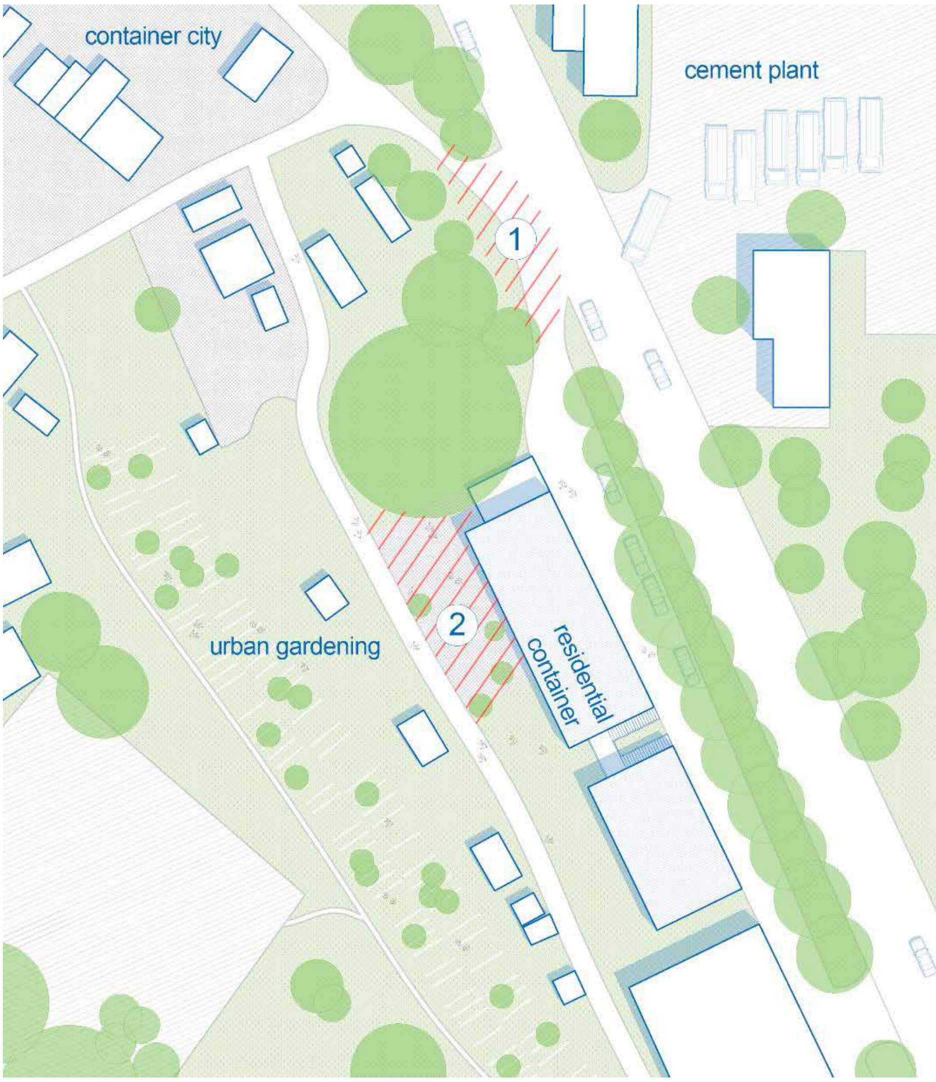

Figure 7. Site plan with location options (no scale). ① Initially favoured position at the entrance to the Container City. ② Final location between residential containers and urban gardening.

With regard to the components of the Impulse Project, space-defining factors were also identified and discussed at the planning meeting. The tanks required for grey water and rainwater storage became decisive space-creating elements due to their volume. The size and design of the tanks were not fixed at this time. It was decided that their realisation should take place aboveground in order to keep the whole project mobile and to make all components experienceable in terms of didactics. For rainwater, a cistern with a capacity of 11 m^3 was intended. The cistern was intended to be equipped with built-in techniques for retention with throttled discharge (compare Section 3.1.2), which could not be transferred to "simple" storage solutions, such as a number of standardised plastic tanks (IBC). Thus, the original idea of giving the rainwater storage tank a different shape so as to integrate it into the container solution had to be rejected. Instead, a reinforced concrete cistern was established as an integral part of the system and design concept.

The storage of raw grey water and process water turned out to be more flexible in terms of design and not restricted to one product. Because grey water is a continuous source of water, fluctuations have to be only slightly intercepted and balanced. Therefore, the storage tanks were designed to be smaller than the rainwater storage tanks. Various volumes and possibilities for integration into the overall system were considered.

Further, the constructed wetland had to be integrated into the design concept. There was no reference for such a compact and mobile constructed wetland, so many questions of operation and requirements had to be discussed with the engineers from TU Kaiserslautern (TUK). The vertical flow constructed wetland is typically filled with sand and gravel and planted with reeds. With a surface area of 4–5 m^2, it results in an expected weight of 10 tons. A two-chamber system was to be realised in order to investigate the filter effect of different substrates. Based on the performance of other filters, it has been estimated that a constructed wetland of such a dimension could treat 400 to 500 L of grey water per day. The exact capacity can only be determined during operation. As already described, the presented design intended to place the constructed wetland in a container frame on the second storey. The architects' idea of distributing the soil volume, and thus the mass of the constructed wetland over a larger area with a lower installation height, was rejected by the specialist planners. The substrate height of ca. 1.5 m had to be retained to ensure the cleaning performance of the filter. An advantage of the elevated position of the filter was the high solar radiation as this has a significant influence on the filtration effect. In terms of safety, the accessibility of the filter had to be considered. Since it is a waste water treatment system, no unauthorised persons should have access to the filter in order to avoid any health hazard. With this in mind, the two-storey solution was pursued, in which the constructed wetland was placed on the roof of the technical room where the access could be regulated by the staircase (Figure 6).

3.2.3. Integration of Technical and Nature-Based Systems into the Architectural Design

In order to be able to make progress in the planning process, numerous detailed questions brought forth by the architectural office had to be discussed with the specialised engineers. The following points came up:

- Required space for equipment in the technical room: the partners' installations as specific products, including dimensions and electrical power, had to be listed in order to dimension the room adequately.
- Integration of wastewater tank: the spatial, functional and design integration of the tanks and the necessary requirements were specified.
- Insulation/frost protection of cistern: the question of frost resistance of the cistern was discussed with the manufacturer. The cistern was not provided with extra insulation but embedding the cistern half a meter into the ground was considered sufficient to prevent it from freezing in winter.
- Weight of the constructed wetland: this turned out as a highly relevant parameter with regard to the statics of the container frames and transportability of the project. The weight varies depending on the level of moisture penetration.
- Function of the container frame: ideas and concepts were collected and developed for the use of the container frame as a (semi) public open space, e.g., as a stage or for public events.
- Design modular vs. integrated: in terms of design, it was considered to what extent an integrated overall concept or a visibly modular composition of the individual parts should be realised.
- Didactic approach: the Impulse Project aims to inform future visitors about blue-green infrastructure and integrated design. For this reason, the planning took into account possibilities of knowledge transfer and visualisation of the functioning (e. g., water flows).

The design variant V 13 formed the basis for further discussion with the specialist planners. The container module with the top-mounted constructed wetland was located south of the willow. This variant entails that parts of the vertical green elements are attached to the residential containers as building greening. In this variant, the cistern and the grey water storage tanks are individually placed next to the container, and thus serve to visualise the water flows (Figure 8).

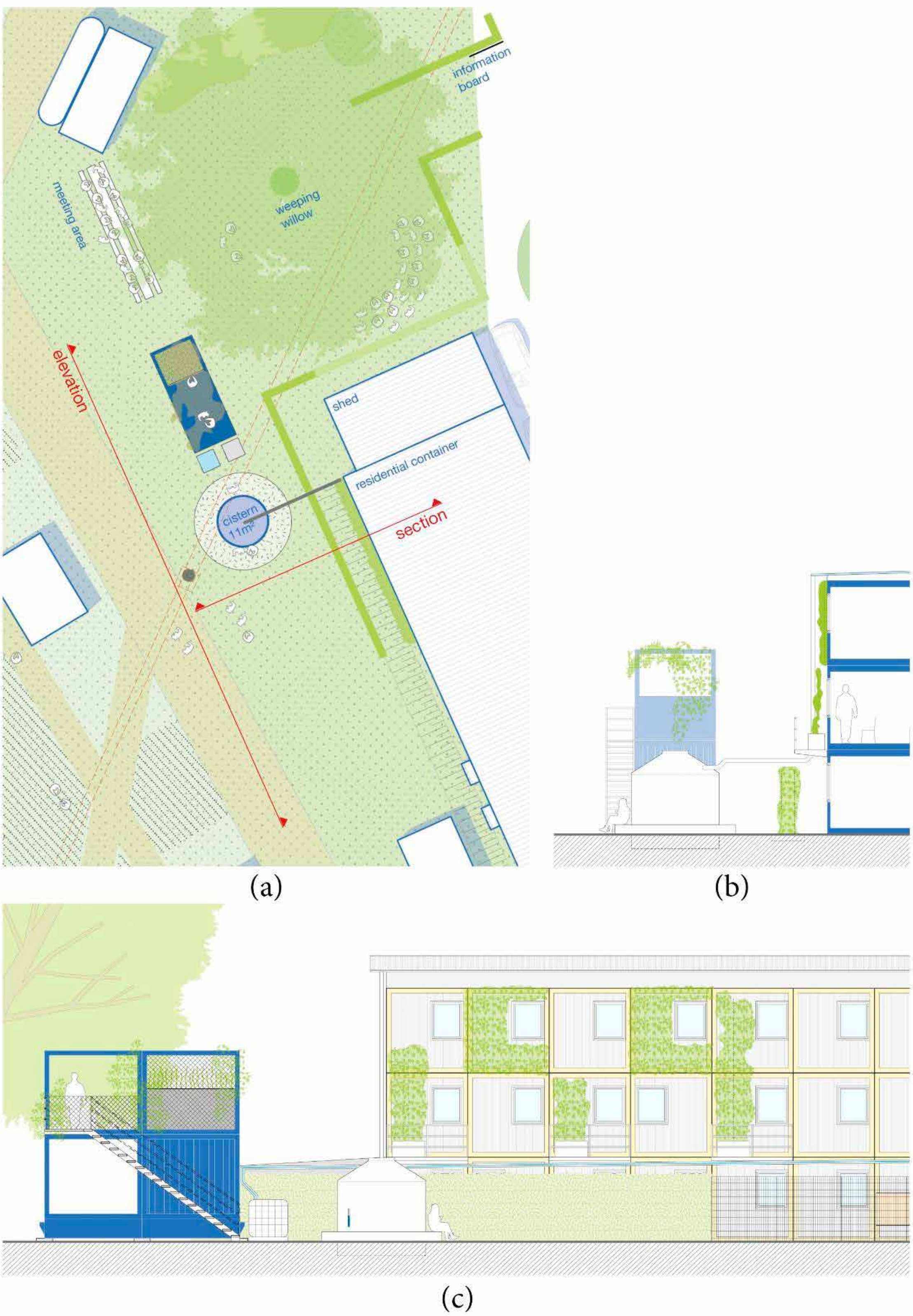

Figure 8. Design Variant V 13 (no scale) as a basis for discussion and elaboration with the specialist planners: (**a**) site plan; (**b**) section through residential container and façade greening; (**c**) elevation of two-storey container module, cistern and facade greening.

The dialogue with the specialist planners revealed weak points in the planning and made it possible to evaluate the project's feasibility. The direct neighbours were also involved in the discussion in order to reduce reservations and to clarify any questions. This communication strategy in the design process enabled all perspectives to be taken into account as well as strengthened the concept.

3.2.4. Budget Constraints and Integrated Solutions

As in all implementation projects, the feasibility of the architectural design was directly dependent on the construction costs and the available budget. The listing of all components conveyed which items had not been previously calculated by the project partners. For example, the responsibility for grey water tanks and flow meters had to be clarified. These are objects that were of interest to several participants because they are located at the interface of storage, treatment and irrigation.

Furthermore, it turned out that the planned architectural adaptations of the overseas container, as well as the integration of the manifold technical components and requirements, posed a high constructive and, thus, also financial effort. Therefore, the original idea of using a discarded container was dismissed and a specialist company was commissioned to manufacture a container in accordance with the requirements for the project. This solution, which was initially more expensive, allowed the direct integration of parts of the electrical installation, as well as the trough for the constructed wetland. This solution was only possible through close cooperation within the planning team because it required flexibility beyond disciplinary budget limits. The joint integrated solution bundles advantages and creates synergies, which, due to the costs saved elsewhere, makes an overall better solution possible.

A closer look at the costs for the vertical green systems revealed that their costs were significantly higher than the originally assumed values. High material costs and the expenditure for pre-cultivation were cost drivers. The planned green systems with approximately 100–120 m^2 surface area had to be reduced by half. The dimensioning of the cistern and constructed wetland remained the same (due to research interest and corresponding needs of measurements of the water engineers) and with it, the available water quantity. Application options for the resulting water surplus were developed later in the planning stage.

3.2.5. Design Variants V 14–15 and Final Design V 16

The two-storey design of the container module turned out to be a significant problem. As described above, it was not possible to achieve a better load distribution on the roof by flattening the filter trough. In addition, the privacy of the adjacent residents would be disturbed by the two-storey-solution, as the height allows for a direct view into the living/sleeping rooms. Therefore, a one-storey solution was developed, which offered great potential for saving construction costs (statics, no stairs) and spatial advantages, such as better visibility of the constructed wetland for visitors (Figure S18). This adaption of the design also contributed to the intended goal of creating a mobile, temporary architecture. A technical disadvantage of this solution is the change of the hydraulic section of the constructed wetland. It is no longer possible to regulate the drain of the filter by gravity. Instead, additional pumps have to be installed.

In the final design variant V 16, the core element of the project is formed by two container frames, which are placed next to each other, but offset by half the container length. (Figures 9 and 10). The first container hosts the constructed wetland and the technical room. The second one contains storage tanks for raw grey water and purified grey water. The four tanks (2 × raw grey water, 2 × filtered grey water) were clad with wooden decks in such a way that two terraces on two levels were created, which are available to visitors as a meeting area (Figures S3 and S8). In the technical room, another tank exists where rainwater and grey water are mixed for irrigation. The central control of all pumps, valves and sensors is also installed there. The pipes (electricity and water) that lead to the cistern and the overflow pipes into the sewer are installed underground.

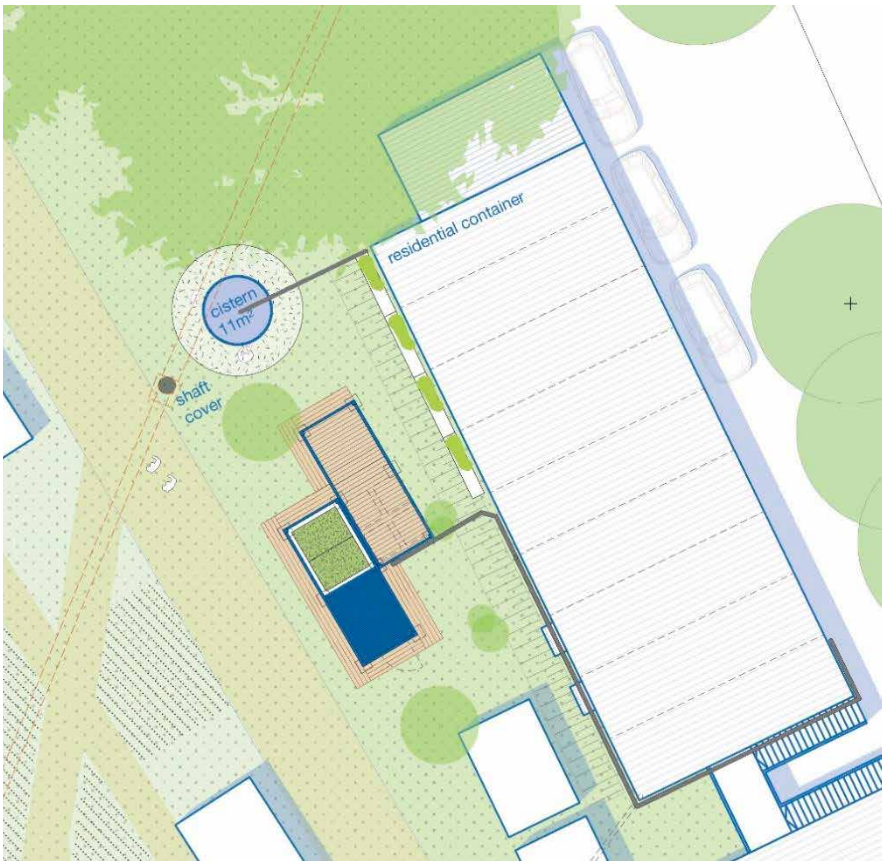

Figure 9. Final design variant V 16 (no scale). The single-storey solution consists of two container frames housing the technical room, the constructed wetland and two terraces, of which one is on top of the grey water storage tanks.

Figure 10. The Impulse Project in built state. On the left: retention cistern made of reinforced concrete with throttled emergency overflow. On the right: two container frames with integrated constructed wetland. In the background: façade greening on residential containers. Rainwater is directed from the roof into the cistern. Grey water is available from the sanitary containers (far right in the picture). Photo: Julian Rettig.

As described above, the amount of vertical greening had to be reduced for cost reasons and, therefore, a larger amount of water than necessary is available for irrigation. It was foreseeable that more water would be available than was needed to irrigate the vertical greening. This resulted in several ideas for its use: infiltration/evaporation on site, transfer to the urban gardening initiative, filling of mobile watering carts for urban greenery. All variants referred to open systems and were therefore dependent on the hygienic safety of the treated grey water. They should, therefore, only be specified after the examination of the process water in order to prevent any health hazard.

The reduction of the amount of green elements also called for a new design concept. The decision was made to focus on facade greening. This resulted in a clear and coherent design solution and offered the most microclimatic advantages, as the inhabitants of the residential containers benefit directly from cooling through evaporation and shading. Three vertical systems were chosen, which differ in their requirements and characteristics. In order to provide mobility, scaffolding was erected directly in front of the façade to serve as a supporting structure for the greening of the upper floors (Figure 11 and Figure S5). On the ground floor, free-standing elements (Helix Elementa®, Kornwestheim, Germany) were installed front of the containers where pavement slabs serve as a simple foundation. These modules consist of wire baskets with a depth of 40 cm. They are filled with substrate and planted with various plants (ivy, lavender, geranium, bluebeard). In the middle level, a combination of planters and trellises planted with climbing plants (ivy, clematis) were installed (Helix Elata®, Kornwestheim, Germany). The upper level was realised with a 'vertical garden' system (Helix Biomura®, Kornwestheim, Germany). These are soilless modules, planted with a variety of grasses and flowering plants (spring cinquefoil, sea thrift, dianthus, lady's mantle, evergreen candytuft, tufted fescue). All three systems have different advantages and disadvantages in terms of evaporation capacity, shading and resilience. The requirements for quantity and frequency of irrigation also differ. These aspects will be examined in the operational phase.

Figure 11. Three different systems of vertical greening were installed to investigate differences in performance. A scaffolding supports the plant boxes of the upper floors. Photo: Julian Rettig.

3.2.6. System Design and Flow Chart

Figure 12 shows the flow chart that emerged out of this interative planning process: The cistern is connected to the rainwater pipe of the residential containers. 7 m^3 of the cistern are available as permanent storage. A further 4 m^3 are used for retention and in the event of heavy rainfall, the discharge is throttled. This effluent is infiltrated directly on site, and thus serves to recharge the groundwater. The cistern is equipped with a pump and a level gauge. The grey water from the showers and hand basins flows directly into the grey water tanks via an open-channel pipe. Since more grey water regularly accumulates than can be treated, there is a direct overflow into the sewage system. The reservoirs for untreated grey water consist of two interconnected 1 m^3 intermediate bulk containers (IBC). From these tanks, the water is pumped into the two chambers of the constructed wetland and spread over the entire surface. The chambers are filled with different filter substrate to detect differences in the filtering effect. The constructed wetland is insulated so that it does not freeze in the winter. Frost would destroy the micro-organisms that provide the cleaning performance. Each chamber has a submersible pump installed at the bottom of a wide pipe. The purified water flows through small openings into this pump sump and is pumped from there into two interconnected 1 m^3 IBC storage tanks. These reservoirs are equipped with UV lamps for the hygienic purposes of killing bacteria, viruses, fungi, etc., and preventing them from multiplying in the water.

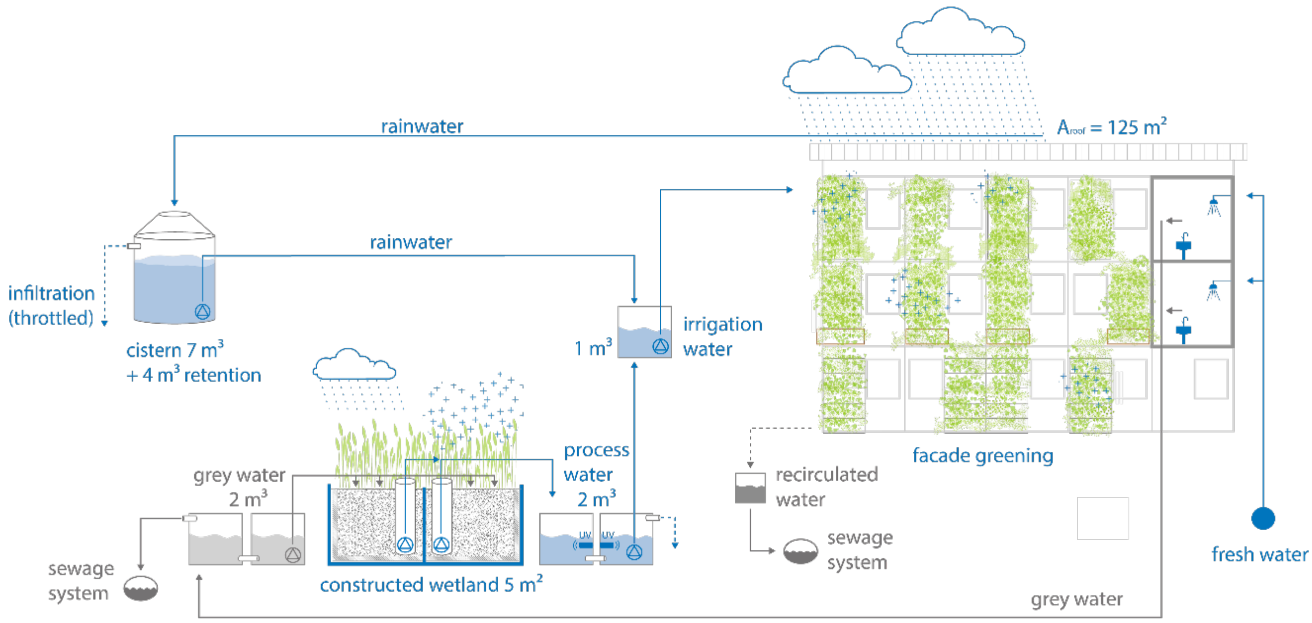

Figure 12. Flow chart Impulse Project: The technical components of the system and their connections are shown here. The drawing is not to scale.

The mixing 1 m^3 water tank, from which the irrigation system is fed, is located in the technical room. It can be filled with rainwater and/or process water depending on demand and availability. Irrigation is carried out as drip irrigation for all three green systems. The excess water of all vertical elements is collected and measured. This allows the actual water consumption and the resulting evaporation capacity to be determined.

3.3. Post-Design Phase: Transfer to a Design Strategy

Following Roggema's description, the third phase consists of reflecting and communicating the results of the first two phases. The findings are to be made available to the wider public and discussed (academically) [20]. In case of the Impulse Project, this results in two main activities: The use of the built object for visiting and knowledge transfer, as well as the transfer of the experiences gained in the planning process into a design strategy.

Due to this two-way approach, the urban public and the academic community are equally addressed. Since this paper is directed at the professional public, the events and activities at the Impulse Project will not be described in further detail below. Instead, the focus remains on the design strategy (Figure 13). Nevertheless, the on-site experience is an elementary part of the concept and a site visit is recommended to all interested.

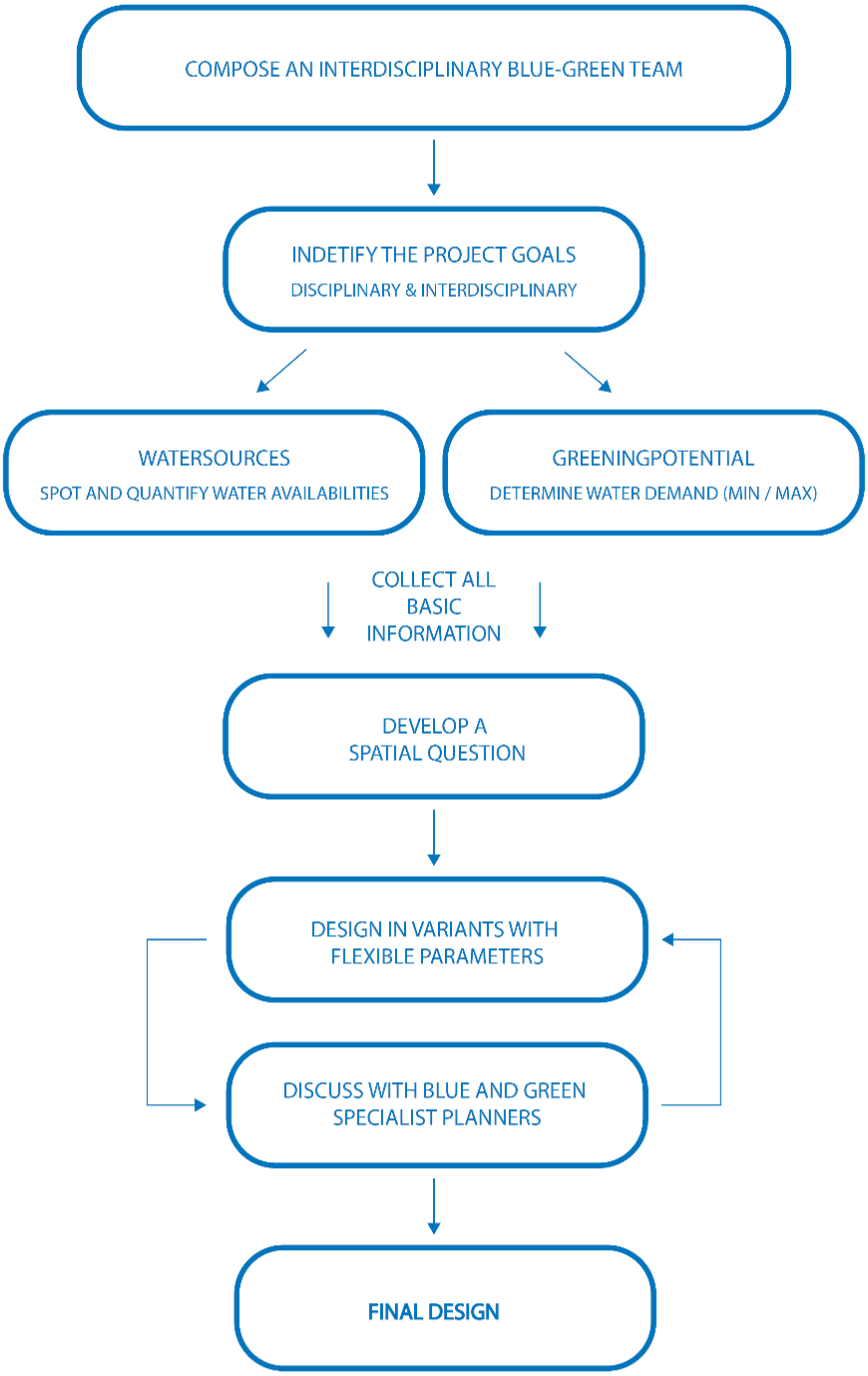

Figure 13. Design strategy for integrated blue-green architecture projects.

The design strategy describes the procedure for a blue-green project step by step and serves as a guide for architects, landscape architects and engineers to coordinate the planning in an interdisciplinary team. The procedure is based on the experiences from the Impulse Project and has been abstracted and generalised accordingly. In its application, the design strategy focuses on the Central European region, respectively on temperate climate zones. The transferability to other climatic and socio-cultural contexts must be examined in each individual case. The work steps presented below are intended to ensure that blue and green objectives are equally taken into account and lead to a synergetic overall solution.

The experience at the Impulse Project has shown that the composition of the interdisciplinary team is crucial for successful integrated planning. Thus, the composition of the planning team is the first step in the process. The exact composition of the team may vary depending on the project, but it should be ensured that the integrating function is taken over by one of the participants. Three possible team compositions are described in more detail below:

1. (Landscape) architect + water engineer. The (landscape) architect is responsible for planning the vegetation and developing the overall spatial concept. He/she also forms the integrative authority and incorporates the analyses, recommendations and objectives of the water engineers into the concept. In this case, the (landscape) architect should have experience with integrated planning in order to implement the "blue" parts in the best possible way. If the architect assumes the integrating function, a landscape architect or specialist for green planning should be included in the team who is responsible for the use of plants and irrigation requirements. This constellation corresponds to the planning team of the Impulse Project.
2. Architect + specialist planners (blue/green) + external consultant. An interdisciplinary team is assembled, in which all functions are represented. The coordination of the integrated planning is carried out by an external consultant with competence in blue-green projects.
3. (Landscape) architecture office with all planning participants in-house. The commissioning of a large planning office, which covers all blue and green sections and can, therefore, carry out the integrated planning on its own, is also a possibility. In this case, the interdisciplinary cooperation takes place in-house. An example of such a company would be Ramboll Studio Dreiseitl, which has already successfully conceptualised, designed, engineered and implemented large-scale blue-green projects.

Once the team has been assembled, it is important to define the disciplinary and interdisciplinary goals. The first planning meetings can be used to identify contradictions and conflicting goals. This promotes a common understanding of the planning task.

In the next step, the necessary fundamentals are recorded. Water sources and greening potential are identified in order to make initial quantified assessments. These investigations are necessary in order to make an assessment of the site-specific problems. This will reveal how the project can contribute to goals, such as water sensitivity, climate resilience, urban climate, etc. Ideally, water availability and water demand are specified in ranges from minimum to maximum to also reflect the available scope. The water sources that are available for a specific project must be checked separately for quantity and quality. Possible sources are, for example, precipitation water, grey water, under certain conditions ground water, water from production processes, condensation water from technical installations or air conditioning systems and surface water. The accessibility of water resources varies significantly and must be taken into account. Necessities for storage and treatment must also be examined by the water engineers. The potential for greening depends on the type of building project on which the blue-green design is based. In principle, the potential for greenery in new buildings is greater than in existing buildings in terms of the integration of climate effective greenery. New buildings enable the implementation of innovative systems that can be specified in terms of water availability. For projects with existing green structures, these should be comprehensively recorded and evaluated in order to determine irrigation requirements. The options for greening potential range from building greening (roof/façade) and open space to urban greenery.

The analysis of the blue and green potentials is incorporated into a compilation of basic information (Figure 13). Based on this data collection, the spatial question that forms the basis of the design for the project is developed. This step of the design strategy may appear delayed or self-explanatory at this point. In fact, it is a central moment in the process and the sequential order described here is indispensable. For any project that aims to combine vegetative elements with comprehensive water management, the data basis must first be created in order to recognise the potential of the site. By translating this into a spatial issue, the possibility emerges to start a creative process which takes all blue and green aspects into account. It is not the aim to find a purely technically optimised solution, but to develop spatial qualities in the sense of (landscape) architectural design.

The spatial question forms the starting point for the design activity of the (landscape) architect. Several variants that can be compared should be drafted in the process. This approach enables the consideration of flexible parameters. Fluctuations in water availability (especially rainfall), seasonal changes and vegetation growth processes influence the blue-green correlation. In addition, many technical details are still open at an early stage of the conceptual design, and these can also be specified by using variants. In iterative phases, the design variants are discussed with the specialist planners in order to incorporate disciplinary knowledge and insights into the overall process. How many of these loops are passed through depends on the project.

At the end, the final design emerges, which takes into account all blue and green components, creates a synergetic relationship and is ready for implementation.

4. Discussion and Conclusions

This study is based on the question of what an integrated planning process for blue-green architecture can look like and what insights can be gained for future planning. The documentation of the interdisciplinary planning for the Impulse Project demonstrates how such a planning process works in practice, which problems arise and where opportunities for synergies and integrated solutions lie. The coordination of the specific objectives resulting from the different perspectives of the involved planners can enable a holistic approach that leads to multifunctional solutions. Blue-green architecture designed according to these principles can allow for the synergetic merging of disciplinary objectives. These include, for example, improving the microclimate, stormwater management, environmental education and sojourn quality.

However, the exemplary design process of the Impulse Project is not able to represent all the parameters that might be considered regarding blue-green architecture. The scale and character of the project does not allow to incorporate all possible blue-green solutions, and there are far more elements available than are shown here. Existing greenery, green roofs, open water areas and many other components of blue-green infrastructure, as well as other alternative water resources, have not been considered in this study. In this regard, please refer to the overview of blue-green systems given by, e.g., Winker et al. [24] and Pötz and Bleuzé [25].

Furthermore, the integration into a larger network of blue-green solutions could only be considered to a limited extent in the Impulse Project. Water flows, in particular, are part of infrastructural constructions that are not constrained by building and property boundaries. Accordingly, it is desirable to consider them across quarters. Water treatment, water storage and retention areas are more efficient and economical on a larger scale [11,26,27]. Green roofs also become more economically and ecologically cost-effective in terms of rainwater management if they are implemented comprehensively [28]. In context of water flows, industrial processes, which often have significant water consumption, should also be considered [29]. The design strategy presented here is oriented on the planning culture prevailing in Central Europe. For countries in other climate zones, some of which are even more affected by water scarcity and the consequences of climate change, integrated blue-green solutions offer high potentials [30,31]. The transferability to regions with other climatic conditions and problems should be addressed in further research.

Still pending is the examination of the microclimatic effects and the filtration of the grey water, which are essential to finally proof the impact of the project in terms of sustainability. First reliable results from the measurements will probably not be available until the end of 2021. Until then, the assumptions on climate effectiveness are based on the empirical values of completed studies, in which cooling by shading and evaporation of greening was proven [32–35]. The filter performance of constructed wetlands is also described in the literature [36,37], but will nevertheless be precisely determined in the Impulse Project by analysing water samples. Precise measurement results on water quantities and water quality will be published by the project partners (ISWA/TUK).

The design strategy was developed using the research by design methodology, which derives knowledge from the design process of a project. In this case, the development of the Impulse Project served as the object of research. As described in the introduction, research by design is a controversial research method whose ambiguity in definition is also due to the fact that it is still under development [38]. Nevertheless, it is appropriate and reliable for the present paper, because the process of gaining knowledge, which resulted from the clear approach according to Roggema [20], is comprehensible and transparent. Schöbel et al. [17] describe the characteristics of qualitative research as follows: "Qualitative research is essentially based on a creative but nevertheless systematic interpretation of data in search of new, previously unknown structures. It therefore has a proximity to research through architectural design." Therefore, in order to develop a design strategy for architectural projects, the application of a qualitative research methodology is the coherent approach (cf. [16]).

The resulting design strategy is intended to be applied in practice and aims to be transferable to other projects. This transferability has not yet been ascertained and will be discussed below. The Impulse Project differs in some points from a conventional planning and construction process. First of all, this is due to the intention and the financing of the construction measure. It took place within the framework of a research project, which influenced the distribution of roles (see Section 1.2). The total budget that was provided had an upper limit. This restriction is comparable to the budget of a potential client. Nevertheless, this comparability has its limits because the decision-making processes of a public research funder are different from those of a private investor. It is unlikely that a commercial client would finance a highly technical plant of this kind. The research background has, therefore, made the project possible. In practice, the financial aspects are more important and the additional cost of a blue-green project usually has to be amortised in the operational phase. Another difference to planning in practice is the composition of the team and the resulting powers, objectives and interests. It can be assumed that, instead of university partners, practicing (landscape) architecture offices and engineering offices that have no research interest in the object would be involved. Potential compositions of the team are described in Section 3.3 and shown in Figure 13. Nonetheless, as far as the procedure itself is concerned, we indeed see the transferability into practice. The development of the design in iterative loops refers to an approach that is established in architectural practice. Although the early integration of the specialist planners has not been tested with regard to water and vegetation, it is already being applied in the field of energy. However, proof of this is still pending and should be provided as soon as possible.

In conclusion, we would like to summarise our experience in planning the Impulse Project as follows: Crossing disciplinary boundaries is no easy task. It requires time and commitment, which makes it essential that everyone involved is willing to learn. However, it also represents a great opportunity for interdisciplinary cooperation. If all those involved consent to change their point of view and to explore new ways of finding solutions together, it will strengthen the project, make it more sustainable, more resilient, more climate effective, more resource efficient and add value for the urban space and its inhabitants. It is our aim to stimulate a new planning culture based on these principles.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13147944/s1, Figure S1: photo constructed wetland July 2020, Figure S2: photo façade greening July 2020, Figure S3: photo impulse project July 2020, Figure S4: photo constructed wetland October 2020, Figure S5: photo greening on scaffolding October 2020, Figure S6: photo façade greening October 2020, Figure S7: photo container frames October 2020, Figure S8: photo impulse project October 2020, Figure S9: design variants v 1–5, Figure S10: design variants v 6, Figure S11:

design variant v 7, Figure S12: design variant v 8, Figure S13: design variant v 9, Figure S14: design variant v 10, Figure S15: design variant v 11–12, Figure S16: design variant v 13, Figure S17: design variant v 14, Figure S18: design variant v 15, Figure S19: design variant v 16, Figure S20: detailed design container frame v 16.

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Article

Integrated Planning and Implementation of a Blue-Green Architecture Project by Applying a Design-Build Teaching Approach

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Abstract: Blue-green architecture (BGA) describes buildings and open spaces that combine nature-based and technical systems of vegetation and urban water management. This creates positive effects on the urban climate, public health, biodiversity, and water balance. In this study, a design strategy for BGA is applied and evaluated on a practical project. The project consists of an interdisciplinary course in which students of architecture and landscape architecture designed and implemented a BGA for a school garden in Munich, Germany. The students worked in an interdisciplinary planning team in which they took on different roles and responsibilities (blue/green/integration). As a result, the design was put into practice by their own hands and a nature-based system was built. The greywater from the school garden is now treated in a constructed wetland and, in combination with rainwater, feeds into a redesigned pond. Biodiversity was increased and a contribution to the environmental education of the pupils was made. The students demonstrated high learning success. Finally, the design strategy for BGA was positively evaluated using a design-based research approach and additional points were added for future applications.

Keywords: blue-green infrastructure; prototyping; nature-based solutions; landscape architecture; greywater; integrated planning; design strategy

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1. Introduction

Urbanization, continuous sealing of soils, and the impacts of climate change are global trends that require a paradigm shift in urban development and urban transformation [1]. Buildings, as well as private and public outdoor spaces, are facing high pressure to meet the resulting structural, social, and climatic requirements [2]. The increase in extreme weather events leads to a complex interaction of water surplus (caused by stronger and more frequent heavy rainfall) and summer drought [3]. The overheating of urban areas in summer is intensified by the urban heat island effect (UHI) [4]. The disadvantages of the UHI were already proven for Munich in the 1980s [5]. Therefore, climate adaptation strategies call for a change in the built environment towards more resilient systems [6]. Nature-based solutions (e.g., roof and façade greening, open water bodies, constructed wetlands) in combination with technical solutions (e.g., public water supply, underground water storage, smart irrigation systems) are particularly effective in terms of urban microclimate, stormwater management, and climate adaption [7,8]. Networks connecting these natural-based and technical solutions are called blue-green infrastructure (BGI) [9,10]. As urban climate adaptation is a highly topical issue, BGI is also of great relevance for the planning disciplines [2,11,12].

BGI connects urban vegetation and water management to a synergetic network. The concept can also be applied on a smaller scale, in which case it is referred to as 'blue-green architecture' (BGA) and focuses on one or several related buildings, the corresponding water flows and greening systems (roof, façade, garden) roughly up to the property boundary [10].

To ensure multifunctional solutions for the complex requirements of such BGI and BGA networks, the planning and design takes place in interdisciplinary teams [13,14]. The disciplines involved include architecture, landscape architecture, urban water management, and urban planning. The interaction of the planning disciplines is a particular challenge in the implementation of BGI and BGA. Due to the different objectives of the disciplines, it is almost unavoidable that conflicts of interest arise between water-related and vegetation-related planning aspects. Therefore, a well-structured planning process connects the specific objectives and fields of action of the disciplines effectively to each other. This ensures that spatial and functional solutions are developed that meet the respective disciplinary requirements [10].

This study is based on an integrated design strategy for BGA that was developed in a previous research project [14]. A BGA project (the so-called Impulse Project Stuttgart) was examined and the results in terms of the integrated design process were abstracted. To date, the design strategy for BGA has not been tested in practice and an evaluation of the applicability is missing. Here, we describe the application of the integrated design strategy in an interdisciplinary course in which students of architecture and landscape architecture designed and implemented a BGA project. The project started with the task of realizing a greywater treatment system for a school garden in Munich, Germany. Greywater is defined as slightly polluted wastewater (free of feces), which is produced, for example, when showering, washing hands, or in the kitchen [15]. The research area is located in the north of the city in an allotment settlement in the immediate vicinity of a huge park, the English Garden. The garden plot has a special situation in terms of building law, resulting in the fact that there is a drinking water connection, but no sewage system.

The planning task was taken as an opportunity to apply the design strategy for BGA in practice. The application in the context of a university course gives the opportunity to provide students with the competence to manage and realize integrated planning processes that focus on the interaction of water and vegetation in the field of buildings and landscape. This research-based teaching approach follows the structure of the prescribed design strategy for BGA and serves as the methodological framework of the presented study. This results in three aims for this study: (1) The design and implementation of a blue-green architecture (built result). (2) A learning outcome for the students in terms of blue-green integrated planning. (3) Evaluation of the design strategy for strengths and weaknesses. The lessons learned were in turn incorporated into the further development of the design strategy for BGA (Figure 1).

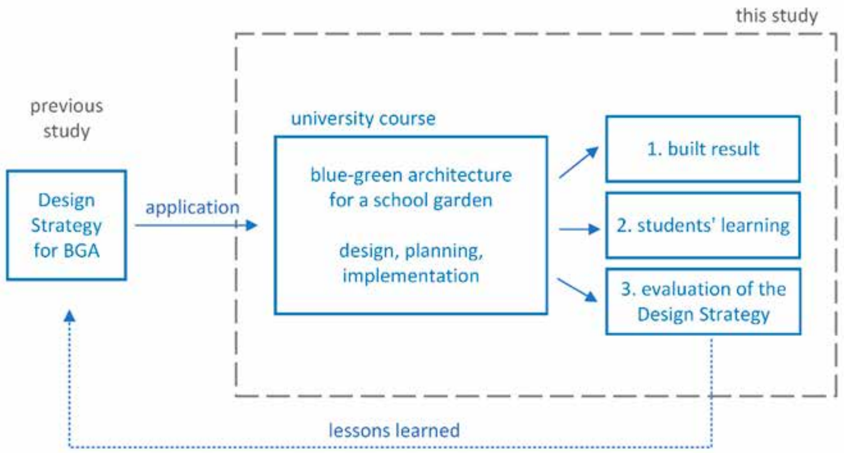

Figure 1. Design of the presented study.

The underlying planning task of is this study was a suitable case for an application and validation. The school garden for which the nature-based greywater treatment system was to be developed is used for teaching purposes and has a school kitchen in the classroom hut with a drinking water connection. However, there is no connection to the public sewage system, which is why the kitchen wastewater has to remain on the property. The teacher responsible for the school garden initiated the project with the aim of creating a natural system for water treatment, e.g., green wall, constructed wetland, or green roof (cf. [16]).

In this study, we focus on the following research questions that relate to the objectives according to the numbering:

1. Can the design strategy for BGA be used to create a functional and aesthetic system that meets the users' requirements?
2. Do the students experience a learning success through the research-based and practical teaching method?
3. What conclusions can be drawn from the design and planning process to improve the design strategy for BGA?

2. Methods

The study is based on a combination of several methods, which are described in more detail below. The design and planning process was based on the design strategy for BGA (Section 2.1.). The course followed a research-based and practical teaching method, also known as design-build (Section 2.2). Starting with the design, through the implementation to the evaluation of the applied design strategy, the overall research method can be described as design-based research (DBR). DBR is one in which the design serves to solve complex problems [17,18]. Reimann (2011) [19] describes the methodology and its characteristics, as well as its application in education:

> "In order to establish the claim that certain aspects of a design are necessary to bring about learning, and are not only contingent, one may employ the logic of control-group designs. However, DBR is conducted in real educational settings where this is hardly practically possible. Instead, DBR invokes the logic of process-oriented explanations. In the process approach, the phenomenon under study is not phrased in terms of variables and their relations, but in terms of events and their order. Researchers are not primarily looking at how quantitative attributes co-vary or change their value over time, but study the event sequence directly, and the 'forces' that move the sequence forward." [19]

There are numerous examples of such an design-build approach, especially in architectural teaching [20,21]. Through the scientific evaluation and systematic analysis of the gained knowledge, "Practice-based Design Research" is conducted, which is particularly useful in the design disciplines [22].

2.1. Design Strategy for Blue-Green Architecture

The aim of integrated blue-green planning is to consider water-related (blue) and vegetation-related (green) aspects right from the beginning of the design process and to integrate them in the decision-making process. This two-sided approach intends to ensure that synergies are created in terms of environmental, social, and spatial impacts (e.g., microclimate, heavy rainfall prevention, water management) [10]. Various blue-green integrated projects have already been implemented [23]. Examples are the Bishan-Ang Mo Kio Park in Singapore or the Uptown Water Circle in Normal, Illinois, US [24,25]. Systematic design approaches that balance water demand and water availability are not documented. For this purpose, a design strategy for BGA was developed in a previous study (Figure 2) [14]. The design strategy is applied exemplarily in this study for the planning, design, and implementation of a BGA.

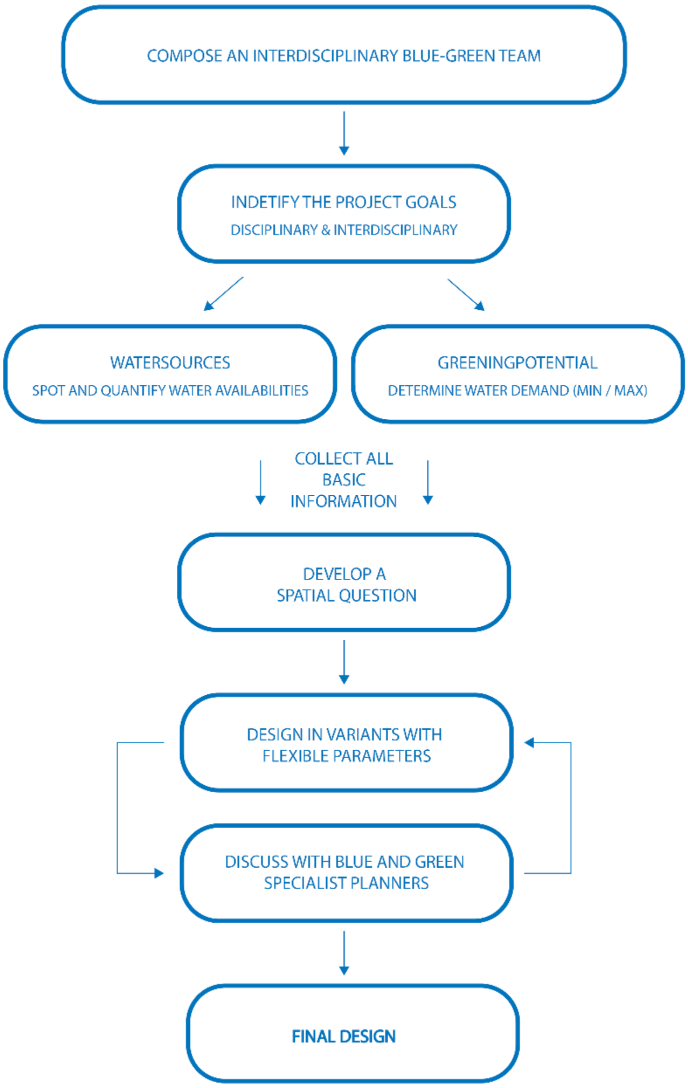

Figure 2. Integrated design strategy for blue-green architecture [14]. The integrated planning approach has been developed in a previous design-based research project. The different steps are described in detail in the indicated reference. The design strategy for BGA is applied for the first time in this study. The design process for the BGA project is guided by this approach in order to achieve a balanced weighting of blue and green aspects.

The design strategy is a guideline for interdisciplinary planning teams and describes specific steps from the goal setting of the intended project to the final design. The planning process for the blue-green architecture in the school garden is based on the described steps and will also be evaluated on the basis of these guidelines (Figure 2).

2.2. Research-Based and Practical Teaching Approach

The design and implementation of the BGA project was part of a university course that followed a research-based teaching approach. This approach creates a high level of interaction between research and teaching, resulting in high synergies for both fields. The sustainable development of design projects plays an increasing role in the professional practice of architects and landscape architects. Therefore, students should already be prepared for this in lectures [26,27]. Design projects are an integral part of teaching in architecture and landscape architecture [28]. The students develop designs that usually address spatial issues in a very concrete and realistic way [29]. The constant revision and further development of the architectural and landscape architectural plans in consultation with the lecturers leads to a steadily growing understanding of problems and solutions [30]. 1:1 projects, which involve the implementation of one's own planning, are still underrepresented [20,31]. For students of architecture and landscape architecture, it is particularly important to have application-oriented courses during their university studies [32,33]. The direct transfer into practical implementation deepens what has been learned through physical experience. Furthermore, students receive feedback on the practicability of their design and have the chance to correct any incorrect assumptions they may have been made during the planning phase [27]. Interdisciplinary courses that teach a holistic approach of sustainable architecture and that are closely related to current research therefore have high learning outcomes [26]. In the best case, there is a close exchange between research and teaching and mutual enrichment takes place [34].

The course reported in this paper was entitled "Prototyping blue-green systems" and was open to students of landscape architecture (M.A.) and architecture (B.A.). The seminar was held in the summer semester of 2021 and covered a period of 16 weeks. It was structured in three phases. The first part provided the necessary basics. It included a theoretical introduction to blue-green systems and integrated planning, as well as a site visit to the school garden. Within four weeks, a design was developed, which then moved into phase two, the prototyping. In this phase, the focus was on the detailed planning of individual elements and the prefabrication of some components. The third part of the course was the implementation on site. Over six construction days, the design was realised by the participants' own hands supported by the pupils of the school. The students wrote protocols of the construction process in which they recorded their own insights into the design and implementation process. The three phases of the course were accompanied by supervision and consultations of the lecturer. Additionally, interim presentations and meetings were held with the school teacher who represented the client.

3. Design and Implementation

3.1. Planning and Design

The structure of the integrated planning was conducted step by step according to the described design strategy (Figure 2). The planning and design process was documented with recordings of the meetings and protocols. It is described in detail below to make the decision-making process comprehensible.

3.1.1. Composition of the Planning Team

Eight students who had registered for the course formed the planning team. Since the students had backgrounds in architecture and landscape architecture, the role of water specialist planning had to be assigned internally. Table 1 shows the division of the students into three groups (blue/integration/green) and the corresponding responsibilities.

Table 1. Students were divided into three interdisciplinary groups. The three groups are shown here in their composition (LA = landscape architecture, A = architecture) and the responsibilities in the overall planning team. The division was specified by the lecturer in order to provide the students with an orientation for their tasks.

Blue Group	Integration Group	Green Group
1: LA student 2: LA student 3: A student	1: LA student 2: A student	1: LA student 2: LA student 3: A student
water sources water qualities and quantities water storages water treatment	conceptualization communication consistent design costs	green design water needs irrigation plant selection

The groups worked on their topics independently and met regularly to exchange their results. This division enabled an equal weighting of the topics and issues resulting from the subject-specific blue-green challenges. The integration group merged the findings and was responsible for the spatial concept, a consistent design, and compliance with the cost framework.

3.1.2. Identification of Framework Conditions and Project Goals

The framework conditions were determined during a site visit. The students prepared the visit to the school garden together in one group and collected questions addressed to the responsible teacher. On site, it turned out relatively quickly that the system would be built in close spatial proximity to the classroom hut with the kitchen and thus also to the grey water source. Therefore, the hut and its surrounding area were surveyed (Figure 3). This identification of a suitable building site had a significant influence on the further work of all groups, because the functional considerations could be put into a spatial relation.

Figure 3. All three groups survey the construction site near the classroom hut during the first site visit.

Later, the students divided into their three groups to collect the framework conditions separately according to responsibilities. The following three subchapters describing the framework conditions are therefore results that were obtained in parallel. In this case, the listing starts with the integration group to give an overview of the planning task and then continues with the blue and green aspects. In some cases, there were overlaps in the subjects of the groups, which were coordinated in bilateral discussions. The interfaces are named in the text.

Integration Group: Definition of Planning Task and Project Goals

The role of the integrating group was to bring all the different demands together and to create a unified concept. The students interviewed the responsible teacher to obtain a detailed profile of the requirements for the project. It was already known from the initial planning preparations that the central task would be to create a nature-based greywater treatment system for the kitchen wastewater. The specifications for the system were defined more precisely during the consultation with the responsible teacher:

- The garden is a utility garden whose cultivation is integrated into classes. The entire landscaping of the ground takes place in cooperation with the children. Maintenance and care tasks include new planting, watering, pruning, and grafting of fruit trees. In addition, there are individual projects such as the construction of insect hotels, beehives, and small huts, e.g., for observing bird broods.

- The pupils also cultivate potatoes and grow cereals. They process the grain by hand into flour, which they use to bake bread in the kitchen.
- Not all areas need to be irrigated. If necessary, water is taken from wells by hand with watering cans. The wells provide sufficient water. There is no shortage even during drought.
- The main time of use of the kitchen sink is at lunchtime, when cooking takes place in the hut. The greywater therefore contains fats, small amounts of food residues, and organic soaps. Up to now, the greywater has been collected in buckets and left to drain unfiltered on the property. The use of the garden will increase in the coming year, as in addition to the school lessons (April–November), an after-school group will be present in the afternoon all year round. Therefore, the current greywater disposal is not a sustainable solution and a nature-based treatment is desired.
- The rainwater from the roof surfaces drips from the gutters into catch stones and runs from there into two pond basins. Much of it seeps away on its way. The water is not taken out of the basins. It evaporates or infiltrates.
- There are several ponds on the site. The small pond south of the hut is hardly looked after (Figure 4). Once a year, the leaves are removed and in spring water is replenished from the well. It serves as a spawning ground for grass frogs. During longer dry periods, the water level decreases significantly, which has an unfavorable effect on the frog population.
- The planned greywater treatment should be as low-maintenance as possible and not cause high running costs. A long lifetime would be welcome.
- In connection with the creation of a disposal solution for the greywater from the kitchen, another washbasin is planned to be installed. This will be available outdoors as a basin for washing hands.
- The total costs for the project are limited to € 4500. These are exclusively material costs. The work is carried out by pupils and students.

Figure 4. The pond in close proximity to the hut has not been well maintained so far. The area to the left of the entrance was identified as a suitable building site.

These remarks, together with the survey of the planning area and a photo documentation of the site, were available to all three groups as a basis for their work.

Blue Group: Water Situation on Site and Quantity Determination for Water Treatment

Building on the integrated design strategy described in Figure 2, the blue group started by recording the overall water situation on site and quantification of water availabilities.

The focus was on two main sources, rainwater (run-off from the roof of the classroom hut) and greywater from the kitchen sink in the hut's kitchen together with the greywater from the planned outdoor washbasin (cf. 3.2.1). A third source of water on the property would be groundwater, but this is not included in the considerations in order to leave the resource worth protecting untouched as far as possible.

Since no fresh water is used for irrigation and the withdrawal for cooking can be neglected, the amount of greywater produced is roughly equivalent to the overall fresh water consumption. The amount of fresh water used in the kitchen could be estimated from the consumption data of the tap water supply and the teacher's report. In recent years, the consumption has been between 6000 and 8000 L per year. Due to the intensified use of the garden (see 4.2.1), it is assumed that an additional 3000 L of water will be consumed throughout the year. Therefore, in the future a grey water volume of roughly 10,000 L per year can be assumed.

No lessons (and no after-school care) take place on weekends and school holidays which means that the kitchen is not used. Thus, the distribution of water consumption and the generation of greywater is not equal throughout the year.

In addition, the garden is only attended to a reduced extent from the beginning of December to the end of March. No horticulture lessons take place during this time, but the after-school care is present from lunchtime onwards. Therefore, the greywater volume is not distributed equally over the school days, but is reduced accordingly in the winter months (Table 2).

Table 2. Distribution of greywater volume over twelve months relative to school days and usage pattern.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
school days/month *	18	17	19	13	17	15	21	0	14	19	19	16
greywater in l/month	287	271	303	979	1280	1129	1581	0	1054	1430	1430	255
greywater in l/school day	16	16	16	75	75	75	75	0	75	75	75	16

* on the basis of a monthly average from 2012 to 2022.

The calculation of the greywater volume is based on the following premises:

- Water consumption horticultural classes (according to previous consumption data) April–November: 7000 L;
- Water consumption after-school care (estimated) January–December: 3000 L;
- The distribution of the total consumption (10,000 L) corresponds to 37% for the months December–March and 63% for the months April–November.

The distribution of greywater volume shows that especially during the summer holidays, very little to no greywater is produced. Generally, greywater is classified as a continuous supply compared to other water resources such as rainwater. Due to the fluctuations in the use of the garden, we have a special case here. The school wishes to have a nature-based system for greywater treatment. In order to ensure functionality, long dry phases are to be avoided. The additional feed of rainwater is therefore being considered. Furthermore, the additional flushing with rainwater (less polluted than greywater) has the benefit of diluting the greywater and reducing the contaminant loading in the substrate. The roof area close to the greywater source was considered for supply to the greywater treatment system (Figure 5).

The quantities of the available rainwater were calculated using average monthly weather data for Munich [35]. The monthly values were multiplied by the surface of the roof area (23.3 m^2). For rainwater runoff, the coefficient of discharge 1.0 was applied, as the water accumulation in the event of heavy rainfall is considered to most relevant [36]. Together with the generated greywater, this results in the average total monthly water volumes (Table 3).

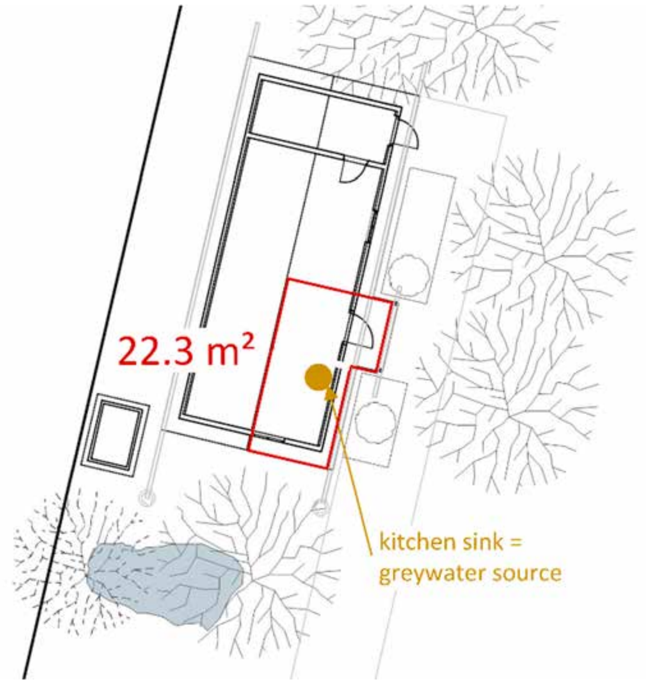

Figure 5. The roof area of 22.3 m^2 close to the greywater source was considered for rainwater harvesting. The rainwater gutters would have to be connected to the system individually.

Table 3. Monthly total water volume from the roof drainage above the kitchen and the greywater from the kitchen and outdoor washbasin. Since the weather data are average values, there can be significant fluctuations from year to year which are not represented here.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
precipitation in l/m^2/month	67	57	75	73	110	109	110	100	86	71	69	73
roof drainage in l/month	1561	1328	1748	1701	2563	2540	2563	2330	2004	1654	1608	1701
greywater in l/month *	287	271	303	979	1280	1129	1581	0	1054	1430	1430	255
water inflow filter/month	1848	1599	2051	2680	3843	3669	4144	2330	3058	3084	3038	1956

* According to Table 2.

The results of the water volume calculation are shown graphically in Figure 6. The water volumes of rainwater and greywater are summarized. From the proportion of the two values, it can be seen that on a monthly average there is a clear dilution of the more polluted greywater by the less polluted rainwater. This reduces the surface load on the filtration bed.

The values of rainwater and greywater were analyzed for their suitability for a nature-based greywater treatment in form of a constructed wetland. The area to the left of the entrance to the classroom hut was identified as a suitable position (through interfacing with other groups). The proximity to the kitchen sink and the existing pond as natural storage presented an advantage in that no long distances had to be bridged with pipes. As the availability of rainwater is subject to high fluctuations, a storage tank should be provided that can be available for additional water supply for the constructed wetland during dry periods. Additionally, during heavy rainfall, a lot of precipitation could be retained. This storage should be placed between the downpipes of the roof and the filtration bed.

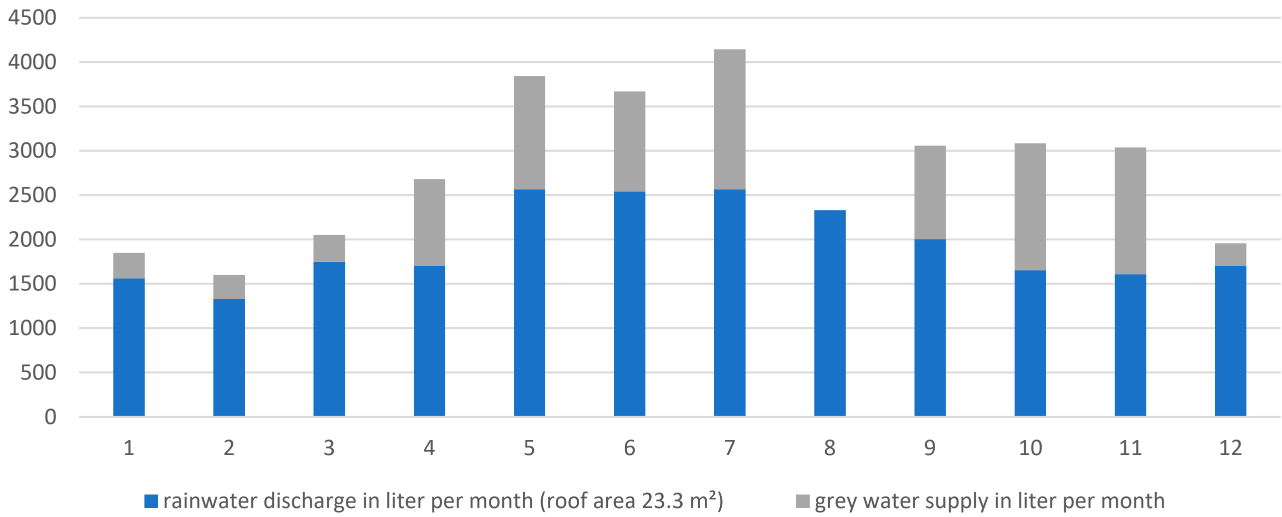

Figure 6. Average monthly water volume from the roof drainage above the kitchen (rainwater) and greywater from kitchen sink and outdoor washbasin.

Since no nature-based greywater treatment on a similar small scale is known, the capacity of the system was estimated. Data from the Impulse Project in Stuttgart, Germany, and from constructed wetland roofs served as comparative values [37,38]. The parameters relevant for the treatment are different in several points in the Impulse Project. These include the nature of the greywater (kitchen vs. showers) and the depth of the filtration bed. The planting of the constructed wetland (interface with green group) also has an effect on treatment performance.

In the Impulse Project, approximately 400 L of greywater from showers and hand basins are distributed daily over 5 m^2 of filtration bed. The filtration bed has a depth of around one meter (except for the loading equipment on top and insulation underneath). This results in a monthly surface load of 2400 L/m^2.

For the filtration bed in this project, an area of 2.0 m^2 and a height of 50 cm are used as initial guide values. For a plant in these dimensions, a monthly maximum loading is assumed to be 4000 L. This results in a surface load of 2000 L/m^2, but from greywater and rainwater (less pollution). In most months, the value is significantly lower, from which it is concluded that the filter performance of the constructed wetland in the envisaged size and under the described conditions should be sufficient.

Green Group: Existing Vegetation and Greening Potential

The tasks of the green group consisted of recording the existing vegetation and a potential need for irrigation. This analysis makes it possible to improve the situation on the ground by creating unused synergies for water availability. In a further step, potentials for additional greening were identified and ideas for design were mapped. The group started with a survey of the garden's vegetation. They focused on the area around the classroom hut and collected their observations: overall, the property has a very high degree of greenery and the soil is almost completely unsealed. The woody plants are predominantly native species and in good, well-maintained condition. The tree population causes a high degree of shading, especially in the area of the classroom hut. For documentation, the students made an inventory of the vegetation. The existing woody plants are shown in Figure 7. Due to the soil conditions (largely unsealed soil with 40 cm topsoil, gravel below) and the groundwater level (1.5 to 1.8 m), the (deeper-rooted) woody plants in particular are well supplied with water (as determined in interfacing with the blue group).

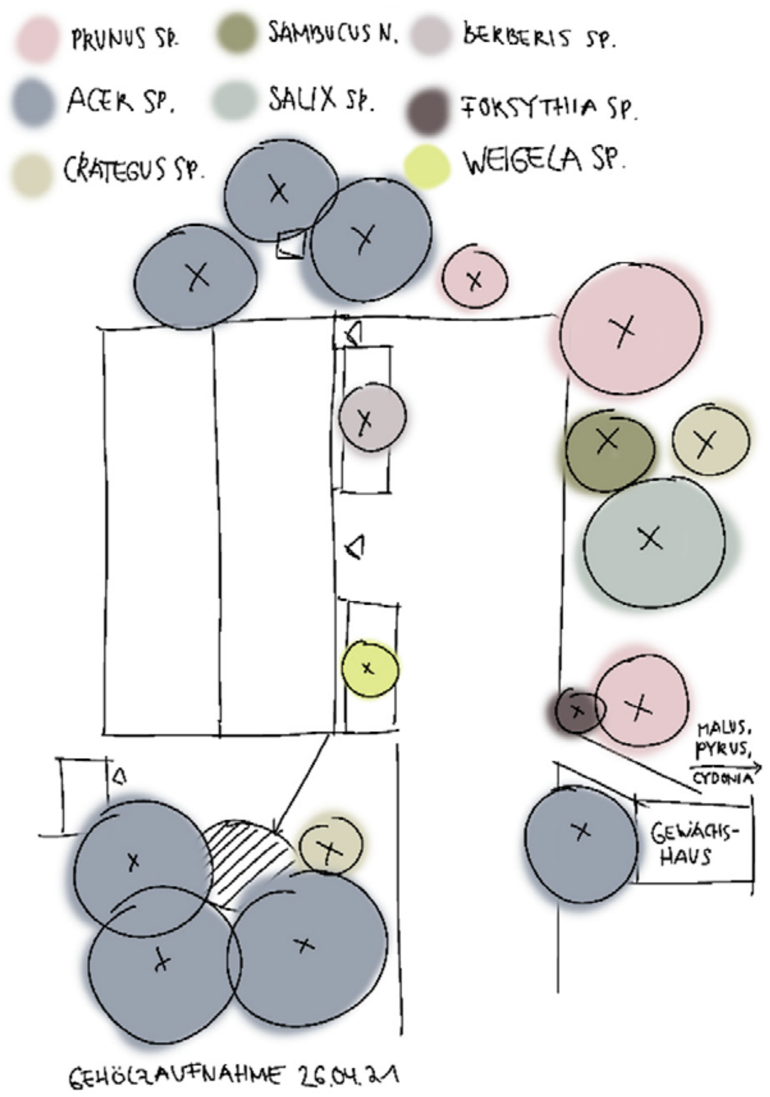

Figure 7. Students' documentation of tree population in proximity to the planning area. The sketch is not north-oriented.

The students of the green group collected their impressions and considerations on a digital white board and gathered all ideas for landscape design there (Figure 8). The whole garden is larger than shown in Figures 7 and 8. To the east of the classroom hut are the fields and greenhouses that are cultivated during lessons. The design of the garden is closely linked to its use. The green group set itself the goal of fitting future measures into the existing structure and of integrating selective enhancements. Potentials for additional greening are derived from the observations on site. In order to give the pupils even more experience of nature and to bring them into contact with different greening concepts, strengthening biodiversity and creating vertical greening were defined as specific objectives. These two aspects were to be incorporated into the planned BGA.

The group conducted extensive research on the topic of marsh plants for greywater treatment [38–43]. The planting of greywater filters mostly focuses on reed rhizomes. The ability of reeds to release oxygen into water and soil enhances the microbial decomposition of organic matter [43]. However, there are other plants that can be used which have a positive influence on the appearance and biodiversity through flowering species (Table 4).

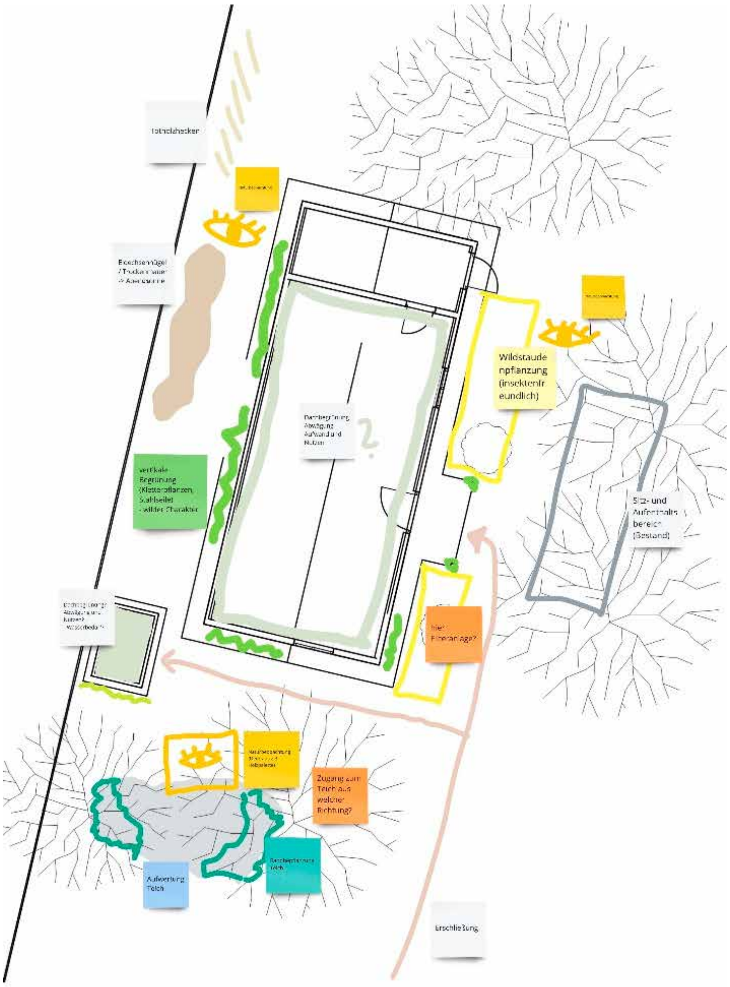

Figure 8. Snapshot of the students' white board while mapping the greening potentials and further ideas to improve quality of experience.

Table 4. List of potentially suitable native marsh plants for greywater treatment as compiled by the green group.

	Habitat	Growth Height	Filtration Effect	Hydrologic Balance	Specific Characteristics	Planting Distance
Schoenoplectus lacustris	humus- and nutrient-rich muddy soil; sunny to semi-shady	80–300 cm	available	average daily ET * = 6.9 mm; water depth from 10–80 cm	suitable neighbours include Iris pseudacorus or Phragmites australis	60 cm planting distance, 2 to 4 pieces per m^2
Phragmites australis	permanently moist to wet, fresh to marshy soil; sunny to semi-shady	150–400 cm	available	average daily ET * = 7.8–9.2 mm; water depth from 10–40cm	autumn colouring	35 cm planting distance, 8 to 10 pieces per m^2
Carex acutiformis	wet soils with high humus and nutrient content; sunny to semi-shady	50–120 cm	available; performance comparable to reed	high water requirement; ET * rate in medium range compared to other species; water depth 0–20 cm	reposition plants; highly adaptable to different types of wastewater	50 cm planting distance
Juncus effusus	nutrient-rich moist to wet soils, low in lime; sunny to semi-shady	70–80 cm	available	up to 10 cm water depth with no problems	evergreen tussocks with long stolons	

Table 4. *Cont.*

	Habitat	Growth Height	Filtration Effect	Hydrologic Balance	Specific Characteristics	Planting Distance
Lythrum salicaria	moist soil flooded by water; sunny to semi-shady	60–80 cm	available	waterside up to 30 cm water depth	insect feed; pink–purple flowers July to September	4 pieces per m^2
Mentha aquatica	moist to muddy soils; sunny to semi-shady	40–60 cm	high nitrogen consumption rate; antiseptic	waterside up to 30 cm water depth	insect feed; pink–purple blooms in June; typical minty smell	35 cm planting distance, 8 to 10 pieces per m^2

* ET = evapotranspiration.

3.1.3. Development of Spatial Question and Adjustment of Project Goals

In the sense of BGA, the framework conditions were analyzed in terms of water availability and water demand [10]. The blue and green group first defined their subject-specific objectives and then incorporated them into the overall planning. This approach ensured that all requirements, from both the blue and green sides, were addressed. Table 5 shows the objectives of the blue and green group.

Table 5. After recording the framework conditions, the groups defined subject-specific objectives. These refer to the conditions on site and the planning task set. The blue and green objectives formed the basis for the spatial question.

Blue Group	Green Group
treatment of greywater for discharge into the small pond	preservation of the 'overgrown' character of the site
year-round operational	selective design enhancement (waterfront planting for the pond, flowerbeds at the entrance, vertical greening)
electricity-free design (gravity driven water flow)	enriching biodiversity
no use of chemicals for water purification	establishing a stable and self-sustaining vegetation
prevention of freezing in winter	environmental education, experience/observation of nature

The greywater on the site requires treatment and is also a resource that has not yet been used. The water demand for the vegetation in the garden is basically covered, but there is still potential for improvement. The fields are irrigated with groundwater, which is in principle a resource worth protecting [44]. A simple infiltration of the greywater would have contributed to groundwater recharge, but it would have remained a 'blue' solution without synergy with the 'green' side. The pond, which functions as an ecosystem for tree frogs, also needs to be refilled with groundwater annually. Here, potential synergies with the generated greywater were identified: The greywater can be fed into the pond in treated form, thus ensuring that the water level remains constant throughout the year which allows for biodiversity enrichment (flora and fauna) as well as more chances for nature observation by the pupils. This resulting synergy of 'blue' and 'green' improvements became the common objective and thus also the central feature of the BGA design.

The integrating group took up these blue and green objectives and formulated additional requirements for the BGA design, which also have an impact on the spatial question. The system should be built in such a way that it results in a practical division of space in which the walkways are not disturbed. It should be a safe system. Children are protected from direct contact with untreated sewage. Likewise, sensitive parts of the system will be protected from the children. The entire system will be designed to be durable, cost-effective and easy to maintain. It needs to work all year round and therefore also be protected from frost. Maintenance must be easy. Therefore, inexpensive, easily purchasable and replaceable parts are used. Everything should be comprehensible and understandable for the children. In this way, the system serves environmental education. The important parts and connections are exposed and visible. This makes the 'path of the water' recognizable (using no underground pipes). Everything should be aesthetically designed so that it fits the informal and rural character of the place. The design will adapt to the place. No 'technical monstrosity' will be created. The objectives created huge interfaces between the groups. Therefore, the first draft was created in a collaborative effort of the whole planning team.

3.1.4. Design

Based on the objectives developed by the groups and the overall team, a first design proposal for the construction area was developed (Figure 9). At this point, many technical and design details were still unresolved. An initial site plan shows the intended interventions. The initial plans were to enlarge and redesign the existing pond and flatten the shore zone to create a vegetated swamp area that provides a spawning site for grass frogs. Strengthening the pond would create a habitat for frogs, newts, and dragonflies. It serves as a watering place for birds, bees and other insects. The pond is intended to be a quiet place that differs from the hustle and bustle around the hut. Therefore, the design concept of the pond planting creates zones and serves as a shield towards the hut. To the south, on the other hand, the greenery is placed in such a way that the children have access to the water. An observation place with seating (e.g., with an old tree stump) will be set up.

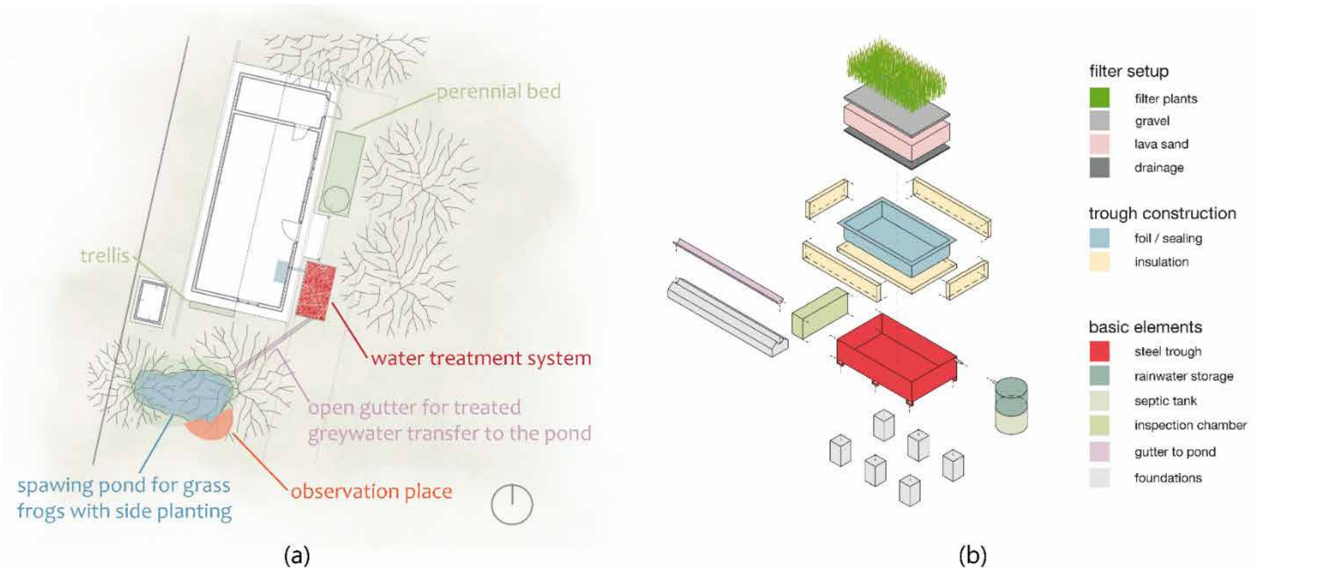

Figure 9. Preliminary design proposal of the students. (**a**) The single components were defined and brought into a spatial context. (**b**) The students' axonometry shows the design of the filtration bed. The structure is based on other small greywater treatment plants (examples for comparable structures: [37,41,45]).

The perennial bed to the right of the entrance of the hut will be replanted. Plants that are currently in the bed on the left and have to give way there because of the water treatment will be moved here. The small tree will also be preserved and given a new location in the garden. This measure also strengthens biodiversity. Flowering species such as great masterwort, lady's mantle, and wood strawberry are nectar sources for bees. A trellis for climbing plants at the hut should complete the design as a vertical element.

The central element of the greywater treatment system is a steel trough. Different variants were considered: the reuse of an old oil tank, plastic basins, and custom-built infrastructure. A steel tank measuring 210 × 130 × 55 cm (length/width/height) turned out to be the most cost-effective and, at the same time, aesthetically pleasing solution and the most suitable for the application. This trough would contain the constructed wetland. With regard to the structure, substrate, insulation, and loading, the knowledge about small, mobile constructed wetlands gained from the Impulse Project in Stuttgart provided a valuable planning guide [37]. Structures of other similar plants were also used for comparison [37,41,42].

The identification of the suitable trough and the construction of the greywater treatment was carried out in cooperation between the integrating and blue groups. Since the constructed wetland would have a considerable weight, point foundations were planned. Six centimters of insulation on the inside of the trough would prevent freezing in winter to keep the microorganisms alive during the cold season. Lava sand was chosen as a filter substrate. The green group's planting plan was to be followed by using flowering and filtering marsh plants.

For the blue group, it became a challenge to develop the system in such a way that the height between the sink drain and the upper edge of the pond water would be used as effectively as possible. In total, only about 70 cm of height was at disposal, of which the main part (about 45 cm) should be available for the filtration bed. The deeper the filter structure, the better the cleaning performance. Therefore, only about 25 cm of height difference remained for connecting pipes, pre-cleaning, filter loading, and water transfer to the pond.

The exact loading technique had not yet been determined. The plan was to create a septic tank for mechanical pre-cleaning and to flush the greywater onto the filtration bed at intervals in order to achieve distribution over the entire surface. A tilting mechanism was envisaged for this purpose. An inspection chamber was foreseen in the area of the filter outlet. All groups provided rough cost estimations for the building material in order to determine whether the entire system would remain within the set framework of € 4500.

At this stage, the concept was presented to the teacher (who acted as the client) to obtain approval for all suggestions and the planned interventions on site. The feedback was positive on all points and therefore the planning could go into the next round.

3.1.5. Revision, Adaption, and Final Design

In further planning, technical details were solved. The groups worked separately in many parts and discussed the problems at the interfaces in regular meetings. The blue group planned a timber framework that would support the septic tank and the rainwater storage. The septic tank consists of three chambers: a sieve filters the coarse solids out of the wastewater. The second and third chambers are arranged in such a way that mechanical grease separation occurs. The tilting mechanism for loading the filtration bed was not implemented as planned. Initial experiments showed that an even distribution of the greywater on the substrate became possible also without interval loading. A simplification of the construction was preferred here to make the system more robust also against playing children. The inspection shaft could be omitted as well. The backwater it would create in the constructed wetland would have no advantages for the design. The timber frame and the corresponding components were prefabricated in the workshop (Figure 10) and later brought to the construction site.

The filtration bed was slightly modified after consultation with specialist planners from the water industry. In order to maximize filtration depth, the insulation on the underside is placed between the trough and soil rather than inside the trough. It is wrapped with wire to keep rodents out. The side insulation remains in the trough. It is sealed with foil. The drainage layer consists of 15 cm of gravel. The lava sand is placed on top and no more gravel layer is placed above it.

An important point was to ensure year-round operation. Therefore, it was planned to remove the septic tank in winter. Otherwise, it could freeze and burst. Since the use of the garden is limited in the winter half-year and no cooking occurs during this time, the greywater is also less polluted. Therefore, there are no solids and the septic tank is not needed. It can be removed and the greywater can feed directly into the filtration bed. An occasional inflow of water from hand washing would also be very beneficial for the filtration bed in winter to prevent freezing through.

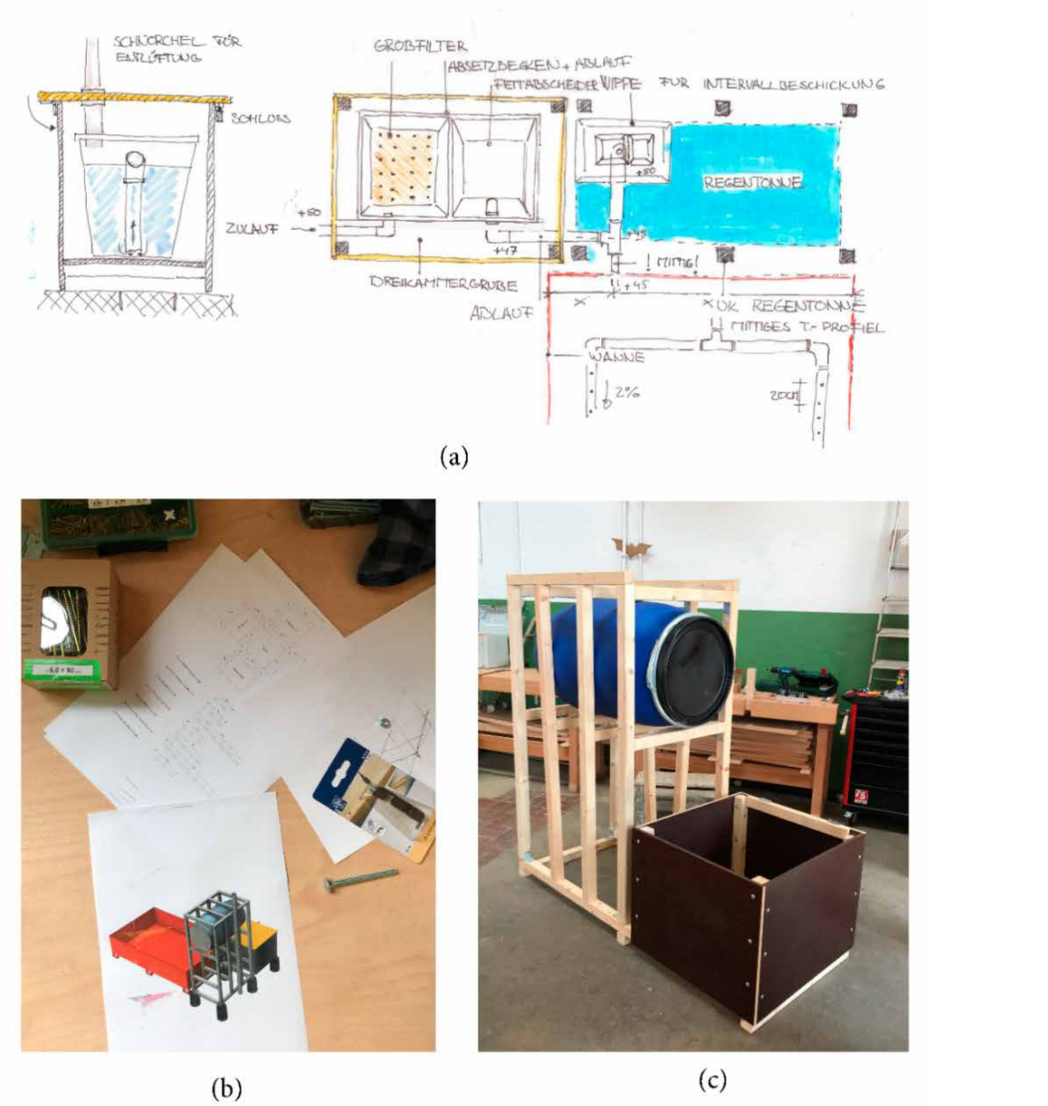

Figure 10. Documentation of the development of technical components for the BGA project. (**a**) Considerations for septic tank design and filter loading. These students' sketches do not show the final design, but an intermediate step in the planning. (**b**) Based on CAD drawings and 3D models, the assembly of the components was prepared. (**c**) The timber framework is pre-fabricated in the workshop.

The integrating group developed a consistent design concept for the greywater treatment plant. The components were differentiated by color: In addition to the blue rainwater tank and red steel trough, the septic tank was painted yellow. This made each functional element recognizable as belonging together and made it playfully understandable for the children. The planning of the gutter between the constructed wetland and the pond turned out to be difficult. Suitable stones for an open channel were not commercially available. Deeper channels had the disadvantage that they could become a tripping hazard. Therefore, covering the channel with a grid in order to make the walkway trip-free was considered. Finally, a suitable solution emerged: with appropriate molded shells, suitable (relatively flat) trough stones could be cast in concrete on one's own. This way, the water remained on the surface and the children could see how the gutter fills up with water after washing the dishes.

The green group developed planting concepts for the filtration bed, the pond, and the perennial bed. According to the previously compiled list and the required planting distances, they chose *Phragmites australis*, *Mentha aquatica,* and *Lythrum salicaria* for the constructed wetland. For the marsh zone of the pond, the species selected were *Caltha palustris*, *Primula rosea, Lythrum salicaria, Mentha aquatica*, and *Juncus effusus*. The plant selection for the perennial wildflower bed included *Astrantia major*, *Alchemilla mollis*, *Galium odoratum*, and *Fragaria vesca*. The green group revised their overall concept insofar as the climbing vegetation (*Clematis*) was no longer placed on the wall of the hut, but directly on the wooden construction around the rainwater barrel and septic tank. This created a synergy of technical construction and vertical greening.

The final design is shown in Figure 11.

Figure 11. Final design of the blue-green greywater treatment system. The greywater from the kitchen sink (not shown in the picture) and the outdoor sink (on the right) is pre-cleaned in the septic tank (yellow). The roof runoff flows via the rainwater storage tank (blue) to the filtration bed and is fed directly in case of heavy rainfall. The timber frame that supports the septic tank and the rainwater storage tank is overgrown with climbers. The insulated filtration bed is filled with lava sand and grown with flowering marsh plants. The treated water is directed to the frog pond via an open gutter. The pond is planted in the shore area and has a nature observation place for the pupils.

With these changes and improvements in the design, the construction work on the site could begin. During the design process and the revisions and adjustments of the detailed planning, the costs were continuously tracked. Most of the structural elements were based on simple solutions using inexpensive components. High positions were especially the steel trough, the special substrate (lava sand), timber, and concrete.

3.2. Implementation

The students realized the design in practice on their own. The intention of this practical teaching concept was to create a holistic learning experience for the students. The approach aimed to enable the students, through the implementation of their own design, to identify planning errors and to achieve a higher learning success than through pure planning and design projects. Logging and reflecting on the construction process was therefore part of the course. The school children were involved in the preliminary work for the construction site. The excavation and enlargement of the pond was already prepared when the implementation started.

The implementation began with a further survey of the construction site. The heights and slopes played a special role to ensure a powerless flow of water. A total of 12 foundations were poured, six for the filter trough and six for the timber frame that will support the rainwater storage tank and septic tank. As part of the concrete work, the swale stones were also poured and dried (Figure 12).

(a) (b)

Figure 12. (**a**) The shore zone of the pond is planted with marsh plants. (**b**) The swale stones are poured and dried on site.

The students planted the perennial bed to the right of the entrance. The pond was completely redesigned. In the shore zone, a step was modeled all around, on which the marsh plants would later be placed. A layer of fleece was laid as protection and the pond liner was laid on top. The pond was half filled with water and then filled with substrate and stones for stabilization. The students arranged the plants according to the design concept and planted them in the edge zone of the pond (Figure 12). The large concrete stone was placed to embellish the pond inlet. The sump zone was further filled with substrate and stones, then the water level was raised to the final height. For the observation site, a wooden trunk with a diameter of 70 cm and other logs were positioned as seats.

The roof gutters were adjusted. Until now, they drained in the direction of the pond. Now they should drain towards the entrance to be available there as an additional water source for the filter.

The work continued with the work on the constructed wetland. For the outlet of the steel trough, the students had to drill a hole in one wall. At the outlet, a recess was made in the insulation and the foil was fixed with a special thread to seal it. The drainage pipe was covered with fleece, connected to the outlet and the slope necessary for the water flow was controlled. The filling began with a first layer of gravel (15 cm) and the lava sand on top (Figure 13), which was heavily compacted.

The three chambers of the septic tank were prepared. A sieve and grease separator provide pre-treatment of the greywater. The filter loading and the connection of the trough to the pond had not yet been finally solved. The students tested what worked and was practicable directly on the building site. From the outlet of the tub to the concrete block marking the inlet to the pond, a straight excavation was made for the swale stones. The heights had to be very precise because the gradient was small. The swale stones were placed on a leveled sand bed and initial feeding tests showed that the slope was sufficient.

Figure 13. Construction work on the filter trough. (**a**) The drainage layer consists of 15 cm of gravel. (**b**) A layer of lava sand follows the gravel.

Towards the end of the construction work, the filtration bed was planted with the selected marsh plants. The swale stones were fixed and connected with concrete. The rainwater storage tank is conceived in such a way that it fills up completely during heavy rainfall. A valve then closes the storage tank and diverts the rainwater into an overflow that discharges into the constructed wetland. The filtration bed thus has several inlets: two narrow pipes distribute the greywater on the planting bed and a wide gutter in the middle is available for the overflowing rainwater.

Wires were stretched between the timber frame beams, which would serve as trellises. The clematis was planted directly as a climber. The final task was to connect the septic tank between the sink and the filtration bed. After everything worked properly, the plant was handed over to the school.

4. Results

4.1. Built Result and First Practical Experiences

The first of three research questions of this study was: can the design strategy for BGA be used to create a functional and aesthetic system that meets the users' requirements? As a key result, it can be concluded that the blue-green architecture that was designed and built as part of the course is a functioning system that meets the requirements of the client. The grey water produced in the kitchen of the classroom hut and by the outdoor washbasin is treated on site and fed into a natural system. The teacher of the school garden is also very satisfied with the design solution. The color differentiation of the system's components makes it easier for the pupils to understand how everything works and fits into the overall appearance of the garden (Figure 14). Consequently, the application of the design strategy to structure the planning and design process has proved to be a useful tool.

The blue-green system has been running trouble-free for about 10 months at the time of manuscript completion. The plants have grown well in the first year, but will only reach their full density and size in the coming years. The pond was swarmed by insects very quickly (Figure 15).

For winter operation, the septic tank was removed as planned and bypassed with a pipe. In this context, it must be ensured that no more solids are discharged into the system. Cleaning of the loading pipes was necessary once so far. The objectives for the built structure have thus been successfully achieved.

Figure 14. Built result of the BGA project 10 months after completion. The operation ran without any disruptions. In winter, the septic tank was bypassed. In the meantime, summer operation was resumed. The plants on the constructed wetland all survived the winter well and will grow even bigger in the next few years.

Figure 15. The pond has become a biodiverse habitat.

4.2. Students' Learning

The second research question of the study was the following: do the students experience a learning success through the research-based and practical teaching method? The course intended to teach the students integrated blue-green planning processes in interdisciplinary teams and to enable them to achieve a high level of learning success through a concrete application and 1:1 implementation. The students' construction site protocols and experience reports contained reflections on their own actions and the procedures in the planning and implementation process. The statements show that a great learning effect has been created by the chosen teaching method. Two exemplary statements from the reports (translated from German into English) are:

- "My hope that this seminar would give me the opportunity to apply my interests in planning and designing blue-green systems in an urban context and also to gain practical experience was completely fulfilled, and it was a great experience to realize, build and see a project that I had worked out myself."
- "I found it very fascinating to realize such a project as a team and to see that we all have a practical skill to implement what we are planning and that we are not pure theoreticians."

In summary, there were differences in how much students felt part of their planning group (blue/green/integration) or part of the larger team. This identification had an effect on communicative aspects. Such manners could also occur in real construction practice and influence the motivation for cooperation. Basically, it is important that all disciplines act independently and represent their (professional) interests. However, the sense of the overall project should not move too much in the background, because the key to good cooperation is compromise and not drawing boundaries.

The students repeatedly gave the feedback that they prefer practice-oriented courses in their studies because it is important to them to be well prepared for their future professional life. The close interlinking of research, teaching, and practice has a particularly positive effect on the education of architects and landscape architects and should be intensified in the future. The fields of activity of architects and landscape architects are currently separate from each other, and architecture usually dominates the design processes [46]. It is important to counteract this development and strive for more equal cooperation. Anchoring interdisciplinary projects in the curriculum is a first step in this direction.

4.3. Evaluation of the Integrated Design Strategy for Blue-Green Architecture and Lessons Learned

The third underlying research question related to the evaluation of the design strategy for BGA: what conclusions can be drawn from the design and planning process to improve the design strategy for BGA? The integrated blue-green planning and implementation process of the described project provided insights into the applicability and practicability of the design strategy for BGA. It was an important goal of this study to reflect these lessons learned back into the design strategy so that it can be revised and improved.

All in all, the design strategy for BGA was a valuable and helpful basis for structuring the planning and design process. In particular, the division of the students into groups and the representation of disciplines and responsibilities was a central support for the entire approach. The specific 'blue' and 'green' aspects were integrated into the project process from the very beginning and were thus decisive for the design and function of the BGA. The students' understanding of interdisciplinary collaboration was enhanced. Since there is potential for improvement in terms of interdisciplinarity not only at universities but also in building practice, this insight can equally be transferred to planning teams of larger projects.

The topics of water and vegetation are comparatively new and unfamiliar to architects. Therefore, they are very challenged in blue-green projects with the understanding of the framework conditions and planning parameters. Pre-structuring the planning process in the form of a design strategy is therefore an important support.

During the application, some situations occurred where the process was different from the one foreseen in the design strategy. In addition, there were points of importance in the planning that were not represented in the design strategy. These aspects are described below and serve as indicators for improving the approach.

Figure 16 shows the design strategy for BGA with suggestions for intervention points highlighted in green. This outlines the lessons learned without including a complete revision of the design strategy. In the case of a new version of the design strategy, the existing terms should also be examined and adapted if necessary. In the sense of blue-green architecture, 'water sources' and 'greening potential' should be defined more broadly in order to reflect the entire spectrum of initial situations and project concerns.

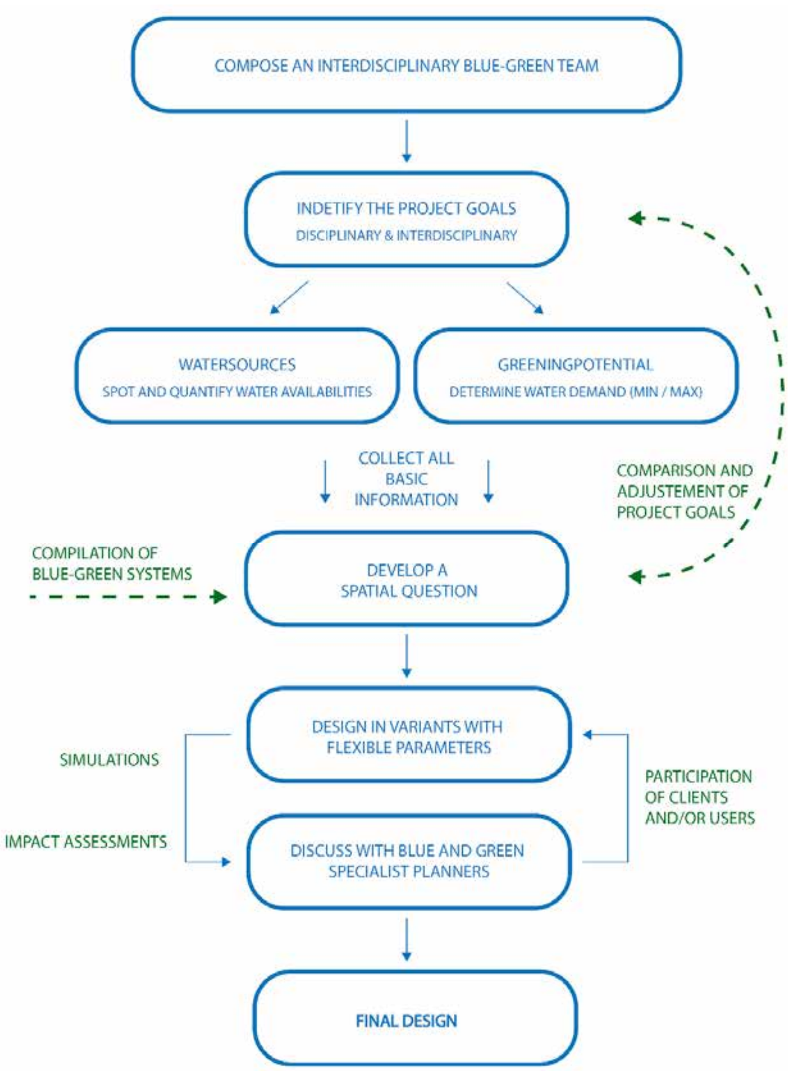

Figure 16. The design strategy for blue-green architecture was evaluated through its application in the presented project. In the course of planning and design, weaknesses emerged that should be considered in a revision. The lessons learned and considerations for possible points of intervention are shown in green.

One of the points that became apparent in the application of the design strategy is the procedure of setting project goals. Here, experience has shown that after the initial definition of project goals a further adjustment is needed once the framework conditions have been recorded. Here, it could be considered whether the definition of the spatial issue could rather consist of a design brief for the project. It could be reconciled with the objectives and these could be specified taking into account the blue-green framework (Figure 16).

When developing the spatial question, it is also helpful to be able to build on compilations of blue-green systems. In the study project, this knowledge was provided by a lecture on blue-green systems. In practice, there are very good overviews that can be of help to planners [13,44,47–49]. As already mentioned, a design brief could be made at this point, which would contain relevant parameters and specific goals for the BGA project.

In the project described above, the development of design variants did not take place as intended in the design strategy for BGA. This was mainly due to the fact that the planning time was very short and there was not enough time to do several loops. Instead, a continuous improvement of the design took place. This point will not be modified in the design strategy for BGA, but some aspects will be added that should be applied within this iteration (Figure 16). The collection of water quantities and the calculation of required storage for larger projects should be completed with the help of simulations [49,50] (pp. 56–61). In the project presented in this study, only monthly values were considered. A more comprehensive analysis of water quantities was not feasible within the scope of the course. A simulation with daily values over several years would provide information about dry periods, storage management, and occasional heavy rainfall events. Impact assessments can also take place here (cf. [51]). There are more and more digital tools on the market that support the comparison of the environmental effects of planning projects [52,53]. Another point suggested here goes back to a very positive experience from the project. The cooperation with the teacher and the pupils has proved to be very successful. The discussion with the client helped to solve challenging design issues in a constructive way. The involvement of the pupils in the implementation created a high level of acceptance and comprehension for the project. Therefore, it is suggested to make client/user participation an integral part of the iterative design process (Figure 16). A discussion of the design variants should not only take place internally in the planning team, but should also be directed outwards at certain points [54]. In this way, valuable inputs can be taken up and users' acceptance can be improved.

A key issue for the success of the project is the cooperation in the interdisciplinary team. There is a certain contradiction in the fact that the representatives of the blue and green aspects argue from their discipline-specific point of view and at the same time an integrated solution is supposed to emerge. There are points in the planning process where disciplines work separately, and other points where the planning team acts as a joint unit. Sensitive coordination is required here to ensure the appropriate weighting of perspectives. This requirement cannot be represented in the graphic. It is based on awareness and experience.

5. Discussion and Conclusions

The design, planning, and implementation of blue-green architecture presented here took place as part of a university course. This results in points for discussion with regard to the two research questions that focus on the built result and the evaluation of the design strategy for BGA. First of all, it becomes clear that this is not a planning project in the classical sense. The students represent their disciplines vicariously, similar to a role play. In practice, the cooperation of several project partners is different. For the approach based on the design strategy for BGA, the planning task and the processing by the students was nevertheless effective. The difference lies more or less in an experiment under laboratory conditions compared to a field study.

With regard to the remaining research question, which focused on the teaching, it can be stated that—in the future—it would be useful to involve students from environmental engineering and thus include water engineers in the planning team. This would possibly also have a positive effect on the learning success of the students, because they would have even more interdisciplinary exchange.

Concerning the built object, an absolute statement about functionality, resilience, user satisfaction, and aesthetics can only be made after several years. The fact that the system has been running trouble-free so far is a positive indicator. It remains to be seen whether the system will also prove itself in the future. Likewise, it would be advisable to take water samples in the pond and evaluate them in comparison to the other water bodies on the property and in the immediate vicinity.

The design strategy for BGA has proven to be target-oriented and effective in its application. Structuring and guiding blue-green planning processes is an effective way to support interdisciplinary project teams. Suggestions for improvements to the design strategy were presented in Section 4.3. There, it was also recommended to integrate digital tools into the planning process in order to obtain more precise values for dimensioning water storage tanks and water treatment plants. For the assessment of the impact of particular measures, digital tools are also a useful addition.

In the application of the design strategy, another point became apparent: the systematic combination of 'blue' and 'green' aspects does not fully cover the spectrum required for BGA. In the presented project, for example, solutions emerged that cannot be classified as blue-green. This includes the timber frame's trellis and the planting of the perennial bed. Both measures contribute to the overall concept, but are not coupled with the 'blue' side, the available water for irrigation. The system boundary of the BGA project must therefore be carefully weighed up and individually exceeded if it is conducive to the respective project.

A further application of the design strategy for BGA should now ideally take place in a larger-scale project. Such a continuation would not only support the implementation of blue-green projects, but also contribute to the further development of the design strategy against the background of different scales, contexts, and planning tasks. It can be assumed that in a practical real-life project, a field of tension will arise from additional requirements for sustainable architecture. Blue-green planning is only one aspect among many. It was the focus here because it has been underrepresented so far—especially in architectural projects. However, integrated planning also includes other sustainability aspects such as energy, mobility, and materiality. With regard to blue-green infrastructure, it is important to create larger networks that go beyond the individual property and span neighborhoods and cities. This increases the effectiveness of blue-green solutions because water needs and water availability can be coordinated on a larger scale. Networks are also more effective than individual projects in terms of biodiversity and socio-cultural impact.

Finally, even though it is a very small-scale project, this study has shown how BGA can be designed and implemented in practice. The future of livable cities depends on the adaptation of planning and building for climate change. Therefore, the knowledge gained here should be further developed and taken into account in future research, teaching, and practical projects.

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4. WEITERER FORSCHUNGSBEDARF UND AUSBLICK

Die vorgestellte Entwurfsstrategie zeigt zentrale Schritte im interdisziplinären Entwurfsprozess auf. In der Anwendung wurde ersichtlich, dass weitere Schnittstellen und Tools den Prozess unterstützen können. Zum Abschluss soll noch in Kürze auf weitere mögliche Ansatzpunkte und zukünftige Forschungsfelder eingegangen werden.

So können etwa Modellierungen dazu beitragen, verschiedene Szenarien in ihrer Wirksamkeit abzuschätzen. Dazu sind sowohl Speichermodellierungen (wie das in INTERESS-I vorgestellte ESB-Modell [58]) als auch mikroklimatische Modellierungen (beispielsweise über *ENVI-met* [106]) nutzbar. Für aussagekräftige Berechnungen ist eine enge Kooperation von Praxis und Forschung sowie die interdisziplinäre Zusammenarbeit mit weiteren ingenieurwissenschaftlichen und geografischen Fachrichtungen von Vorteil. Besonders die Modellierung hydrologischer Zusammenhänge, beispielsweise über *MIKE SHE*, kann wichtige Erkenntnisse liefern [106]. Das von dem Ingenieurbüro Ramboll entwickelte Tool *Green Scenario* vergleicht Planungsvarianten und bezieht dabei Vegetation, Wasserhaushalt, Mikroklima und Wirtschaftlichkeit mit ein [107]. Als Nachteil dieser Software ist zu nennen, dass sie sich auf den natürlichen Wasserkreislauf beschränkt und alternative Wasserressourcen unberücksichtigt lässt. Deren Erschließung ist aber ein wichtiger Bestandteil von BGA, um in Trockenphasen nicht ausschließlich auf gespeichertes Regenwasser und wertvolles Trinkwasser zur Bewässerung zurückgreifen zu müssen. Im Sinne der BGA sollten die Optionen für dezentrale Wasseraufbereitung immer mitgedacht werden – wo möglich auch naturbasiert und in die Gebäudehülle integriert [108–110].

Ein weiterer Aspekt in der Weiterentwicklung der Entwurfsstrategie für BGA ist die Kopplung mit Energiesystemen. Die im Wasser gespeicherte Wärme kann grundsätzlich durch Wärmepumpen nutzbar gemacht werden. Das sollte insbesondere in den Wintermonaten, in denen unterirdische Zisternen in der Regel gut gefüllt sind, in Betracht gezogen werden. Im Sommer kann durch gezielte Verdunstung von Niederschlagswasser Kühlenergie nutzbar gemacht werden. Dieses Prinzip kommt u. a. im Lise-Meitner-Haus in Berlin zur Anwendung [111]. Die natürliche Verdunstungskühlung durch Dach- und Fassadenbegrünung sowie die Kühlung durch Verschattung, die durch den Einsatz von Vegetation an der Fassade erreicht werden kann, sollte energetisch und wirtschaftlich gegenüber mechanischem Sonnenschutz abgewogen werden. In Bezug auf Energie ist BGA allerdings auch als Verbraucher zu berücksichtigen. Technische Aufbereitungssysteme, künstliche Bewässerung und insbesondere smarte Systeme müssen daher auf ihren Verbrauch hin überprüft und in das Gesamtenergiekonzept des Projekts einbezogen werden. Dazu gehört auch die Betrachtung über den gesamten Lebenszyklus, in welche die sogenannte graue Energie, die aus Produktion und Entsorgung resultiert, mit einfließt.

Digitale und smarte Systeme bieten darüber hinaus ein hohes Potenzial für die Effektivitätserhöhung von BGA. Wasserspeicher können größenmäßig optimiert werden, wenn sie an Wettervorhersagen gekoppelt sind. Auch der Bewässerungsbedarf von Grünelementen kann durch Sensorik und digitale Tools genauer bemessen werden. Je nach geplanter Haustechnik gilt es hier das Aufwand-Nutzen-Verhältnis

ABB. 27 + 28
Das Quartier Norra Djurgården in Stockholm ist ein Beispiel für wassersensible Gestaltung in Kopplung mit intensiver Durchgrünung am Gebäude und im Freiraum [119]. Fotos: F. Well

abzuwägen und nach Möglichkeit auch mit Low- oder No-Tech-Systemen zu arbeiten.

Auch im Sinne der Kreislaufwirtschaft bieten blau-grüne Systeme viele Schnittstellen. Die Berücksichtigung weiterer Stoffkreisläufe, wie z. B. Schwarzwassernutzung oder Müllrecycling, kann hier einen Beitrag zur Ressourceneffizienz leisten. Das Projekt ROOF WATER-FARM zeigt auf, wie die Düngergewinnung aus Schwarzwasser mit Nutzpflanzenanbau und Fischproduktion gekoppelt werden kann [112]. Bei der Konstruktion blau-grüner Systeme sollte außerdem auf ressourcenschonende und kreislauffähige Bauweisen geachtet werden. Ein veränderter Umgang mit Abfallstoffen in allen Lebensphasen eines Gebäudes ist wesentlich für zukunftsfähige Städte.

Zuletzt soll noch die Einbeziehung sozialer Aspekte in die Planung von BGA erwähnt werden. BGA kann einen positiven Beitrag zum gesellschaftlichen Miteinander leisten, indem klimawandelangepasste und lebenswerte Räume geschaffen werden. Beteiligungsprozesse können ein wirksames Mittel sein, um die Akzeptanz in der Bevölkerung zu erhöhen und Bewusstsein für die Chancen und Herausforderungen zu schaffen, die in einer veränderten Bauweise liegen [113]. Diese Beteiligung sollte unabhängig vom sozioökonomischen Status stattfinden [114]. Darüber hinaus gilt es im Blick zu behalten, dass der Zugang zu lebenswerten und klimawandelangepassten Räumen kein Luxusgut ist, sondern allen Menschen gleichermaßen zur Verfügung stehen sollte. Daher muss auch der Wirtschaftlichkeit von blau-grünen Projekten eine entsprechende Bedeutung beigemessen werden. Die Klimawandelfolgen verursachen erhebliche Kosten, die in der Regel von der gesamten Gesellschaft getragen werden. Eine klimawandelangepasste Bauweise auf allen Maßstabsebenen kann dagegen einen hohen Mehrwert schaffen, der auch wirtschaftlich messbar ist [115, 116]. Sowohl unter sozialem wie auch wirtschaftlichem Blickwinkel ist es daher wichtig, dass über eine realistische Kostenberechnung ermittelt wird, ob die Mehrkosten für Planung und Umsetzung durch geringere Folgekosten aufgewogen werden [117]. Gerade die stärkere Berücksichtigung der sozialen Gerechtigkeit und der Wirtschaftlichkeit kann ein ergiebiges Feld für die weitere Forschung zu BGI und BGA erschließen. Im Zentrum steht dabei die Frage nach der Übertragbarkeit des Konzepts auf Länder des globalen Südens [118], und inwieweit Regionen, die besonders stark von Klimawandelfolgen betroffen sind, davon profitieren könnten, sofern die Herangehensweise auf die Bedingungen vor Ort abgestimmt ist.

Die untersuchten Fallbeispiele und Umsetzungsprojekte in dieser Arbeit haben allerdings deutlich gemacht, dass auch hierzulande ein Umdenken in der Bau- und Planungskultur erforderlich ist, um BGA-Projekte erfolgreich zu realisieren und damit einen Beitrag für zukunftsfähige Städte und Gebäude zu leisten.

Die frühzeitige Integration von Wasser und Vegetation in den architektonischen Entwurf ist möglich. Mit der entsprechenden Entwurfsstrategie können die relevanten Faktoren ermittelt, sowie funktional und gestalterisch aufgegriffen werden. In der bisherigen Praxis ist die Verbindung von Wassermanagement mit klimawirksamer Vegetation bei weitem nicht ausgeschöpft. Die interdisziplinäre Zusammenarbeit mit Fachplaner:innen der Landschaftsarchitektur und Siedlungswasserwirtschaft muss zum Standard werden, um klimawandelangepasste Netzwerke in der gebauten Umwelt zu schaffen. Die Entwurfsstrategie für BGA kann (und sollte) dabei bereits in der Lehre eingesetzt werden, um Studierende an die integrierte Vorgehensweise heranzuführen.

Sobald wir Gebäude und angrenzende Freiräume grundsätzlich als blau-grüne Netzwerke betrachten, werden hohe Synergien aus Umweltwirkungen und Ökosystemleistungen entstehen.

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ABBILDUNGSVERZEICHNIS

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Abb. 24: Planungsbesprechung am Bauplatz des Impulsprojekts im interdisziplinären Team. Foto: F. Well. S. 40.

Abb. 25: Integrierte Entwurfsstrategie für BGA (blau) mit Ansatzpunkten für die Weiterentwicklung (grau). Eigene Darstellung basierend auf [67]. S. 42.

Abb. 26: Interdisziplinäre Lehrveranstaltung (Design-build) mit Umsetzung eines BGA-Projekts, Prototyping Schulgarten. Foto: F. Well. S. 43.

Abb. 27 + 28: Das Quartier Norra Djurgården in Stockholm ist ein Beispiel für wassersensible Gestaltung in Kopplung mit intensiver Durchgrünung am Gebäude und im Freiraum [119]. Fotos: F. Well. S. 112.

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