SDG-driven design

Guidelines for sustainable early design
based on the Sustainable Development Goals

Scientific work to obtain the degree of **Master of Science (M.Sc.)**
At the Faculty of Architecture / Civil, Geo and Environmental Engineering at the Technical University of Munich.

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Abstract

The building sector has strong leverage in setting the pathway for sustainable development. The construction industry and the built environment set great pressure on the world´s climate, its ecosystem and its resources, on the global economy at macro and micro levels, and similarly on the social infrastructure on the global and local scale. The application and evaluation of sustainability in the built environment are strongly driven by building certification labels. With around 600 labels around the world, which define sustainability differently, the definition of sustainability becomes blurry and difficult to apply.

The SDGs can be seen as a global framework for the definition of sustainable development, nevertheless, the definitions through targets remain general and complex to use in urban developments and architectural design. The topic of this work uses the SDGs to define general targets for sustainability, focusing on the built environment, to encapsulate a framework for sustainable architectural practice. By transforming the SDGs into sector-based architectural SDGs, a set of guidelines can be created to aid planners and designers in the application and evaluation of sustainability in their designs. In the end, a practical example offers insights into an SDG-driven design process by comparing it to standard architectural design approaches and other performance-based design methodologies like the LCA-driven approach

The work entails a theoretical part and a practical section for which different but embedded objectives are evaluated. The theoretical part offers insights about an implementation methodology for the SDGs in the built environment through a pathway or roadmap to apply the created architecture-related targets. The results from the literature research contradict, nevertheless, the ones found in the case study, opening the door to further exploration of the intricate interactions among the SDGs and their targets.

The results of the comparison of design methodologies corroborate the hypothesis of the practical part of this work, which implicates that an SDG-driven approach offers a more extensive inclusion of targets than the standard and LCA-driven (LifeCycle-Assessment-driven) cases. Nevertheless, a refinement of the methodologies for the calculation of the KPIs should take place in future work.

Zusammenfassung

Der Bausektor spielt eine wesentliche Rolle bei der Schaffung der Grundlagen für eine nachhaltige Entwicklung (Tam et al. 2004). Das Bauwesen übt großen Druck auf das Weltklima, sein Ökosystem und seine Ressourcen. Genauso auf die globale Wirtschaft auf Makro- und Mikroebene und auf die soziale Infrastruktur auf globaler und lokaler Ebene aus. Die Bewertung von Nachhaltigkeit in der gebauten Umwelt wird stark von Gebäudezertifizierungssiegeln vorangetrieben. Bei rund 600 Siegeln weltweit, die Nachhaltigkeit unterschiedlich erfassen, wird die Definition von Nachhaltigkeit allerdings unscharf und hochkomplex.

Die SDGs können als globaler Rahmen für die Definition nachhaltiger Entwicklung angesehen werden, dennoch bleibt die Definition durch Unterziele zu allgemein, um sie auf Stadtentwicklung und architektonische Gestaltung anzuwenden. Diese Arbeit verwendet die SDGs, um allgemeine Nachhaltigkeitsziele zu definieren, die sich auf die gebaute Umwelt konzentrieren, um einen Rahmen für eine nachhaltige architektonische Praxis zu schaffen. Durch die Umwandlung der SDGs in sektorbezogene, architektonische SDGs kann eine Reihe von Handlungsempfehlungen erstellt werden, die Planer:innen und Designern bei der Anwendung und Bewertung von Nachhaltigkeit in ihren Entwürfen helfen. Am Ende bietet ein praktisches Beispiel Einblicke in einen SDG-gesteuerten Designprozess, indem es ihn mit standardmäßigen architektonischen Designansätzen und leistungsbasierten Designmethoden wie dem lebenszyklusorientierten Ansatz vergleicht.

Die Arbeit umfasst einen theoretischen und einen praktischen Teil, für die verschiedene, aber vernetzte Ziele bewertet werden. Der theoretische Teil bietet Einblicke in eine Implementierungsmethodik für die SDGs in der gebauten Umwelt durch einen strategischen Fahrplan zur Berücksischtigung der erstellten architekturbezogenen Ziele. Die Ergebnisse des theoretischen Teils widersprechen jedoch denen der Fallstudie und öffnen die Tür für eine weitere Untersuchung der komplexen Wechselwirkungen innerhalb der SDGs, ihren Unterzielen und ihren Indikatoren.

Die Ergebnisse des Vergleichs von Designmethoden untermauern die Hypothese des praktischen Teils dieser Arbeit, die impliziert, dass ein SDG-getriebener Ansatz

einen weitreichenderen Einbezug von Zielen bietet als die Standard- und lebenszyklusorientierten Fälle. Dennoch sollte in zukünftigen Arbeiten eine Verfeinerung der Methoden zur Berechnung der KPIs erfolgen.

List of Abbreviations

DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
	German Sustainable Building Council
LBC	Living Building Challenge
LEED	Leadership in Energy and Environmental Design
SDG	Sustainable Development Goal
A-SDG	Architectural Sustainable Development Goal
UN	United Nations
AEC	Architecture, Engineering and Construction
DIN	Deutsches Institut für Normung
HOAI	Honorarordnung für Architekten und Ingenieure
HVAC	Heating, Ventilation and Air Conditioning
LCA	Life cycle analysis
LCC	Life cycle cost
LOD	Level of detail
USGBC	U.S. Green Building Council
VOCs	Volatile organic compounds
UTCI	Universal Thermal Climate Index
GWP	Global warming potential
AP	Acidification Potential
EP	Eutrophication Potential

PEtot	Primary total embodied energy
PENRE	Primary Energy non-renewable
PERE	Primary Energy Renewable
LPH	Leistungsphasen (similar to Engl. Design phase)
KPI	Key Performance Indicator
WWR	Window-to-wall ratio
FAR	Floor Area Ratio
BCR	Building Coverage Ratio
LM	Load Match

Glossary

Total Primary Energy (PE): Primary energy use is the direct use of an energy source which occurs in nature and which can be supplied to energy users without any conversion or transformation process.

Total Primary Energy non-renewable (PEnr): Primary energy focused on the amount of non-renewable or fossil fuel-based energy used as an energy carrier.

Total Primary Energy renewable (PEtot): Primary energy focused on the amount of renewable or bio-based energy used as an energy carrier.

Total Exported Energy: This KPI refers to the total amount of energy exported from the building, building site, block, or urban area, to the grid. This would be the case for buildings achieving the energy-plus standard, producing more energy than they can consume over their lifetime.

Air exchange rate: The air exchange rate is the rate at which outdoor air replaces indoor air within a room. It is an essential parameter to determine the indoor air quality of any workplace and affects the energy consumption of buildings.

Solar transmittance parameter: A measure of the amount of solar radiation (heat) passing through the entire window, including the frame. SHGC is expressed as a number between 0 and 1.0. The lower the SHGC the less amount of solar energy can pass through the glazing.

WWR: Window-to-wall ratio: Ratio between the glazing area of a particular wall orientation to the area of the same wall.

LM: Energy Load Match: Temporal coverage ratio of total energy consumption by on-site renewable energy generation

EUI: Energy Use Intensity: It's calculated by dividing the total energy consumed by the building in a given time by the total gross floor area of the building (measured in square feet or square meters).

Floor Area Ratio: Ratio between the building gross floor area to the site area

Site coverage: Ratio between the building footprint and the site area

Biodiversity index: The biodiversity index is the sum of the project area's sub-areas (Sealed or partially sealed land, green spaces, etc) multiplied by the specific factor, as a proportion of the total plot area, which is rated using the site occupancy index.

Adaptation: Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist; e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature shock-resistant plants for sensitive ones, etc.

Climate change: A change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings or to persistent anthropogenic changes in the composition of the atmosphere or land use.

Resilience: The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation and the capacity to adapt to stress and change.

Urban heat island (UHI): The relative warmth of a city compared with surrounding rural areas, is associated with changes in runoff, the concrete jungle effects on heat retention, changes in surface albedo, changes in pollution and aerosols and so on.

Embodied carbon: carbon dioxide (CO_2) emissions associated with materials and construction processes throughout the whole lifecycle of a building or infrastructure.

Embodied energy: sum of all the energy required to produce any goods or services, considered as if that energy was incorporated or 'embodied' in the product itself.

Net Zero Site Energy: produces as much as it uses.

Net Zero Energy Emissions: aims for a carbon-neutral result.

Figure 1: SDGs and the built environment

Introduction

The title of this Master´s thesis is called “SDGs-driven design”. This work is based on the research, extraction and definition of targets and indicators, which represent the architecture-related features of the United Nations´ 17 Sustainable Development Goals (SDGs) presented in the “2030 Agenda for sustainable development” in the year 2015 (United Nations 2015). These targets, design strategies and indicators are corroborated within practical design examples found in literature and with an own developed design project.

Problem and motivation

The building sector plays an essential role in laying the foundations for sustainable development (Tam et al. 2004). The Architecture, Engineering and Construction industry (AEC Industry) currently produces nearly 40% of global carbon dioxide emissions and approx. 30% of the global final energy consumption is destined for its performance (IEA 2020). It consumes around 30% of the world´s resources, with 12% of the global water use, and is responsible for 40% of the global waste (Koen Claes et al. 2012). Furthermore, urbanization and population growth are predicted to continue in the coming decades, increasing the consumption of resources (Sun et al. 2020) and proposing an even greater challenge to the environment (Babí Almenar et al. 2021). Additionally, 9,4% of the world´s population live with less than $1,90 per day (World Bank Group 2020), which puts pressure on the building sector to increase the number of affordable housing projects (Reeves 2014). On the building scale, people spent over 90% of their time inside them (D’Amico et al. 2021), which renders the importance of the indoor environment on the health of its users (Bluyssen 2014) and subsequently sustainable development. It becomes clear that the effects of the built environment on society, the economy and the environment are extensive.

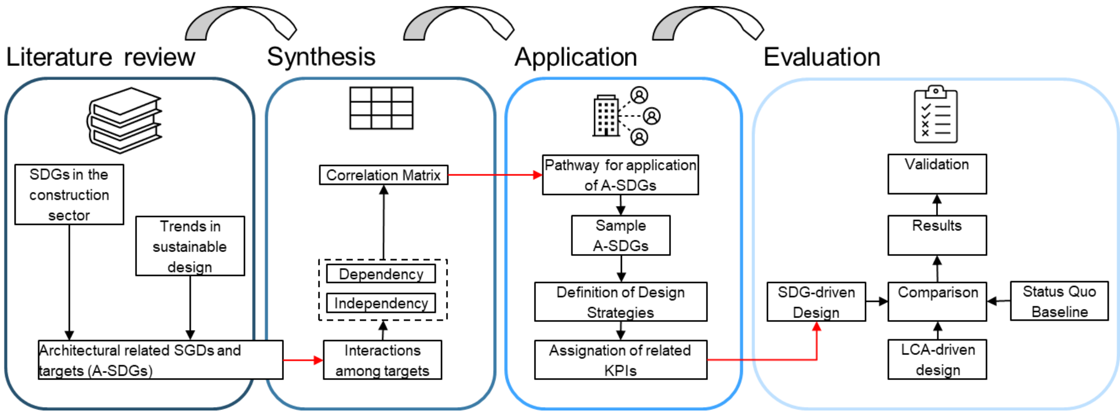
Recognizing the importance of sustainable building practices has been introduced for many years through green building rating systems, like BREEAM (Serrano-Baena et al. 2021). Nevertheless, “If construction and real estate are to play a role in sustainable development, the building sector needs to work towards achieving the Sustainable Development Goals (SDGs)” (Goubran 2019). The SDGs present an integrated and indivisible plan to deal with all these interlinked issues (ECLAC 2018) and present an opportunity for the building sector to tackle an expanded scope of topics at once (Goubran 2019). Nevertheless, the research about possible implementation processes and the integration of the SDGs into the building practice has been so far limited, focusing mainly on individual goals exclusively (Goubran 2019).

The sustainability assessment of buildings is for all stakeholders of an architectural development a very difficult task to perform. The definitions of sustainability cover a great spectrum of fields with more than 100 definitions (Doan et al. 2017) and 600 assessment methods (Bernardi et al. 2017) available, which can make the application of sustainability in the built environment complicated and unclear. Researchers have been for decades reflecting on the incompleteness of assessment standards in describing sustainability with its full complexity (Cucuzzella 2011) and that their focus lies especially on the energy performance and a limited number of environmental parameters (Bernardi et al. 2017), ignoring other dimensions of sustainable development (S. Alyami and Y. Rezgui 2012). Therefore, taking the SDGs as the framework to achieve sustainability, a set of guidelines and design strategies representing each SDG will be proposed in this work. UN SDGs are promoting far-reaching sustainability with proactive, global social goals, which can only be addressed by employing a holistic approach. Rephrasing the above-mentioned attributes of sustainable building to a net-positive and holistic approach would then imply a truly sustainable building (Emanuele Naboni and Lisanne Havinga 2019). Naboni et al 2019 suggest that such attributes could lead to increasing the value of sensitive sites, creating new ecological infrastructure, enhancing natural features and site ecology during construction, repairing environmental damage from emissions and outflows, contributing to global environmental regeneration, creating new energy, clean water, and materials by circular approaches, increasing the comfort and well-being of building occupants and creating beneficial substances within the building.

Objectives

The purpose of this work is to link the SDGs to the built environment in a comprehensive set of guidelines to be used by designers, planners and developers. Each SDG is represented as a list of targets representing the actions required to approach the goal. In a deeper level of research, the primary SDGs serve as a reference to develop an analysis of the interactions among the different targets (see 1.3 Which Indicators / Goals have the higher relevance to the built environment according to the research?). Furthermore, a sample of selected targets is decomposed into design strategies and key performance indicators extracted from the literature to provide the targeted audience with benchmarks to follow when evaluating design alternatives.

Research questions and structure of the work



The objective of this Master's thesis is to evaluate the existing literature linking the SDGs to the building sector to create a methodology for integrating them into architectural development. These tools will support the early stages of the design by extracting architecture-related targets out of the existing SDGs. By doing so, the following question arises:

- Could the SDGs serve as a base to define Sustainability in urban and building developments?

Breaking this broad research question into smaller parts results in the following questions, which will guide the progress of the master thesis:

- Chapter 1: What approaches already exist, linking the SDGs to the building sector? What are the current trends in sustainable design? Can architecture-related sustainable targets be extracted from the previous research?

- Chapter 2: How can these sectorial SDGs be structured to facilitate their application? How can a set of planning/designing strategies be extracted from the architecture-related targets? How can key performance indicators (KPI) be assigned to the targets of the selected architecture-related SDGs? Can the performance indicators be represented qualitative or quantitative?

- Chapter 3: How is it possible to create a road map to implement the SDGs in the design practice? How do the targets interact with each other?

- Chapter 4: What are the main differences among the selected design methodologies? Is it possible to validate the application pathway for the targets through the practical approach? What are the main challenges in the application of an SDG-driven design?

Hypothesis for the theoretical research

The hypothesis of the previous research questions can be then derived as “Planning guidelines extracted from the SDGs can be used to create a framework for sustainable design”. The aim is in the best case scenario to lay the foundations for a holistic sustainability framework to aid designers and planners approach sustainable architectural design in the practice.

Hypothesis for the practical design

The second part of this work revolves around the idea that “Implementing an SDG-driven architectural design approach results in comparable results for environmental impacts than an LCA-driven approach, fulfilling at the same time other dimensions of sustainability”. For this, three design frameworks are compared: the baseline case representing the status-quo, a high-performance design approach based on LCA indicators (LCA-driven design) and the elaborated SDG-driven design.

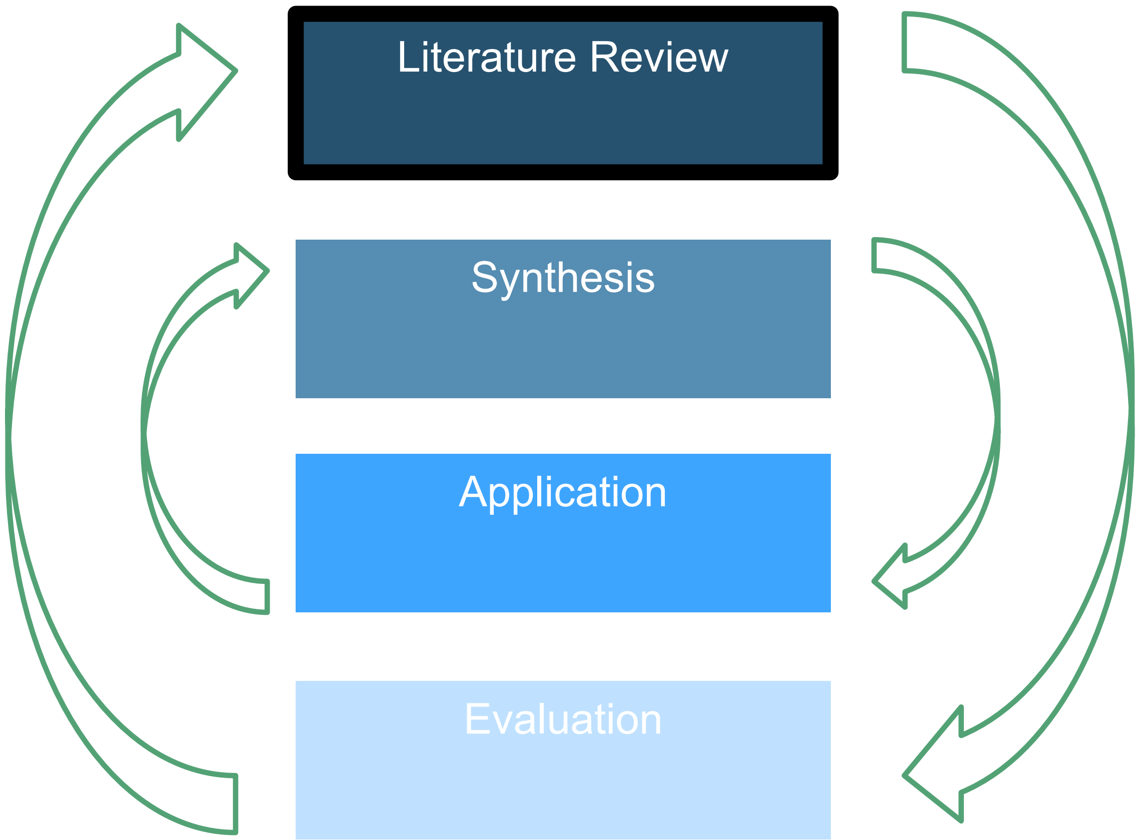
Delimitation of the topic

The investigation covers the state of the research regarding the integration of the SDGs into the building sector only. Due to the extent of the scope, further filters have been set. A list of guidelines, displaying important design strategies to be used when addressing an SDG-driven design is proposed for the selected context. Furthermore, the analysis of interactions among the Goals and subsequently among targets has been limited to the primary SDGs determined in section 1.3 (Figure 4 SDG Categories representing their relevance in the built environment) and to the selected targets filtered in Chapter 3.

. For the assignation of KPIs relevant to the targets contained in each SDG, extensive research on the current evaluation methods for each target is performed, focusing as well on the aforementioned targets from the primary SDGs. To validate these findings, a study case is proposed, which deals with the application of the theoretical results, employing building certification labels such as LEED, WELL, DGNB and LBC, and current sustainability concepts to realign the theoretical findings to the practice.

The design project focuses on the context of vertical and horizontal expansion scenarios. The constraints of the focus are:

- Location: Kempten
- Design Scale: Urban / Building
- State of development: Refurbishment / New Construction
- Design stages: Early design / Competition
- Typology: Residential / Mix-use


Literature Review
Synthesis
Application
Evaluation

Chapter 1: SDGs and the built environment

1.1. Introduction to the SDGs

The 2030 Agenda for Sustainable Development is the document containing the proposal for the 17 Sustainable Development Goals (Figure 2). In the year 2015 in New York, while celebrating its seventieth anniversary, the United Nations emitted a set of goals with the aim of “Transforming our World”, envisioning it without poverty, free of hunger, violence and fear, a world that offers opportunities to all humans equally with the foundation that their needs for education, health and wellbeing can be assured. These visions integrate the sustainable development of all habitats, creating a resilient and safe place for all species while pursuing the regeneration of the lost biodiversity.

The contents of the Agenda propose a plan to tackle the main issues impeding the equal development of all nations. This plan containing 17 goals and 169 targets should be carried out until the year 2030 while addressing five categories: People, Planet, Prosperity, Peace and Partnership. (United Nations 2019)

People

The People category pursues the great challenge of ending poverty and hunger to provide the proper environment for human development. (United Nations 2019)

Planet

This category envisions a planet without degradation, focusing on sustainable consumption and production measures, which will address the required actions on climate change and create a consciousness about the limited resources available on earth. (United Nations 2019)

Peace

The core of this category is to enable the transformation to provide peace, justice, and inclusion, and eradicate any form of violence. (United Nations 2019)

Prosperity

And lastly, the category Partnership encourages the revitalization of global solidarity to work together and lift the most vulnerable and poorest up of their degraded situation. (United Nations 2019)

Under these categories, the following 17 Sustainable development goals (Figure 2) have been allocated:

Goal 1: End poverty in all its forms everywhere

Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

Goal 3: Ensure healthy lives and promote well-being for all at all ages

Goal 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

Goal 5: Achieve gender equality and empower all women and girls

Goal 6: Ensure availability and sustainable management of water and sanitation for all

Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all

Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

Goal 10: Reduce inequality within and among countries

Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable

Goal 12: Make cities and human settlements inclusive, safe, resilient and sustainable

Goal 13: Ensure sustainable consumption and production patterns

Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

Goal 16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels

Goal 17: Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Figure 2 SDG Poster

Each goal has a set of targets and indicators, which provide useful information about how to measure them. Due to their extensive content, they will not be discussed individually but summarized in this work.

1.2. Current research on the integration of the SDGs in the building sector

The research shows that the available literature regarding the integration of SDGs into the built environment is momentarily in the early stages. Publications usually explore the implementation of SDGs in focused sectors like energy or healthcare. Most research papers normally explore the intersection of the existing assessment criteria to the SDGs, overseeing the importance of creating a framework in the opposite direction. Only a few sources are analyzing the role of the 2030 Agenda in the building sector (Goubran 2019). The Oslo Manifesto (The Norwegian centre for design and architecture 2015) and both editions of the architecture guide to the UN 17 Sustainable Development Goals (Royal Danish Academy et al. 2020) offer a reinterpretation of the SDGs focusing on the built environment and open a door for the application of the Goals in design. Both approaches offer references to design teams on how to consider the SDGs while planning, the Oslo Manifest is based on design questions for professionals and the architectural guide to the UN SDGs is based on case studies. Nevertheless, both methodologies remain general and broad, lacking specific indicators that could clear the pathway for design teams in the implementation of the SDGs in the building sector.

1.3. Which Indicators / Goals have the higher relevance to the built environment according to the research?

From the exploration of the abovementioned architecture guide to the UN 17 SDGs, it is possible to address all SDGs through architecture targets and there is no hierarchy addressing the relevance of single goals to the built environment. Goubran et al. on the other hand analyze the relevance of SDGs in the real state defining goals 7, 11, 12 and 13 as the most significant due to their relation to energy, cities, consumption and production patterns, and climate. Habitat for Humanity, a non-profit organization, explores in its SDG Booklet the impact of housing on the SDGs and defines three categories for the integration between housing and the SDGs (Shulla et al. 2021) described in Figure 3.

The main SDGs derived from this publication (integrated + direct) refer to the goals 1, 3, 7, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16, 17.

Moving forward, the extensive research paper linking the SDGs to the construction industry conducted by Groubran S. shows that 79 targets (44%) of the 169 targets in the SDGs are dependent on construction and real state activities, defining 29 targets (17%) as directly dependent and 45 targets (27%) as indirectly dependent (Goubran 2019).

When analyzing the integration of SDGs to the building certification labels DGNB, LEED and BREEAM, the research shows that for the DGNB, the main SDGs linked to the building sector are goals 3, 7, 11, 12 and 17 (DGNB GmbH 2020a). The integration of SDGs in BREEAM defines the most relevant SDGs as goals 3, 6, 7, 9, 11, 12, 13, and 15 (BREEAM). On the side of LEED, the main SDGs are 3, 11, and 12.

Figure 3 How Housing supports the SDGs

After assimilating the findings, as shown in Table 1, the relevance of architecture for the SDGs becomes clearer by creating relevance categories. The SDGs that appear most frequently in the research have the designation of “Primary” goals, marked with orange colour in Table 1. The next category is called “Secondary” and contains 5 Goals, as shown in Figure 4. Lastly, the third category, the “Tertiary”, consists of 7 Goals. This categorization will be very important for the design guidelines presented in Chapter 4.

Table 1 Relevant SDGs according to references

Available References	Most relevant SDGs																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Royal Danish Academy et al. (2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Goubran, Sherif (2019)	X	X	X	X		X	X		X		X	X	X	X	X		
Shulla et al. (2021)	X		X		X	X	X	X	X	X	X	X	X			X	X
Walker et. al. (2018)							X				X	X	X				
DGNB (2020)			X				X				X	X	X				X
LEED (Alawneh et al. 2018)			X								X	X					
BREEAM			X			X	X		X		X	X	X		X		
Sum	3	2	6	2	2	4	6	2	4	2	7	7	6	2	3	2	3

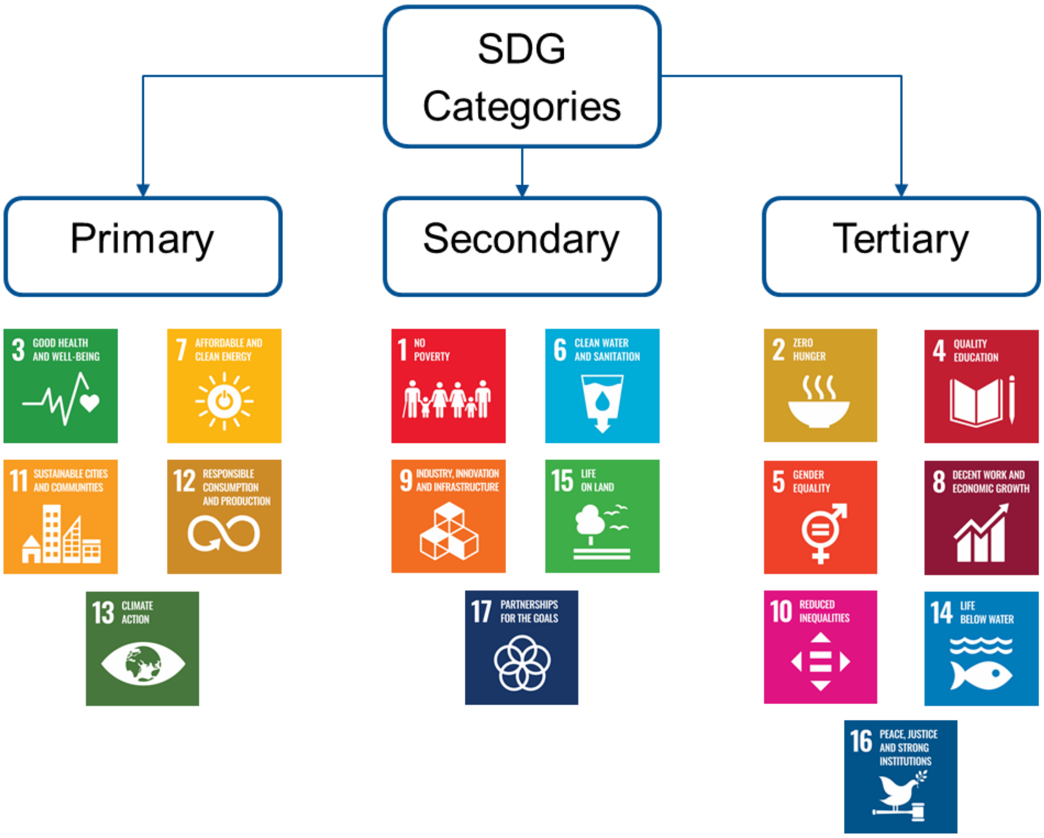


Figure 4 SDG Categories representing their relevance in the built environment

1.4. Trends in Sustainable Design

Before defining architectural targets with their design strategies and key performance indicators (KPIs), extensive literature research has been performed to gain perspective on the state of the art regarding sustainability approaches. This research is a cornerstone to creating architecture-related targets, which are proposed in Chapter 2. In this section, the essence of these trends is summarized.

The planetary boundaries (Johan Rockström et al 2009) offer a general benchmark for the current impact of humankind on the terrestrial system. It is important to create architectural proposals, which operate within the boundaries given, aiming to regenerate the risk zones.

Doughnut Economics (Raworth 2017) made the case for incorporating climate change into all business strategies. The doughnut maps out nine planetary boundaries that economies need to stay within. The causes of planetary boundary violations need to be addressed by all economic stakeholders.

Furthermore, sustainable design tendencies are regenerative, based on a process that restores, renews or revitalizes, incorporating the needs of society with the integrity of the natural environment. The main objective behind this concept is to stop trying to minimize harm by starting activities to restore and regenerate ecological systems (Roös 2021b). In *Regenerative Design In Digital Practice. A Handbook for the Built Environment* (Emanuele Naboni and Lisanne Havinga 2019), the principles of regenerative design require the design process to be inclusive and collaborative, aiming to create a further positive impact to allow ecological systems to recover and maintain a healthy state. The main goals in generative design are to mitigate climate change create adaptation strategies and incorporate urban microclimate and decarbonization into the design equation.

Likewise, the concept of circularity aims to remove the concept of waste. The urban mining approach can limit waste landfills and avoid extraction of raw materials, giving more value to the existing building and avoiding demolition waste increasing the longevity of buildings' subsystems and elements. It is possible to open a new cycle for the unavoidable waste generated by demolition parts of buildings as secondary resources within the construction sector to produce new materials aimed at upcycling.

During the renovation process, the construction of new parts for the existing building can be designed and completed with disassembly solutions, using materials that are reusable and recyclable, without toxic or hazardous materials (Della Torre et al. 2020).

Another important concept tries to revive the vernacular architecture, which adapts passively to the macro- and microclimate. The architecture design needs to be based on detailed climatic analysis, taking into account the impact of solar radiation, temperature, humidity and wind on buildings. Only close attention to the climate and the local architectural tradition can produce fully adequate buildings and optimal energy concepts (Hausladen et al 2012).

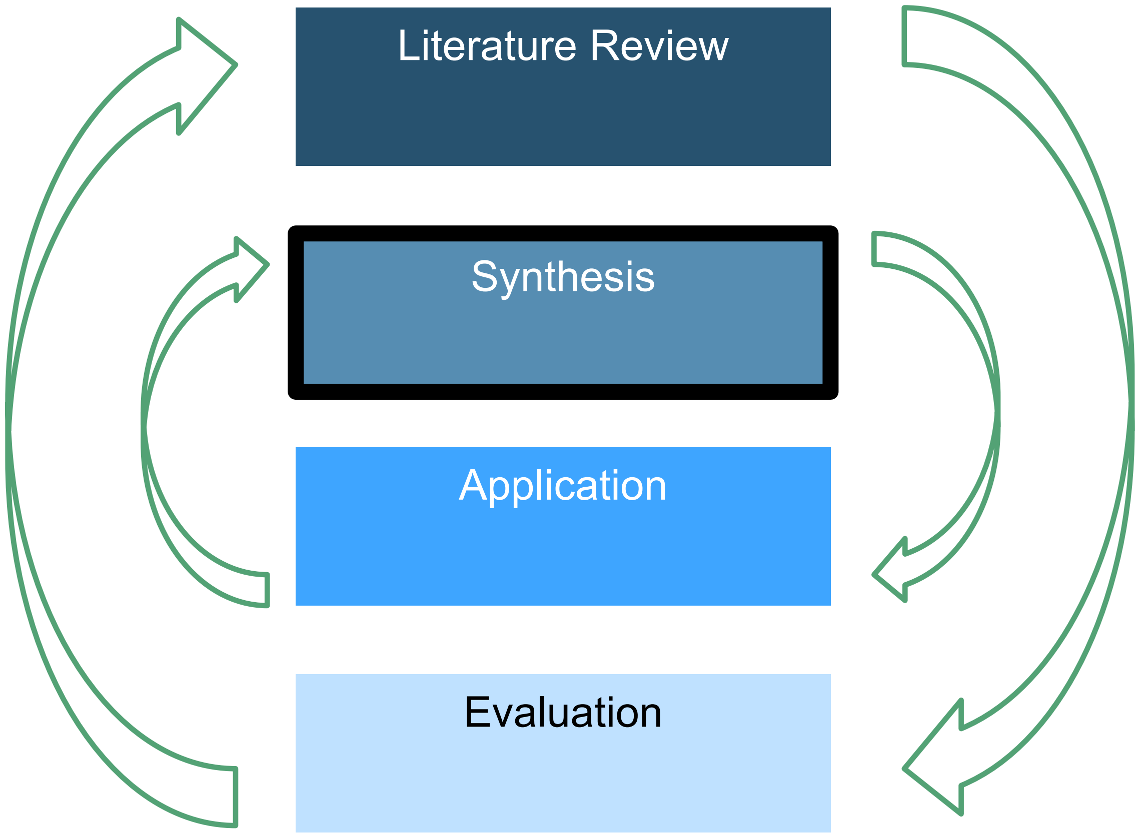
But we do not have to forget that the building's primary function is to offer shelter to humans. Therefore, they should focus on the health and well-being of their users by incorporating biophilic design strategies. In architecture, biophilic design explains why some buildings are considered to perform better than others regarding their nature-connectedness, which presents all sorts of benefits in the living, working, learning, entertainment, and medical environments. (Zhong et al. 2022). Human beings need contact with nature and the natural environment. They need it to be healthy, happy, and productive and to lead meaningful lives. Nature is not optional, but essential quality of modern urban life. Conserving and restoring the considerable nature that already exists in cities and finding or creating new ways to grow and insert new forms of nature are paramount challenges of the twenty-first century. (Beatley 2016).

The concept of biophilia can be seen as well from the other side of the coin. Implementing nature to increase the health of humans can also increase the well-being of nature itself when complemented with animal-aided design strategies. Animal-Aided Design can be used in urban areas in particular and can be used in a variety of planning fields: from the climatic renovation of buildings to the small-scale redesign of an inner courtyard to the planning of extensive parks. Animal-aided design can also contribute to bringing nature conservation and urban planning closer together when implementing compensatory measures. Animal-Aided Design improves people's living environment by helping to create a green infrastructure that is attractive to people and animals (Thomas E. Hauck & Wolfgang W. Weisser 2015).

The October 2018 report by the Intergovernmental Panel on Climate Change (IPCC) calls for unprecedented urban adaptation as well as an energy transition to net zero carbon by 2050 to keep the global average temperature rise below 1.5 ºC (IPCC, 2018). The energy transition is critical in many countries whose share of renewable energies is extremely low, and more specifically in cities since they account for approximately 75% of global primary energy consumption (UN Habitat, 2018). Improving energy efficiency with the aim of climate neutrality should be the minimal requirement of the new constructions. Net-zero design approaches explore the feasibility of creating buildings and districts without emissions or external energy requirements, by producing their energy supply and becoming prosumers for their surrounding infrastructure (Voss et al 2013).

Finally, as derived from all the definitions above, multiple disciplines come into play when designing sustainable developments. For this, the concept of integrated design is essential. Since the energy crisis in the 70s, the standards for buildings have become more strict, turning the building praxis into a very complex assignment. Conventional sequential design and planning methods could not handle the complexity of these new requirements. Thus, the concept of integrated design has been developed to overcome this issue, gaining increased acceptance nowadays (König et al 2010). Contrary to the sequential design process, where the design team divides up the work and only becomes fully formed at the end of the design process after the responsibility has been continuously shunted from one project stakeholder to another, in an integrated design approach, the design team is assembled including the client's representatives at an early stage in the design (Wiegand 2005). This method offers an integration of the interdisciplinary lines throughout all life cycle phases (Rödger et al. 2021). An integrated design demands, nevertheless, an impartial interrupted flow of information and neutral coordination among the disciplines to maintain the quality and ensure the compliance of the objectives. (König et al 2010).

Architectural design and urban planning are becoming increasingly complex. The planners and designers need to be a part of a well-structured interdisciplinary team, able to span their knowledge to cover the intrinsic requirements of the built environment. The sustainable trends anticipate the development of our future cities to respect the planetary boundaries, creating and performing in a safe space for humanity and nature. The future urban settlements are seen as material banks, which can redistribute their resources, minimizing waste exponentially, and making use of the potential of the local climate while respecting the requirements of climate change.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Chapter 2: Transforming SDGs into Architectural Sustainable Development Goals

The previous research sources shown in Table 1 and the information extracted from the "Trends in Sustainable Design" served to synthesize architecture-related targets for each SDG. In the coming section, a deep exploration of the SDGs is performed, offering insights into the general objectives of each SDG and its relation to the built environment. At the end of this Chapter, a list of the SDGs with their architecture-related targets is presented. There are 74 architecture-related targets allocated to the 17 SDGs.

2.1. Overall objectives of the SDGs in the built environment

Goal 1: No Poverty

Poverty comes in many shapes, from lack of food, education and health to the lack of shelter and clothing. It affects people in different contexts and from diverse backgrounds. This SDG has as its main objective to eradicate poverty in all its forms, defining extreme poverty as people living on less than $1,25 a day. (United Nations). This indicator does not offer any direct derivative to the building sector but architecture influences all poverty forms at different levels.

Providing affordable housing is a key step in reducing vulnerability to economic, social, health and climate-related disasters (Shulla et al. 2021). But the provision of an "affordable" shelter is not enough. Affordable housing must secure access to sanitation, educational institutions, health facilities and all public spaces for all citizens/stakeholders (Royal Danish Academy et al. 2020). Addressing poverty also means equal access to land rights and the economic resources they produce.

Goal 2: Zero Hunger

The general objectives for this goal are to eliminate hunger by developing food security, and by improving the nutritional state of humans while ensuring sustainable agricultural methods in food production (United Nations 2020l). Home-grown food approaches can be used to alleviate hunger and malnutrition and to offer nutritious alternatives while offering affordable, resilient food sources. (Jayasinghe 2022, p. 58)

The built environment can contribute to this Goal by enabling food production in the urban realm. Architecture can contribute to securing food supplies by supporting sustainable farming as an integral part of building development (Royal Danish Academy et al. 2020).

Goal 3: Good Health and Well-Being

With the premise that “Ensuring healthy lives and promoting well-being is important to building prosperous societies” (United Nations 2020c) and that most people spend the majority of their lives indoors, architecture plays a crucial part in creating a built environment that supports good health and well-being (Royal Danish Academy et al. 2020).

Being able to access a safe, stable, resilient, affordable shelter is an important factor in the mental health of individuals (Shulla et al. 2021).

The main objective of this goal, referring to the built environment, is to protect all human beings from potential negative impacts on their health due to pollution indoors and outdoors, by designing for comfort and the needs of the inhabitants of a building or quarter (DGNB GmbH 2020a).

Goal 4: Quality Education

Education is a cornerstone of sustainable development. Ensuring inclusive and quality education supports socio-economic development and represents a door to escape poverty while contributing to the reduction of inequalities and intolerance (United Nations 2020h).

The built environment can shape the learning environment to promote productive learning and teaching environments (Royal Danish Academy et al. 2020). For this, the construction of new and the refurbishment of old education facilities is required (Goubran 2019).

Goal 5: Gender Equality

The basis of this goal revolves around the fact that “In 2019, women only held 28% of managerial positions worldwide”. Representing half of the world´s population, women are still treated unequally, depriving them in some cases of salary, health care, access to nutritive food, and inducing premature deaths. (United Nations 2020b)

An equalitarian environment for everyone means designing spaces for inclusion, integration, participation and cohesion. This can be supported by human-centred architectural design (Koch 2021).

Goal 6: Clean Water and Sanitation

Water consumption from the construction sector accounts for 12% worldwide. (Alawneh et al. 2018). The potential for protecting this valuable resource is, therefore, very clear. With measures like using water efficiently, and making use of rainwater in places where there is water scarcity, by protecting and conserving the water balance in the environment, great reductions can be achieved (Walker et. al. 2018, p. 200). A sustainable built environment must offer as well access to sanitation and potable water for all populations as a human right.

Goal 7: Affordable and Clean Energy

The built environment is the major consumer of energy accounting for the whole life cycle of buildings and structures, from the extraction of building materials to the disposal of buildings at the end of their life cycle (Royal Danish Academy et al. 2020). On the other hand, energy poverty is a form of housing poverty addressing a wide range of communities; for this, the availability and affordability of energy are for sustainable development essential (Shulla et al. 2021).

The building sector can address all these issues by ensuring investments in the energy sector, updating infrastructures, integrating renewable energy in a wider scope, and finding synergies to couple with other sectors (DGNB GmbH 2020a).

Goal 8: Decent Work and Economic Growth

The construction and real estate sectors play a key role in GDP growth considering their contribution to the economy. Additionally, sustainable construction and real estate can help to create new growth opportunities (The Economist: Intelligence Unit 2019).

The built environment can influence the economy in many ways, by providing healthy, productive workplaces or by ensuring safety and accessibility (Royal Danish Academy et al. 2020)

Goal 9: Industry, innovation and Infrastructure

The built environment is responsible for 40% of the generated waste worldwide (Koen Claes et al. 2012). Therefore, it is imperative to develop sustainable and resilient infrastructures to support economic development and human well-being. (Goubran 2019). The implementation of new technologies can help to elevate the quality and efficiency of processes, ensuring at the same time, a waste-free industry (Shulla et al. 2021).

Goal 10: Reduce inequalities

"Inequalities based on income, sex, age, disability, sexual orientation, race, class, ethnicity, religion and opportunity continue to persist across the world. Inequality threatens long-term social and economic development, harms poverty reduction and destroys people's sense of fulfilment and self-worth. This, in turn, can breed crime, disease and environmental degradation" (United Nations 2020i).

The relation of this goal to the built environment is complex. negative effects can be induced and amplified. (Royal Danish Academy et al. 2020) Therefore, the design of buildings and urban developments must address inclusion, accessibility and community for all stakeholders. (Shulla et al. 2021)

Goal 11: Sustainable Cities and Communities

By 2050 the world will be holding two-thirds of its population in cities (Goubran 2019). Cities represent only 3% of the world's land, nevertheless, they consume 60-80 % of the global energy and account for 75% of the carbon emissions worldwide. (United Nations 2020k).

Population growth demands at the same time urbanization growth. this expansion results in biodiversity loss, as cities replace natural landscapes with artificial ones, reducing the richness of the fauna in the reduced natural spaces left. (Martin 2012). Integration of ecosystem services into city planning can increase the resiliency, acceptance and adaptability of our urban settlements. (Gatrell et al. 2016).

Goal 12: Responsible Consumption and Production

The development of the world has carried out environmental degradation, putting pressure on the natural systems humans rely on for their survival. (United Nations 2020j). For example, the construction industry demands 25% of wood harvest and 40% of stone, sand and gravel. (Doan et al. 2017) and consumes up to 50% of all extracted materials (Shulla et al. 2021).

A change of perspective regarding the typical linear „use and dispose of “ production and consumption scheme is necessary. Intending to reduce consumption, the concept of “urban mining” takes place, offering a circular alternative to the construction industry.

Goal 13: Climate Action

Climate change affects everyone. National economies suffer under the natural catastrophes accompanying the climate crisis. The Paris Agreement called for controlling the rise of the global temperature to 1.5°C, stressing that if the temperature rises over 3°C, every ecosystem will be affected and extreme weather events will become more frequent (United Nations 2020a). The development of the building materials industry has numerous problems related to climate change and global warming, generating and releasing large amounts of carbon dioxide (Omer and Noguchi 2020, p. 4) in the production, transportation, construction and disposal of structures. The leverage to steer the direction of future sustainable development is, therefore, very clear.

Goal 14: Life Below Water

The objective of this goal is to sustainable use of the ocean, seas and marine resources. The relevance of this goal lies in the fact that oceans support life and regulate our world's climate, absorbing approximately 23% of anthropogenic CO2 emissions and 90 % of the excess heat in the climate system. Marine life supports the world's economies and global needs and has been affected by the rise of global temperatures, leading to biodiversity loss in the aquatic ecology. Furthermore, the amount of waste that reaches the ocean is impacting tourism, the overall economy and the environment. (United Nations 2020d).

The construction sector interacts with this goal through its emissions. The acidification of the ocean relates to the CO2 emissions and the pollution caused by the built environment.

Goal 15: Life on Land

The main objective behind this goal is to establish sustainable management of forests, address and fight against the unnatural propagation of deserted lands, and stop and regenerate land pollution and biodiversity loss (United Nations 2020e).

"The amount of built structures, buildings, settlements and cities taking up land, is rapidly growing" (Royal Danish Academy et al. 2020)

This puts a lot of pressure on ecosystems. To counteract the effect of the built environment on nature, it is required that buildings and settlements include habitats for plants and animals. The aim is to restore their natural habitats and also to regenerate them. The nature networks should be further developed and assisted to create a healthy environment for *all inhabitants*, offering a way to coexist in the same plane and also establish synergies among their structures. (Royal Danish Academy et al. 2020)

Goal 16: Peace, Justice and Strong Institutions

Peaceful, just and inclusive societies are necessary to achieve the Sustainable Development Goals (SDGs). Fear and violence need to disappear. This is primordial to guarantee safety to all people, regardless of their ethnicity, faith or sexual orientation. Inclusiveness and education should be based on the core of each community, establishing the ground base for economic development and environmental protection. (United Nations 2020g).

Architecture represents symbols of what people can relate to. Therefore, these symbols must reflect the core values of our society. Design measures must ensure safety, inclusiveness and affordability. "The building industry must also ensure that the extraction, production and handling of building materials do not rely on abuse, exploitation, human trafficking or child labour" (Royal Danish Academy et al. 2020).

Goal 17: Partnerships for the Goals

Lastly, a successful sustainable development framework requires partnerships to move forward. Governments, private entities and society need to set a joint vision, which revolves around the well-being of all inhabitants of tour planet (United Nations 2020f).

“Every home, building and settlement is built by many hands, and the development of a sustainable future similarly requires that we work together, in partnership. No single stakeholder can reach the UN 17 sustainable development goals alone” (Royal Danish Academy et al. 2020)

"If everyone is moving forward together, then success takes care of itself " – Henry Ford

Sustainability in the built environment through the SDGs

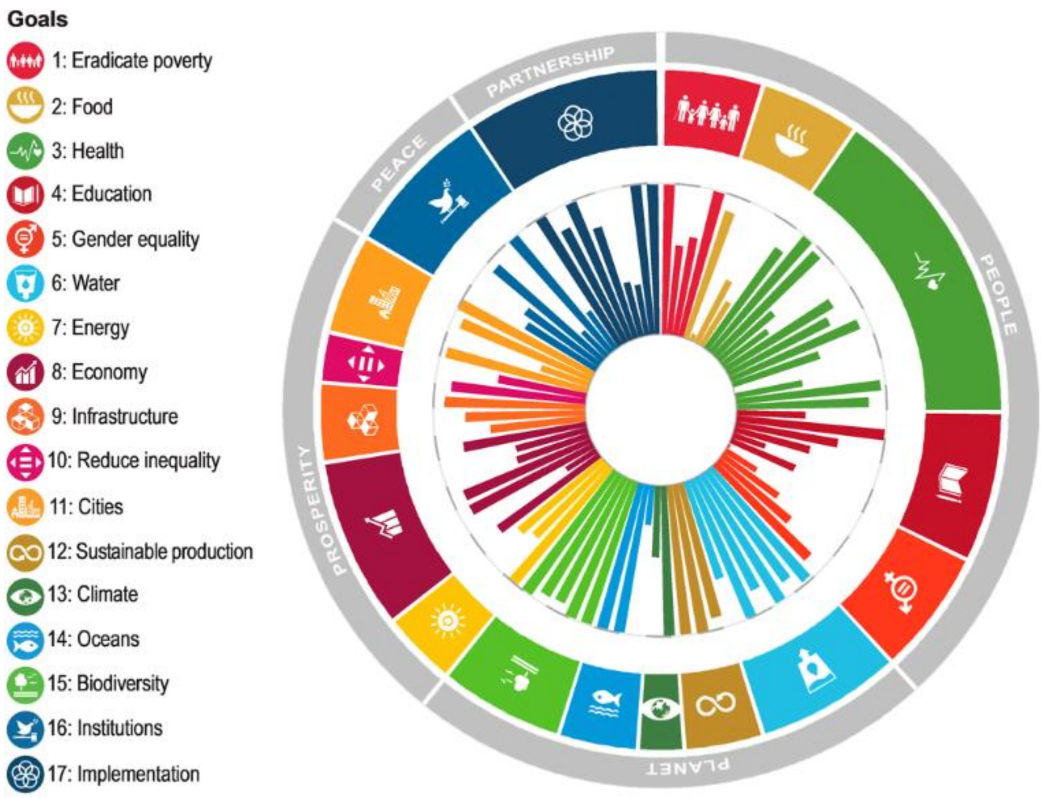


Figure 5: Germany’s distance from achieving 103 SDG targets. From http://dx.doi.org/10.1787/888933963253

Finally, as an outlook for this chapter, the Figure above shows the distance from achieving the targets proposed by the SDGs for the case of Germany. Maybe the framework of the SDGs, when applied to the built environment, can create a public certification label, which can qualify the sustainability of architectural developments, merging the vision and approach of the multiple different existing building certification labels, remaining always open to change and exploration. The next section shows the synthesized architecture-related SDGs with their targets. These have been derived from the literature handling the SDGs in the built environment, from building certification labels, like the DGNB, LEED, WELL and LBC, and from literature resources revolving around sustainable design trends.

2.2. List of SDGs with their corresponding architectural targets

1	a	Integrate space Flexibility and Efficiency
1	b	Use passive strategies for reducing energy consumption
1	c	Design for Modularity and Prefabrication
1	d	Adapt to local climate and geographical and cultural con-texts
1	e	Refurbish and reuse
1	f	Provide affordable housing

2	a	Provide areas for food production
2	b	Use sustainable food production strategies

3	a	Provide a healthy and comfortable indoor climate
3	b	Support healthy and comfortable outdoor micro-climate
3	c	Avoid the use of environmentally hazardous materials and substance
3	d	Encourage physical activity
3	e	Provide accessibility to all spaces

4	a	Enable a productive learning environment
4	b	Provide accessibility to all spaces
4	c	Create multifunctional areas

5	a	Create safe public places and pathways for everyone, especially women and LGBT+ citizens
5	b	Reinforce Inclusion, Cohesion and Equality

6	a	Provide potable water
6	b	Restore groundwater
6	c	Use building materials that do not contribute to groundwater contamination
6	d	Reinforce climate resiliency related to water
6	e	Protect, conserve and collect rainwater
6	f	Use synergies among Goals

7	a	Reduce operational and embodied energy
7	b	Recycle and conserve energy
7	c	Design with the climate: resilient and adaptive
7	d	Use renewable energy to cover the demand

8	a	Support safe public spaces and affordable transit routes to the workplace
8	b	Support access to marketplaces
8	c	Design accessible and productive work environments
8	d	Use materials extracted and produced in safe and healthy work environments
8	e	Provide safety in building sites and in demolition processes

9	a	Eliminate waste in the whole life-cycle
9	b	Reduce energy consumption and cover the demand with renewables
9	c	Employ local renewable resources from local industries
9	d	Adapt to climate and culture
9	e	Promote prefabrication, industrial production and modularity

10	a	Consider the needs of all stakeholders
10	b	Provide accessibility to all spaces
10	c	Encourage and support gathering, community and exchange

11 SUSTAINABLE CITIES AND COMMUNITIES

11	a	Promote Inclusion and Community
11	b	Use regenerative design strategies
11	c	Implement resilient and climate-adaptive measures
11	d	Provide sustainable mobility

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

12	a	Design for a long lifetime
12	b	Design for disassembly and circularity
12	c	Reduce or restrict the use of non-renewable natural resources
12	d	Encourage prefabrication

13 CLIMATE ACTION

13	a	Design for carbon neutrality
13	b	Use local resources
13	c	Integrate and expand green areas and biodiversity

14 LIFE BELOW WATER

14	a	Stop acidification of water bodies
14	b	Avoid the use of materials transported by sea
14	c	Restrict the discharge of wastewater or any sort of waste or pollutant into the oceans or any body of water
14	d	Abolish one-use non-renewable non-degradable materials
14	e	Generate and support knowledge and awareness about fragile aquatic ecosystems
14	f	Support and restore biodiversity by integrating nature into the design

15 LIFE ON LAND

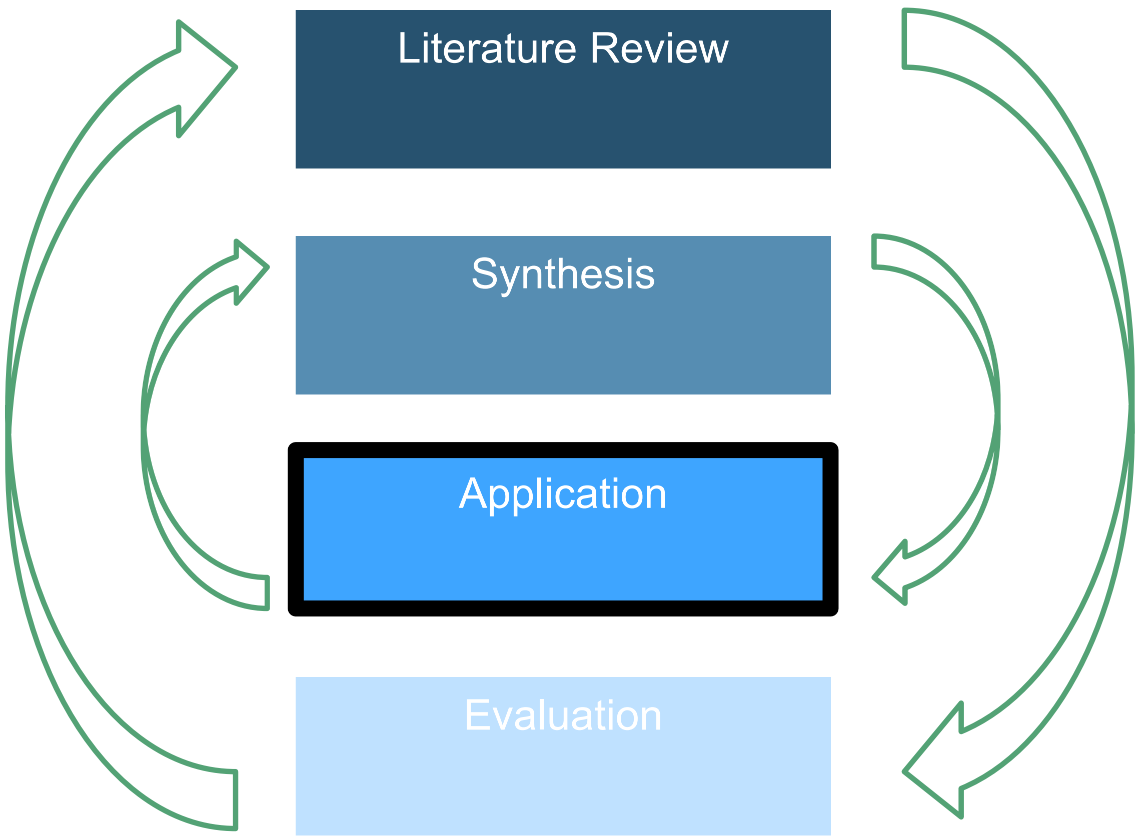
15	a	Support biodiversity
15	b	Avoid the development of virgin lands
15	c	Provide nature networks that allow the co-existence of insects and animals in the urban realm
15	d	Promote sustainable forestry
15	e	Raise public awareness
15	f	Protect freshwater
15	g	Create synergies between natural spaces and humans
15	h	Build with nature, not against it

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

16	a	Involve all stakeholders in the design process
16	b	Ensure that public spaces and institutions are inclusive, welcoming, secure and non-discriminatory
16	c	Support transparency in procurement and construction processes
16	d	Ensure that the extraction, production and handling of building materials do not rely on abuse, exploitation, human trafficking or child labour

17 PARTNERSHIPS FOR THE GOALS

17	a	Contribute by sharing knowledge
17	b	Engage in collaborations with research and innovation
17	c	Create partnerships directed to fulfil the goals
17	a	Involve all stakeholders in the design process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Chapter 3: Exploring the primary SDGs and their interactions

3.1. Analyzing interactions among SDGs

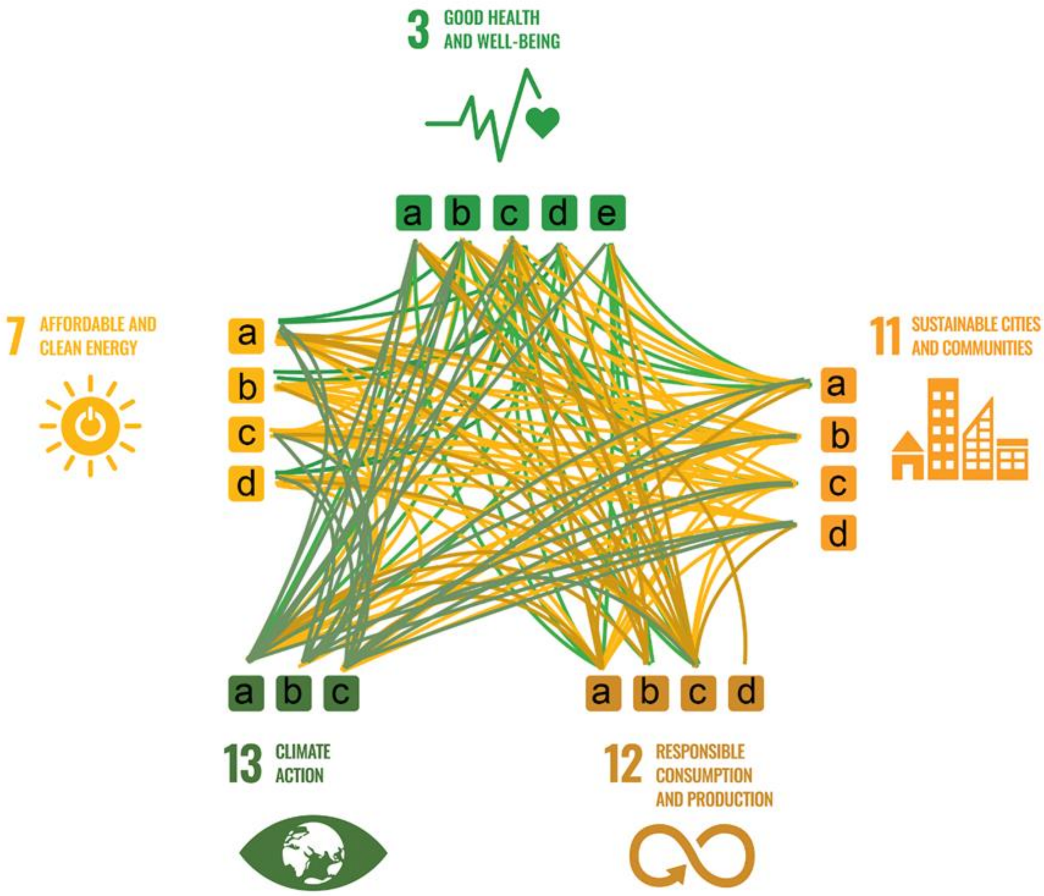


Figure 6: Analyzing interactions among goals and targets

This analysis served to find the degree of interactions among SDGs in the construction sector and to gain valuable knowledge about the organizational approaches to be steered in the design processes. This analysis focuses only on the primary SDGs (see Figure 4 SDG Categories representing their relevance in the built environment) and presents a methodology to evaluate the rest of the SDGs in further research. It is important to mention that the evaluated interactions do not differ between synergies or trade-offs, which need to further be researched to establish more accurate frameworks. Many sources are exploring the interactions among SDGs, like the research presented in *"A guide to SDG interactions: from science to implementation"* (International Council for science 2017). These researchers show clearly the interactions between SDGs differentiated in synergies and trade-offs (Pham-Truffert et al. 2020). Nevertheless, the evaluated papers do not focus on the building industry. For this, the conclusions drawn in these previous works cannot be assumed in this thesis and further research on the type of interactions among Goals and targets will be performed.

Next, the degree of interaction among Goals and targets is based on the author´s ability to find fitting references. For this, a matrix approach was taken to evaluate if targets from the Goals in the rows (sensors) depend on the targets in the columns (Actuators).

The interactions will be evaluated at the level of the targets based on a design structure matrix (DSM) with a 20x20 structure. As shown in the Figure below:

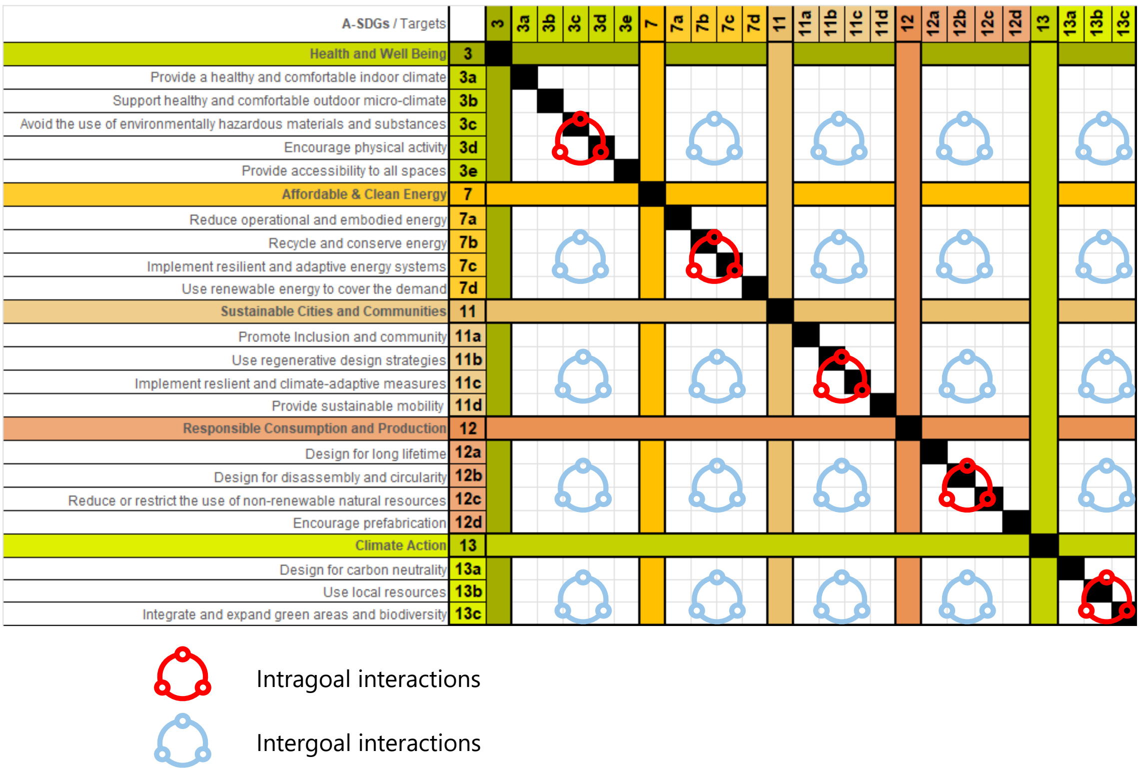


Figure 7: DSM for evaluating interactions among targets

The methodology used in DSM studies is to evaluate the dependence of components, in this case of targets, with each other by asking the question: Does target A (row) requires target B (column) to be fulfilled? The results of these questions are proposed for each target, therefore 380 arguments with their sources have been gathered and are shown in Appendix A.

For a better understanding of this process, the example of the evaluation of interactions between targets 3a (Provide a healthy and comfortable indoor climate) and 3b (Support healthy and comfortable outdoor micro-climate) is here explained. Firstly, the question to evaluate the dependence of 3a on 3b is performed. Is supporting a healthy and comfortable outdoor necessary to provide a healthy and comfortable indoor climate? If the answer is yes, a plus (+) will be found in the table. If the answer is no, a minus (–) will be displayed. The figure below shows that target 3a is not dependent on target 3b. In the case of 3b being dependent on 3a, the answer is yes. The outdoor environment is dependent on the indoors, because of the energy necessary to condition most of our buildings. The current dependency on fossil fuels produces emissions, which subsequently pollute the air and induce the global warming effects like higher temperatures globally. These effects shape the health and comfort conditions of the outdoors.

	A-SDGs / Targets	Health and Well Being	Provide a healthy and comfortable indoor climate	Support healthy and comfortable outdoor micro-climate	Avoid the use of environmentally hazardous materials and substances
A-SDGs / Targets		3	3a	3b	3c
Health and Well Being	3				
Provide a healthy and comfortable indoor climate	3a			-	+
Support healthy and comfortable outdoor micro-climate	3b		+		+
Avoid the use of environmentally hazardous materials and substances	3c		-	-	

Figure 8: Analysis of interactions between two targets of A-SDG 3

From this same figure, we can extract the types of interactions. The dependent and the independent relation are represented in the following graphic.

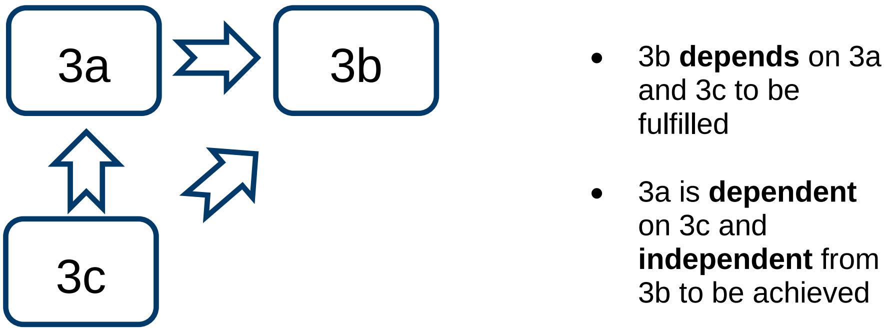


Figure 9: Types of interactions: dependent and independent

There is the last type of interaction called interdependent, in which both targets depend on each other, interdependently, as represented in the following Figures:

		Support healthy and comfortable outdoor micro-climate **3b**	Reduce operational and embodied energy **7a**
Support healthy and comfortable outdoor micro-climate	**3b**		**+**
Reduce operational and embodied energy	**7a**	**+**	

Figure 11: Interactions between 3b and 7a

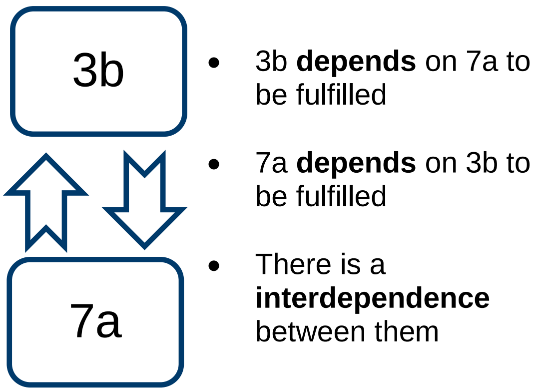


Figure 10: Interdependent interaction

Finally, the table above shows the final result of the evaluation of interactions among targets. The *Influence*, given by the number of targets relying on another particular target, defines the main character to distribute the targets in a hierarchical order. The concept of *Dependence* is the opposite, representing the number of targets another particular target requires to be fulfilled completely. The targets with higher influence need to be addressed first. If there are targets with the same degree of *Influence*, the evaluated target with the lowest *Dependence* goes first. For example, targets 11c and 11a have the same degree of *Influence* (13) but target 11c (5) has a lower degree of *Dependence* than 11a (9). Therefore 11c needs to be addressed before 11a. The results for all interactions are shown in the DSM in the tables on the next pages below. The sequencing of the DSM is shown in Appendix A.

Table 2: General pathway to integrate A-SDG targets into the architectural design based on the level of influence and dependence

A-SDGs / Targets	A-SDGs / Targets	DEPENDENCY	INFLUENCE
Encourage prefabrication	12d	1	1
Use local resources	13b	2	10
Design for disassembly and circularity	12b	3	9
Provide accessibility to all spaces	3e	5	8
Implement resilient and climate-adaptive measures	11c	5	13
Recycle and conserve energy	7b	6	8
Use renewable energy to cover the demand	7d	7	9
Implement resilient and adaptive energy systems	7c	8	7
Encourage physical activity	3d	8	9
Integrate and expand green areas and biodiversity	13c	8	10
Use regenerative design strategies	11b	9	7
Promote Inclusion and Community	11a	9	13
Provide a healthy and comfortable indoor climate	3a	11	3
Design for a long lifetime	12a	11	6
Reduce or restrict the use of non-renewable natural resources	12c	11	11
Avoid the use of environmentally hazardous materials and sub-stances	3c	11	12
Reduce operational and embodied energy	7a	12	7
Provide sustainable mobility	11d	12	9
Support healthy and comfortable outdoor micro-climate	3b	14	8
Design for carbon neutrality	13a	16	9

This methodology has led to the creation of a general pathway to implement the A-SDGs and their targets. The planner has to filter the targets which cannot be addressed in specific contexts. For instance, target 3b deals with comfortable and healthy outdoor environments. Remodelling indoors might not address this target directly and therefore it might be neglected.

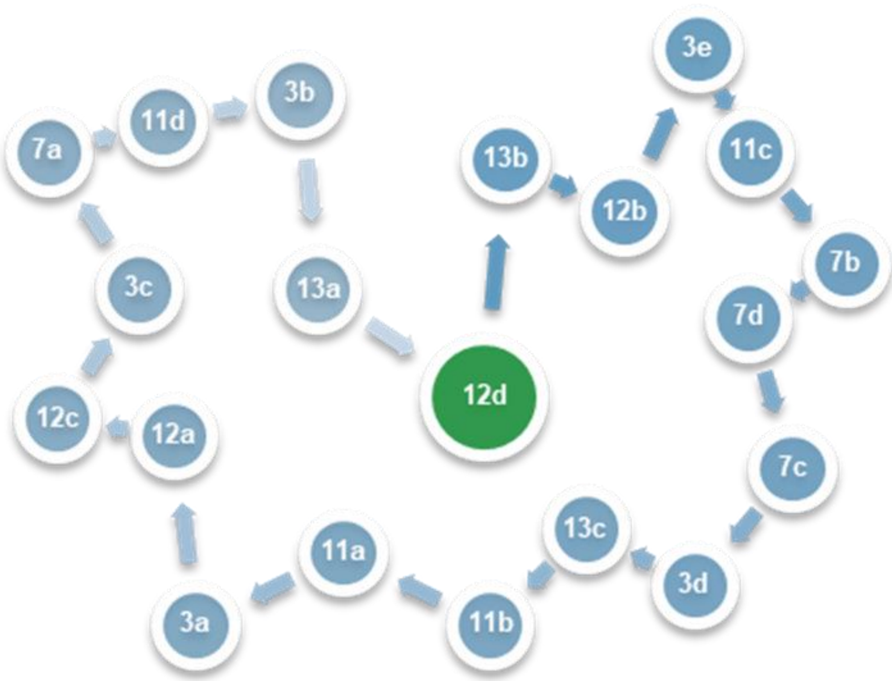


Figure 12: General pathway to apply the A-SDG targets

Together with the strategic application of targets in specific stages of design, as shown in Chapter 5, the planner has tools and methods to integrate architecture-related SDG targets into their design in the early design stages.

Selection of targets to test the methodology

The design strategies elaborated in the next sections will be put into practice through the development of a case study. Due to the extent of the full application of the derived architectural targets, which exceeds the scope of this master thesis, another filter is proposed to focus on the most relevant targets of the primary SDGs.

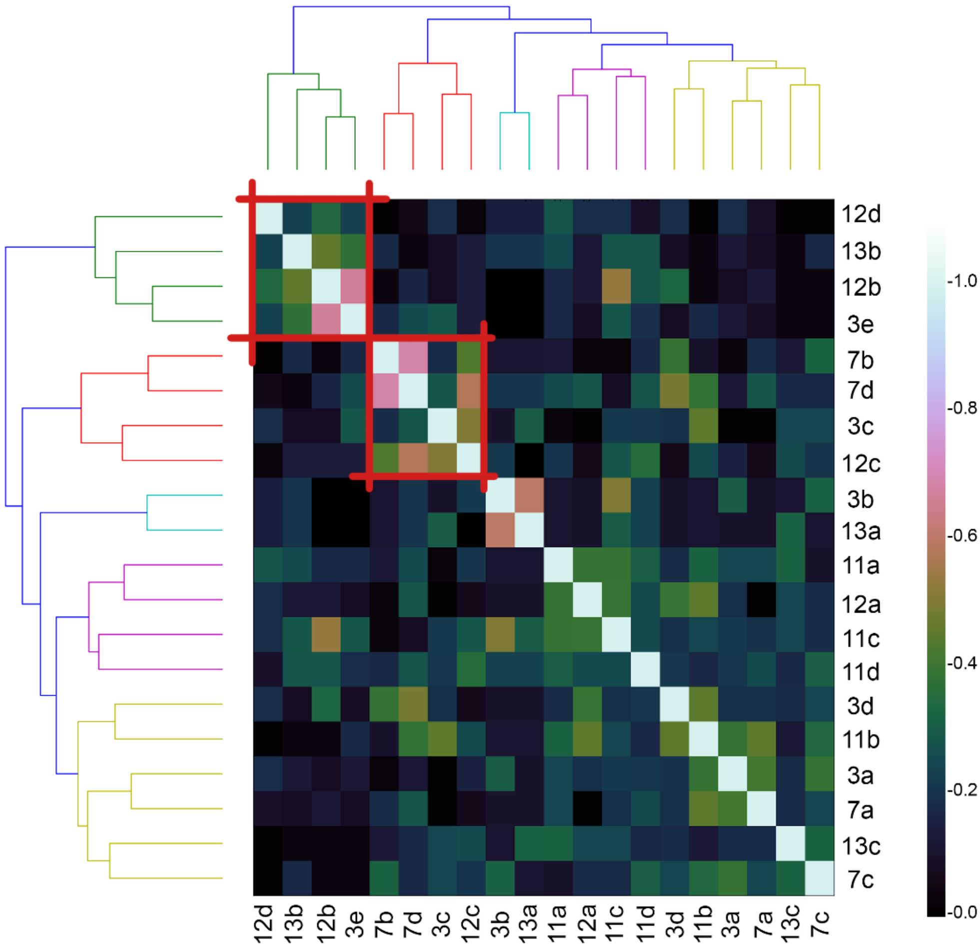


Figure 13: Clustering based on correlation algorithms

To identify the targets that correlate the most with each other and the ones that are independent of each other, a machine learning algorithm was performed on the targets´ matrix. The results of this process are shown in the Figure above. There are two clusters in the top left corner. These two clusters are the most independent clusters of the whole system.

The targets contained in the two marked clusters below represent, in contrast, the most dependent groups, meaning that their fulfilment relies on the realization of the targets higher on the stair. These two clusters represent the highest impact of the application of the methodology and are the foundation of the design project.

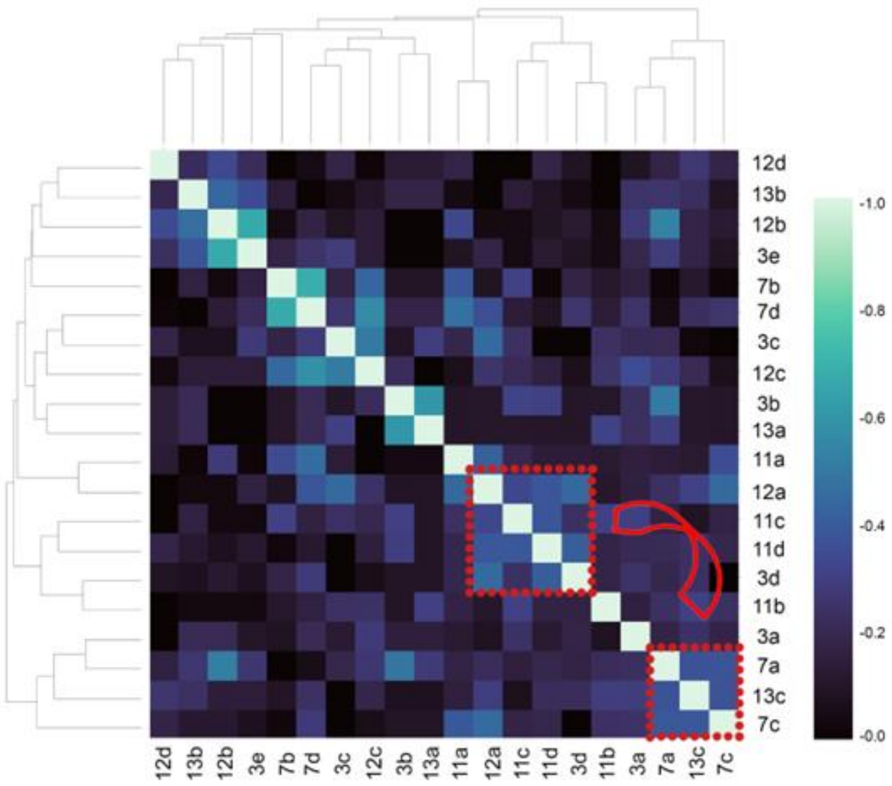


Figure 14: Hierarchical Clustering based on correlation

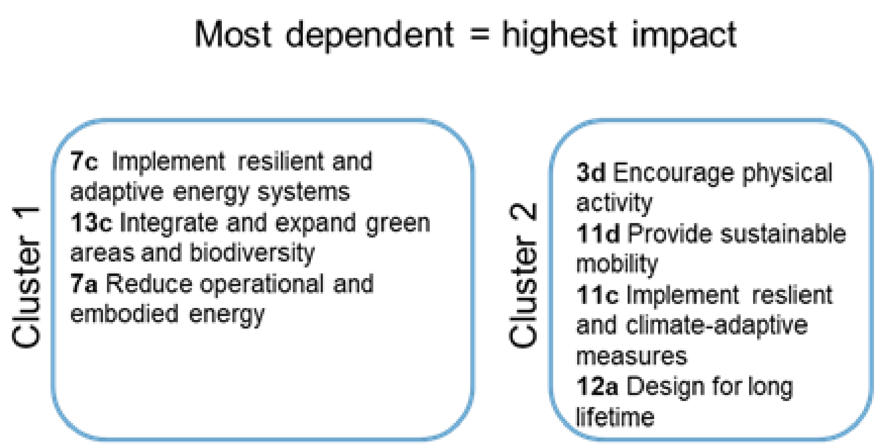
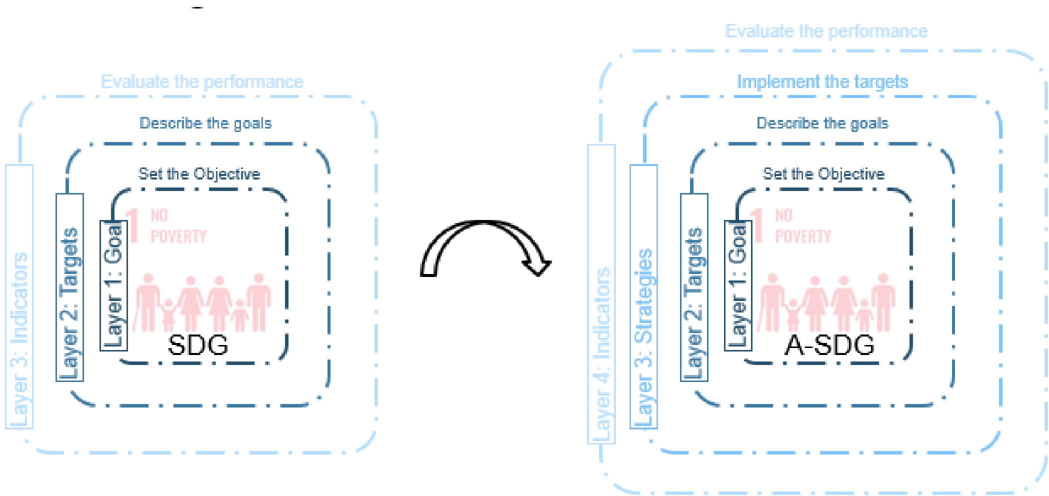


Figure 15: Selected clusters with their targets

3.2. Structure of architectural-related SDGs

The next sections will all focus on the primary SDGs and will serve as a methodic approach to explore the architecture-related SDGs in future research. Each SDG is composed of targets. Subsequently, each target presents specific design strategies relevant to the context presented in **Error! Reference source not found.** and the main key performance indicators to evaluate their fulfilment. The evaluation of the interactions among targets is performed at the level of the targets' definitions (as shown in previous section 3.1). Interactions on deeper levels like the design strategies or the KPIs are not assessed in this section but serve to validate the results of this chapter after the completion of the case study in Chapter 6.

The approach to decomposing the A-SDGs (Architectural SDG) is based on the same structure found in the standard SDGs. This is shown in the figure below.



The general SDGs (left) propose three layers in their structure. The first layer describes shortly the overall objective of the goal. The second layer represents the target level. The targets break down the overall goal into smaller pieces, easier to handle. The next and last level is the indicators layer. This last phase proposes performance markers (KPIs) to evaluate the fulfilment of the targets and eventually of the overall goal.

There is an extra layer included in the structure of the A-SDGs (right), the strategies level. The standard SDGs do not offer any strategies for the implementation of their targets. This might be due to the complexity of proposing general tactics for countries or cities with very different contexts. The case of the A-SDGs is similar. Therefore the context has been previously set up, in this case, the city of Kempten (Allgäu) in Germany.

The context is important due to the local regulations and climate defining the built environment. The strategies proposed to approach each target are based on the local climate, the local regulations and the local context regarding demographics, economy and others. These strategies serve the planners and designers with easy-to-handle ***recommendations*** (design strategies), which can lead the design to a sustainable approach. The figure below shows the structure of the architectural decomposition of SDG 3 into the four different layers: goal, targets, strategies and indicators.

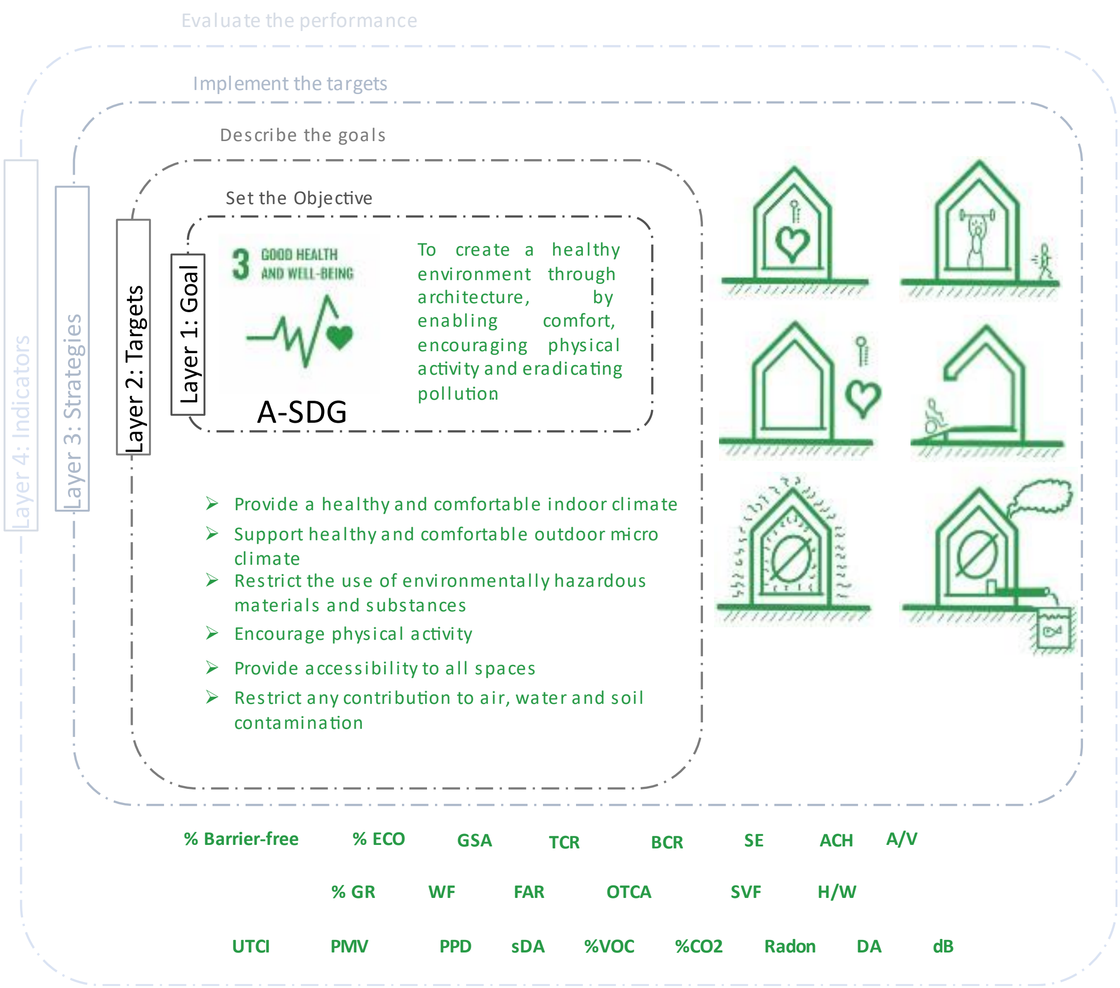


Figure 16: Goal, targets and KPIs

Analyzing the target “Provide a healthy and comfortable indoor climate” reveals the recommended design strategies for its fulfilment and KPIs relevant for the validation of the design strategies, which are integrated with scenarios derived from the assessment of the status quo as shown in Appendix E.

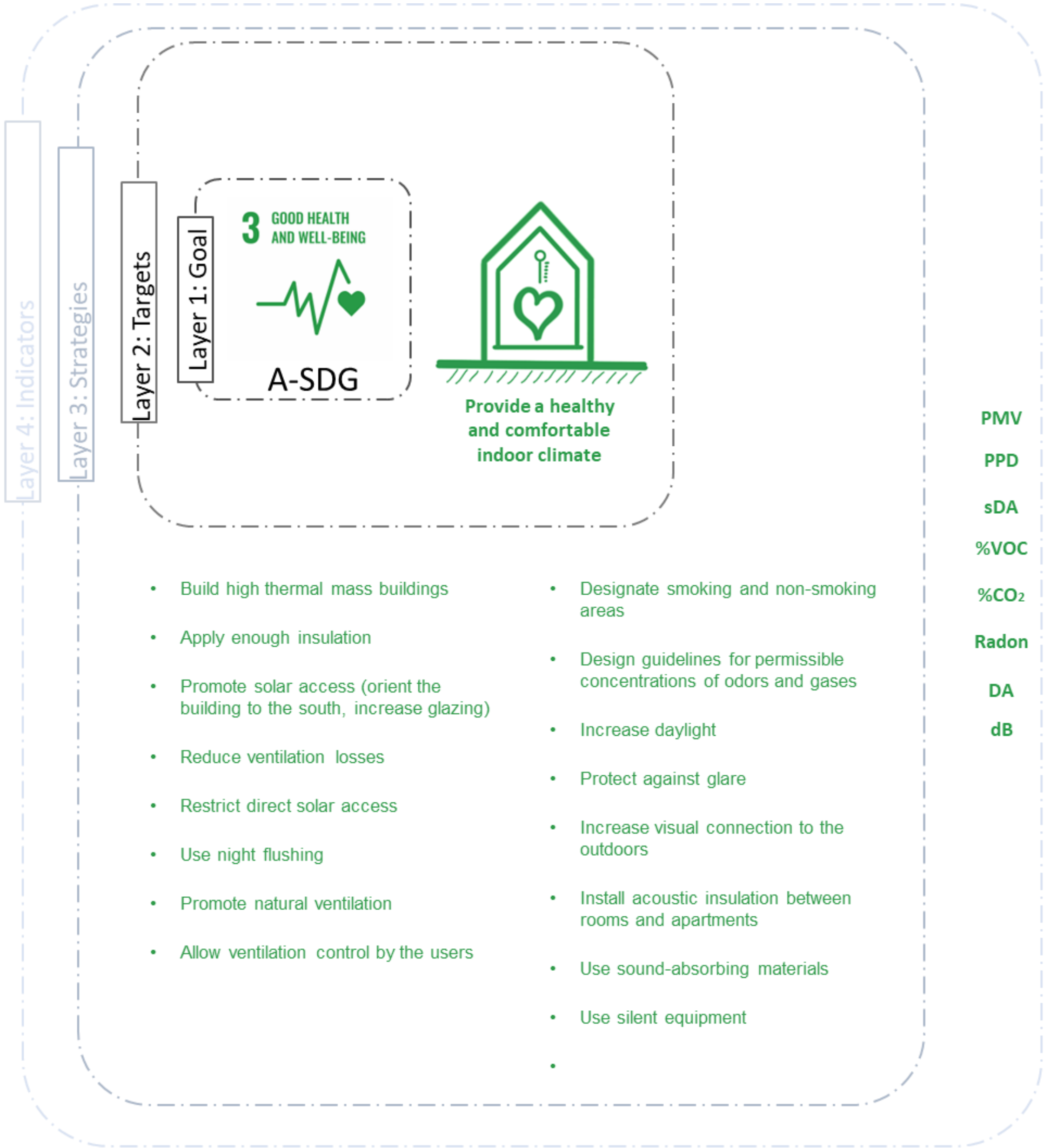


Figure 17: Strategies and KPIs

In the next section, each one of the sampled targets will be decomposed, serving as an example of the SDG-driven design methodology.

3.3. SDG 3 – Good Health and Well-Being

3d Encourage physical activity

“ Today, the majority of public health problems are related to chronic diseases. The built environment influences the public’s health, particularly concerning such diseases. However, many urban and suburban environments are not well designed to facilitate healthy behaviour or create conditions that protect health. Health officials can provide information about healthy living, but if people live in poorly designed physical environments, their health will suffer ” (Perdue et al. 2003).

Sedentary lifestyles and poor nutrition can lead to obesity, which is the main factor for some of the leading causes of mortality, including cardiovascular disease, diabetes, stroke, and some cancers (Mokdad et al. 2003; Glanz et al. 2016). But what can the built environment and architectural design do to alleviate this issue?

Many urban settings lack safe open spaces that inspire exercise and access to nutritious food and promote the use of alcohol and tobacco products through outdoor advertising (Perdue et al. 2003). A spread-out suburban design facilitates reliance on automobiles, increasing pollution and decreasing the time spent walking. Research has indicated that the way neighbourhoods are planned can affect both the physical activity and mental health of the communities’ residents (Renalds et al. 2010; Kent and Thompson 2014). Studies have shown that built environments designed to improve physical activity do demonstrate higher rates of physical activity, which in turn positively affects health (Carlson et al. 2012). The environment is integral in promoting physical activity (Goldstein 2002).

Studies have indicated that accessibility, connectivity, public open spaces, and natural parks have a strong correlation to human health in general and, in particular, early child development and health (Hu 2021). Walkability has been strongly related to land use diversity (multifunctionality of spaces) and the number of destinations within walking distance (Christian et al 2015). People living in neighbourhoods with a higher density of trees on their streets reported a significantly higher health perception and fewer cardio-metabolic conditions (Ewing et al 2010).

Design Strategies

- Increase diversity of spaces with overlayered functions and clear routes
- Give access to exercising areas with proper equipment
- Provide a comfortable microclimate (See 3a & 3b)
- Ensure gender-neutral designs without stereotypes
- Increase vegetation and scenery. Promote the journey to outdoor activities.
- Connect to nature increasing biophilic design principles.

Key Performance Indicators

- Exercising zones available (True/False)
- Shaded outdoor spaces (True/False)
- Barrier-free accessibility to sports facilities and spaces (True/False)
- Gender-neutral design of sports facilities (True/False)

Based on: (Zhong et al. 2022; Lorenzo-Sáez et al. 2021; Skiba and Züger 2020; Dovjak and Kukec 2019; Beatley 2016; Bluyssen 2014)

3.4. SDG 7 – Affordable and clean energy

7a – Reduce operational and embodied energy

In Germany, a noticeable trend towards greater comfort and more technological equipment is tending to raise energy demand. The consumption of living space has increased due to decreasing household size and increasing demand for personally available living space. Adding up to this, the number of electrical appliances used at home has also increased significantly. Energy efficiency is, therefore, essential to protect the climate and balance this trend. Three main strategies are for this relevant: increasing energy saving by reducing the amount of energy consumed to deliver the same function; improving efficiency by reducing energy losses, and using renewable energies to primarily cover the energy demand. On the urban scale, many factors can be influenced to reduce energy consumption like the compactness, density and orientation of buildings. Combining this with energy generation strategies like photovoltaics on the roofs, central or semi-central heat generation or implementing bans to reduce fossil fuels, greater efficiencies for the energy systems can be achieved. (Bott et al. 2019).

Alongside operational energy, the construction, renovation and after-life dismantling and disposal of the building also result in appreciable energy demand. This energy demand is called **embodied** energy and includes the energy used to manufacture and transport the materials used in the building as well as the energy used during the construction process itself. Key factors which determine the embodied energy of a building include building form, compactness, the ratio of net usable area to gross area, and of course the materials used. It is important during the design process to consider areas where alternative design solutions could reduce the embodied energy of the building, and also identify situations in which decreasing a building’s operating energy might be associated with increased embodied energy. The choice of building construction system and material (e.g. concrete, steel, timber) affects embodied energy, but also other factors such as thermal mass. The choice of building materials can also impact energy performance in other ways; e.g. the use of interior finishings and fit-out materials with low VOC-emitting materials can reduce the required ventilation rate and improve indoor air quality (Brian Cody 2017).

Design Strategies

- Increase natural ventilation in the summer:
- Support natural ventilation with decentral mechanical air ventilation with heat recovery for the winter
- Use the earth as a cooling/heating device to support heat pumps
- Use the night ventilation to cool down the mass of the building in the summer
- Implement low-temperature-gradient energy delivery systems like floor heating/cooling or thermal component activation
- Install photovoltaics extensively
- Plan compact buildings (low A/V ratio). If not possible, create buffer zones to balance the irregularities of the shape
- Insulate according to the energy standards, the climate and the context
- Allow solar access in the winter and sun shading in the summer. Orient the building to the south. Increase WWR on the south and reduce it on the east, west and north facades.
- Conduct an LCA for different constructions to reduce the embodied energy, using as many biogenic materials as possible

Key Performance Indicators

- Total Primary Energy (PEtot – kWh/m²a)
- Total Primary Energy usage(PEtot.u – kWh/m²a)
- Total Primary Energy construction(PEtot.c – kWh/m²a)
- Heat transfer coefficients, differentiated by different exterior components (U-Value – W /m²K)
- Window-to-wall ratio for all facades (WWR - %)
- Load Match (LM - %)
- Energy Use Intensity (EUI - KWh/m²a)

Based on: (Hausladen et al 2012; Alexander Zhivov et al 2022; Pan and Du 2022; Jonathan Natanian 2020; Brian Cody 2017; El Khouli et al 2015; Hegger et al 2007; Voss 2007; BRE, Passivhaus Institut)

7c – Implement resilient and adaptive energy systems

The term resilience describes the ability to survive and quickly recover from extreme and unexpected disruptions. A high energy system resilience is of utmost importance to modern societies that are highly dependent on continued access to energy services (Jasiūnas et al. 2021). The most widely accepted and used definition of energy system resilience is given by the International Energy Agency (IEA) and includes an exceptionally long set of specifications: *"The capacity of the energy system and its components to cope with a hazardous event or trend, to respond in ways that maintain its essential functions, identity and structure as well as its capacity for adaptation, learning and transformation. It encompasses the following concepts: robustness, resourcefulness, recovery".*

Many factors can affect the performance of an energy system, such as political, human, market or environmental dimensions. This work focuses on the interaction between energy systems relevant to the built environment and environmental parameters, such as climate change.

The lack of resilience in energy systems can have deep consequences on the infrastructure of a city affecting the proper functions of hospitals, schools, businesses and homes. Therefore, resilience must become an integral goal in the energy master planning of all new or refurbishment developments. Best practices for resilient electric and thermal energy systems favour the use of installed energy sources rather than the use of emergency generation for short durations, and promote the use of multiple and diverse sources of energy, with an emphasis on favouring energy resources originating within the community (Alexander Zhivov et al 2022).

Different system options can be considered on the building level, building cluster level, or community level. Selection of these alternatives should consider the existing status of these systems, and the goals and objectives of the project, including improvement in systems resilience, local constraints, and economic and non-economic co-benefits (Alexander Zhivov et al 2022).

The creation of scenarios is useful to evaluate the implementation of possible systems and their interactions with other targets.

Design Strategies

- Identify key characteristics of the location: potentials and threats
- Establish the baseline case
- Analyze Energy system alternatives
- Conceptualize goals and constraints
- Create scenarios for future climate
- Integrate renewable energy generation systems
- Integrate energy-efficient systems for distribution
- Define backup systems and storage
- Develop implementation strategy

Key Performance Indicators

- Share Primary Energy renewable (%)
- Share Exported Energy (%)
- Test Reference Year - EPW
- The efficiency of the energy generation systems
- Load Match (%)
- Energy storage capacity (kWh)
- Energy Use Intensity (KWh/m^{2}a)

Based on: (Hausladen et al 2012; Alexander Zhivov et al 2022; Jasiūnas et al. 2021; Ujang et al. 2021; Otto-Zimmermann 2012; Hegger et al 2007)

3.5. SDG 11 – Sustainable cities and communities

11c – Implement resilient and climate-adaptive measures

In the realm of cities, resilience can take up many forms and shapes. There are three main approaches to allocating resiliency to the urban system.

The first one, Engineering resilience, deals with the ability of systems to recover after disruptions or perturbations, rendering them more resilient the sooner they recover.

The second approach, ecological resilience, measures the magnitude of disturbance an ecosystem can manage before it cannot go back to its original state. Ecological environments are dynamic and any perturbation can lead to a reconfiguration of their core variables.

The third approach, social-ecological resilience, comes from the analysis of the interconnectivity among ecological systems and social environments. (Ayyoob Sharifi et al. 2022). This last approach implements adaption and restructuring as an ability to counteract disturbances. This chapter is based on socio-ecological resilience.

Design Strategies

- Provide energy security by incrementing the share of on-site generation
- Provide equitable solar access: use deciduous trees on the south and evergreen on the north, east and west
- Analyze wind patterns and barriers to promote thermal comfort
- Introduce areas for food production
- Assess vulnerability hotspots within a region: Flooding, sea level, etc.
- Introduce measures to counteract the vulnerabilities: catchment areas, improved peak discharge coefficient, etc.
- Utilize local water resources like rainwater and grey water and support natural loops to preserve them
- Integrate shading in the outdoor spaces to reduce the heat stress in the summer
- Install green roofs and facades to use the evapotranspiration of plants as cooling potential

Key Performance Indicators

- Checklist design strategies
- Share Exported Energy (%)
- Universal thermal comfort index (°C)
- Areas for food production available (True / False)
- Rainwater use planned (True / False)
- Grey water recycling system available (True / False)
- Water use intensity (l/m²d)

Based on: (Otto-Zimmermann 2012; Ujang et al. 2021; Dubbeling et al. 2009; Norbert Lechner 2015; Brears 2021; Friedman 2021a; Lorenzo-Sáez et al. 2021; Bott et al. 2019; Koch and Krellenberg 2018; Tavares & Swaffield 2017 2017; Schröpfer 2015)

11d – Provide sustainable mobility

Sustainable developments are characterized by the prioritization of the needs of pedestrians over vehicles (Cervero 2009). Investing in active mobility such as pedestrian pathways, buses, bike roads and green infrastructure, increasing its public appeal and minimizing car-centric infrastructure can boost chain reactions. Active mobility includes walking, running, biking, skateboarding, rollerblading and using a wheelchair (Government of Canada 2014).

Active mobility benefits individual and public health, the environment, and the economy. As the European Heart Network states, the transition to active mobility and public transportation can only occur if sustainable transport choices become more attractive, convenient, and affordable than private vehicular transport (European Heart Network 2008). Planners should design transit systems to be sustainable in every way possible, using renewable energy sources, green technologies and low-impact strategies.

Design Strategies

- Analyze the availability of public transport routes in the vicinity of the development
- Provide access to different low-carbon means of transportation such as bikes, scooters, electric vehicles
- Evaluate the accessibility to bus/tram stops for barrier-freedom
- Assess the conditions of bus/tram stops regarding the protection against the climate and comfort: Shading, lighting, sitting
- Provide clear information and directions relevant to the public transportation
    - Provide car sharing and charging stations for electric vehicle

Key Performance Indicators

- Availability of public transit (True / False)
- Intermodality available (True / False)
- Proximity of bus stops to homes (True / False)
- Adapted transport for barrier-free access (True / False)
- Bus shelters in good conditions (True / False)
- Display of bus schedules at the entrance of houses (True / False)
- Bike rental station available (True / False)
- Car sharing facilities within the development´s premise (True / False)

Based on: (Friedman 2021a; Lorenzo-Sáez et al. 2021; Bürstmayr and Stocker 2020; Skiba and Züger 2020; Bott et al. 2019; Gatrell et al. 2016)

3.6. SDG 12 – Responsible consumption and production

12a – Design for a long-term and circularity

Material resources, such as water, fossil fuels and minerals, should be used in an environmentally responsible way. Resource depletion can be slowed by consciously limiting material use to a minimum, using building products that are manufactured in a resource-efficient and environmentally friendly way, implementing renewable raw materials and making optimal use of all properties (e.g. use of durable materials with long renewal cycles).

The significance of a component's embodied energy rises in buildings with low energy demand and very long use phases (usually residential buildings and office buildings in upmarket areas). The Nearly Zero-Energy Standard is to become mandatory for all new builds in Europe as of 2021. At the latest from this time onwards, all new residential buildings will invest around 50 % of the total life cycle energy input in the construction.

To make full use of the design life of durable components, it is beneficial to choose a timeless building design. The components in very long-lasting buildings can rarely be designed in such a way that they reach the end of their service lives at the same time. It is best therefore to divide the replacement measures into smaller portions of work. As a result, buildings can retain their value for longer but are less flexible when it comes to changes in use.

Design Strategies

- Plan for flexibility of use
- Plan the majority of inner partitions not load bearing
- Shaft configuration should allow flexible planning
- Adapt the material input to the intended use
- Adapt the durability of building materials and constructions to the intended use
- Plan for disassembly using separable constructions

Key Performance Indicators

- Expected lifetime of the construction (Years)
- Building elements planned for disassembly (True/False)
- Shafts provide uninterrupted vertical access (True/False)
- Lifecycle of building materials evaluated and documented (True/False)

Based on: (Theilig et al. 2021; El Khouli et al 2015; König et al 2010; Nurgül Ece 2018; Migliore et al. 2020; DGNB-Criteria-Set-Buildings-In-Use-Version 2020 2020; DGNB GmbH 2020b, 2020b; Hillebrandt and Seggewies 2019; Yang et al. 2022)

3.7. SDG 13 – Climate action

13c – Integrate and expand green areas and biodiversity

The built environment is responsible for nearly 30% of biodiversity loss globally (World Economic Forum, 2020). This target is based on the concepts of the green city, the regenerative city and animal-aided design (AAD) to create a synergetic landscape for humans and other living beings.

The green city revolves around the fact that exposure to natural environments (green space) can help reduce many health issues like depression and stress, improve cognitive capacity and help manage the symptoms of anxiety disorders, schizophrenia, ADHD and dementia. Nature exposure in childhood reduces the risk of developing mental health problems in adulthood. The impact of green space on mental health is modified by the amount of green space involved, accessibility of that green space from home, the type of green space, views of nature, perceived quality of green space, the richness of biodiversity involved, usage patterns and the amount of exposure. There are inequalities in people's experiences of – and access to – the green city that impact mental health. Design approaches should focus on maximizing green space quantity, quality and accessibility across the city, with particular investment for children, youth, older people, and marginalized groups (Roe, J., & McCay, L. 2021).

The regenerative city envisions a system in which humans participate as nature, coevolving as a whole system. Designing activities like agriculture, land development and transportation should lead to harmonized natural systems supporting the local green infrastructure (Rob Roggema 2022). The concept of regeneration goes beyond sustainability, which envisions a zero-impact approach. To regenerate means to become a positive asset to the environment.

Lastly, the core idea behind the animal-aided design is to integrate the lifecycle of animals, especially the ones in danger, into the landscape and building planning. By integrating these lifecycles, there is a higher probability to increase the population of particular species, restoring the health of species and their populations (Thomas E. Hauck & Wolfgang W. Weisser 2015; Hauck and Weisser 2015; Hauck et al 2017).

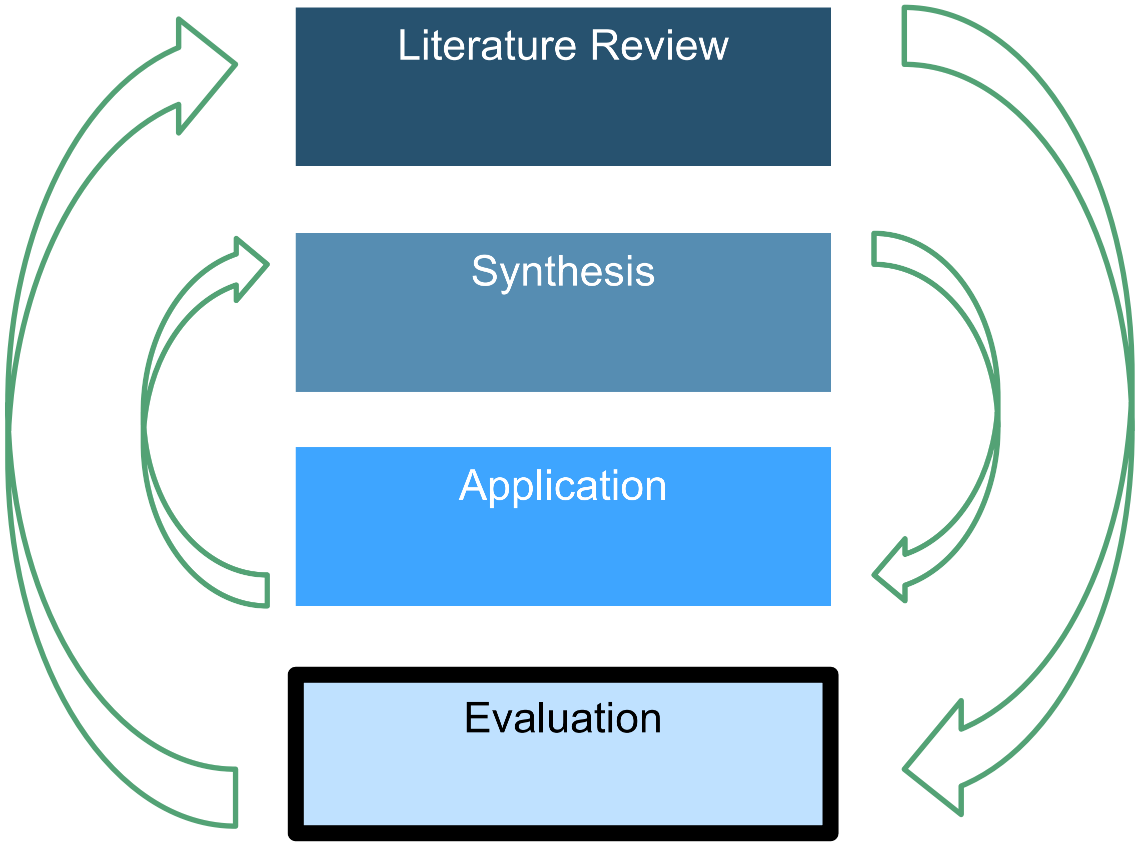
Design Strategies

- Install green roofs and/or green facades
- Evaluate the synergies and trade-offs between the green and blue infrastructure
- Provide accessibility to the not protected green infrastructure
- Place green features in such a way that it is visible and usable by the majority of the inhabitants
- Introduce high-quality green infrastructure to nurture the biodiversity
- Reduce impervious surfaces
- Analyze the requirements of the local habitats and introduce measures to strengthen them
- Introduce AAD strategies by locating the endangered and local species that could thrive in the new development

Key Performance Indicators

- Biodiversity Index (-)
- Share of green roofs (%)
- Share of green facades (%)
- AAD strategies (True/False)
- Impervious / Pervious surface ratio (%)
- Accessibility ratio to outdoor spaces (-)

Based on: (Roe, J., & McCay, L. 2021; Thomas E. Hauck & Wolfgang W. Weisser 2015; Beatley 2016)(Rob Roggema 2022; Zhong et al. 2022).(Hauck and Weisser 2015; Andreucci et al. 2021; Rob Roggema 2022; Roös 2021b; Roe, J., & McCay, L. 2021; El Khouli et al 2015)


Literature Review
Synthesis
Application
Evaluation

Chapter 4: Design Project

4.1. Relevance of the design project

The design project is coupled with the research project “Densification in the context of climate change”. Building upon the work of Elena Kühner (2022) presented in her master thesis “ Planning living space within the available German GHG-Budget”, this section of this work aims to compare the design approach selected by Kühner, described further as an “LCA-driven” approach, with the SDG-driven design approach explored in this work. As an example of the “standard” design approach, the “baseline” case is derived from the analysis of the existing structures and serves as a third methodology to compare. The proposed design guidelines address the necessity for more living space while remaining within the sustainable design framework based on the SDGs. This section should give the reader an idea of the potential of implementing this SDG-driven design methodology and how to effectively apply it.

4.2. Defining the foundation for the analysis

The design project is located in Kempten, Germany. The requirements concerning the building codes are drawn from the previous analysis performed by Kühner in her thesis. In short form they describe the main use of the plot (Residential) and its surrounding usages, allowing the possibility to deviate from the “only” residential use to a mix-use, in case it is required. There are strict rules given by the local government, as to the conservation of the architectural impression of the place and as to the conservation of its established ecosystems. The selected location does not have any risks of flooding or any restrictions imposed by natural treasures. The main demand from the city regulations is that vertical and horizontal expansions do not jeopardize the local context and preserve the local biosphere.

In the case of the evaluation of the existing structures, Kühner has established that vertical densification of one extra floor could be performed in most cases for this type of construction. Nevertheless, the possibility of adding more than one floor, by reducing the loads located in the concrete roofs is taken.

LCA Assumptions

Few KPIs are relying on results from the LCA. The phases included are the manufacture (A1 to A3), the construction (C3 and C4) and the use phase (B6). The LCA workflow developed for the parametric multiple-variate simulation of scenarios should be extended to include the stages B2, B3, B4, B5 and B7. The evaluation of module D, attributed to the reuse, recovery and recycling potential should be as well included in further explorations. The piping in the floor heating system, the construction located in the staircases, and the HVAC systems have been in these early design stages neglected, require therefore further adjustments to get a clear assessment of the environmental impacts of the SDG-driven approach. The construction of the floor slabs envisions the use of basalt plates as a recyclable option for floor heating substructures. Nevertheless, there is no data regarding the environmental performance of that particular material and mineral wool was selected as a replacement. The hollow stone ceilings are modelled with 2% of steel reinforcement.

4.3. Design Process

The design process is presented while comparing the results to other design methodologies, such as the LCA-driven approach and the baseline. Each one of the evaluated targets is compared separately, providing information about the decisions taken in the SDG-driven approach. Besides the 20 targets representing the primary SDGs, 24 KPIs for the evaluation of the urban and building setting were added. These have been filtered to lead the design process more comprehensively.

Urban and building setting

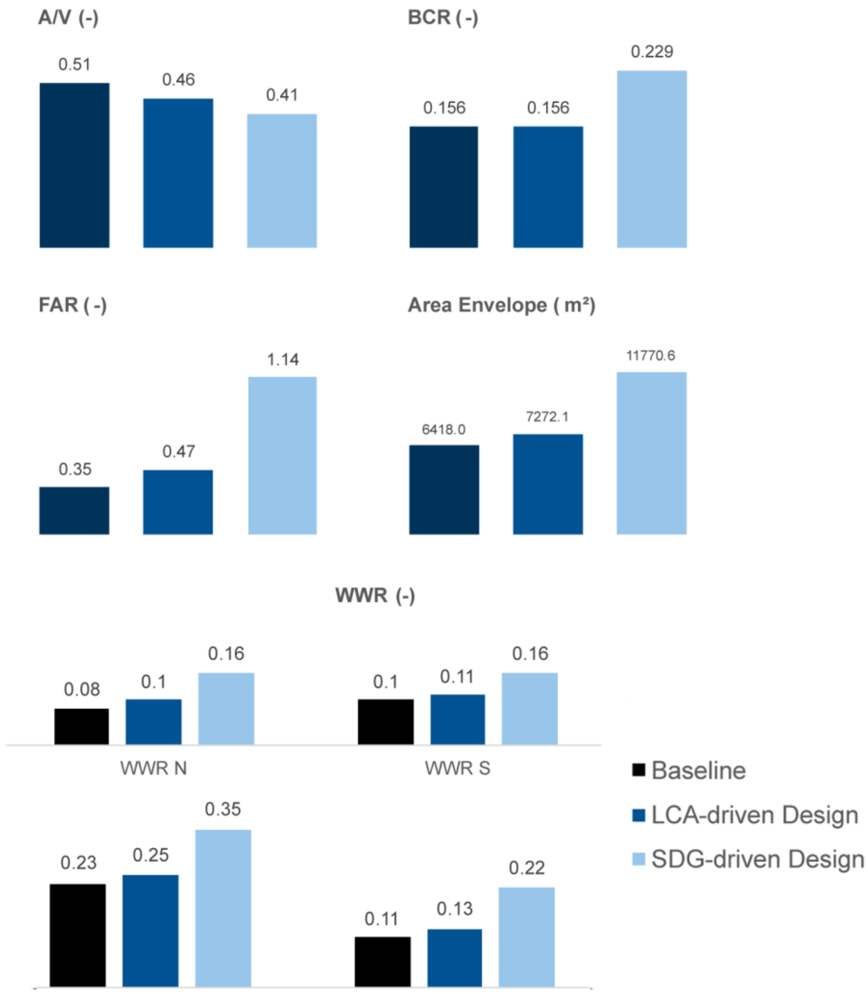


Figure 18: Urban and building geometry KPIs

The SDG-driven proposal shows an increase in the built volume of around 227 % and 182 % compared with the baseline case and the LCA-driven proposal respectively. This increase is due to the more extensive vertical and horizontal expansion. The compactness, the ratio of building footprints to the urban site area, can be used to assess prematurely the impacts of a building´s energy efficiency, carbon footprint, energy use and others (Natanian,2020). The lower values of this indicator represent higher densities, leading to increased energy efficiency and reduced energy use and carbon footprint (Natanian,2020). The presented SDG-driven design shows an improvement in compactness, reducing it by approx. 20% from the baseline and 11% from the LCA-driven case. The vertical and horizontal extension has a positive impact on this indicator.

The building coverage ratio (BCR) reflects the impacts on the existing green infrastructure (GI). There is an increase on the sealed surfaces from approx. 46% compared to the baseline and the LCA-driven approach. This increase results in a reduction of 37 % of the GI surface, which will require adaptive measures to maintain its quality.

Another indicator of the density of development is the floor area ratio (FAR). The German Federal Land Utilisation Ordinance (BauNVO) indicates that for urban developments, a maximal NFA of 3 can be achieved. The SDG-driven proposal shows a FAR of 1.14, which remains below the permitted maximal FAR. The remaining density potential requires deeper evaluation to avoid compromising the integrity of the green, blue and grey infrastructure.

As previously stated, the reduction of the GI requires adaptive measures. Extending the GI vertically on the exterior walls can not replace the quality of the ground-level GI, nevertheless, it can expand the habitats of selected species to support their regeneration (Hauk et al. 2015). The main differences between the different design strategies can be summarized with the following indicators. The number of floors increased to two in the SDG-driven and one in the LCA-driven cases. This increases the building´s envelope by approx. 83% and 33% respectively, compared to the baseline case. The window-to-wall ratios (WWR) suffer similarly very perceptible changes. The SDG-driven design promotes inclusion and connection to the surroundings, which leads to the design strategy of creating an extensive net of interconnected balconies. In response to this, the WWRs had to be adapted to host the main entrance to the apartments and open the indoor spaces to the outside. In the SDG-driven approach, the average WWR increases around 70 % and 50% compared to the baseline and the LCA-driven case, which requires special measures regarding thermal comfort and energy loss.

SDG 3: Good health and well-being

In the same structure as before, the following figure summarizes and visualizes the quantitative indicators for this goal.

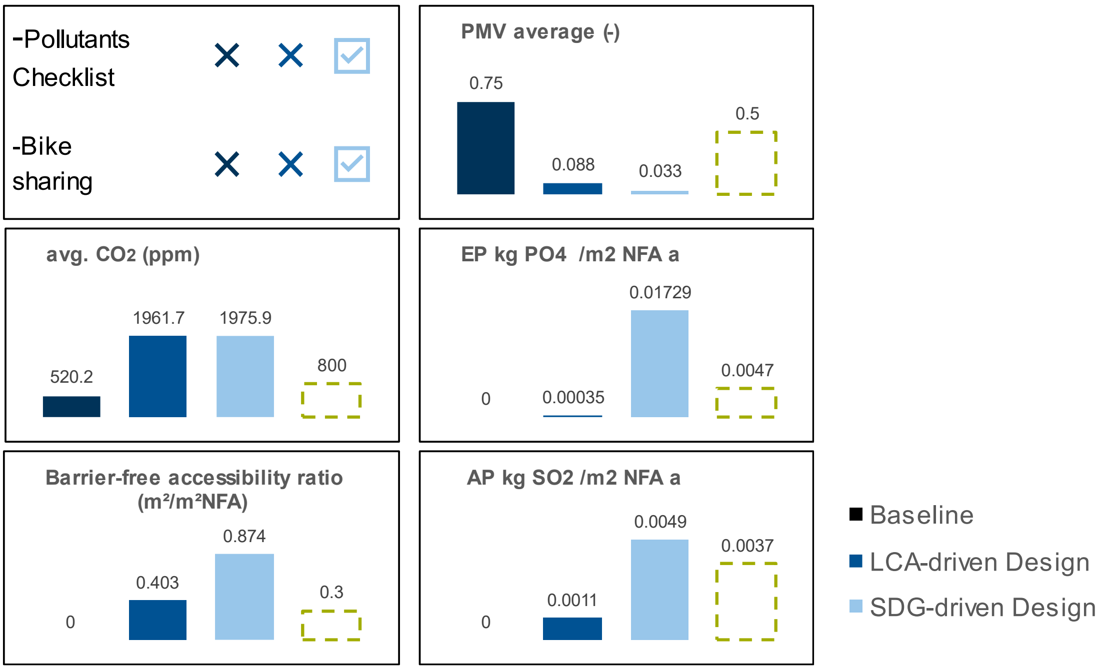


Figure 19: SDG 3 - KPIs

The Living Building Challenge, an international building certification institution, created in 2015 the "red list" of building materials, which should not be used in construction. This list is used to control the pollutants in the SDG-driven scenario. For example, the use of asbestos in Germany since the year 2003 is prohibited. Nevertheless, the baseline scenario dates from the years 1945-1957. Therefore, asbestos could be found in the building and requires special evaluation on-site. The "red list" should be carefully checked to avoid using hazardous materials for humans.

The results of the simulations show that the indoor air quality, represented by the concentration of CO2 indoors, has decreased in the LCA-driven and the SDG-driven cases. It is necessary for higher stages of the development to further analyze this indicator to bring the concentration of CO2 within boundaries (max. 800 ppm).

The results for the evaluation of the thermal sensation indoors show that the baseline case, with a PMV average of -0.75, fails to meet the recommended benchmark (DIN 7730) for the PMV (-0.5 to +0.5). Both, the SDG-driven and the LCA-driven scenarios fulfil the requirements for thermal comfort.

The SDG-driven case envisions the integration of bike and car-sharing facilities as a sustainable mobility initiative. Access to bikes should contribute to the health of the inhabitants of the site. The other design methodologies only consider bike parking. The accessibility to indoor and outdoor spaces represents a measure of inclusion, strengthening the community (Zhong et al2022) and encouraging physical activities (Roe, J., & McCay, L. 2021).

The eutrophication potential, which causes over-fertilisation of soil and water bodies, shows to be 50 times higher in the proposed SDG-driven construction than in the LCA-driven approach, missing the benchmark (0.0047 kg PO4/m² NFA*a) by approx. 270%. Further optimization should be carried out to minimize this KPI within the recommended boundaries.

The acidification potential (AP), similarly to the EP, exceeds the established benchmark of over 30% and needs to be optimized. The LCA-driven approach remains within boundaries with an almost 4.5 times lower AP than the SDG-driven approach.

SDG 7: Affordable and clean energy

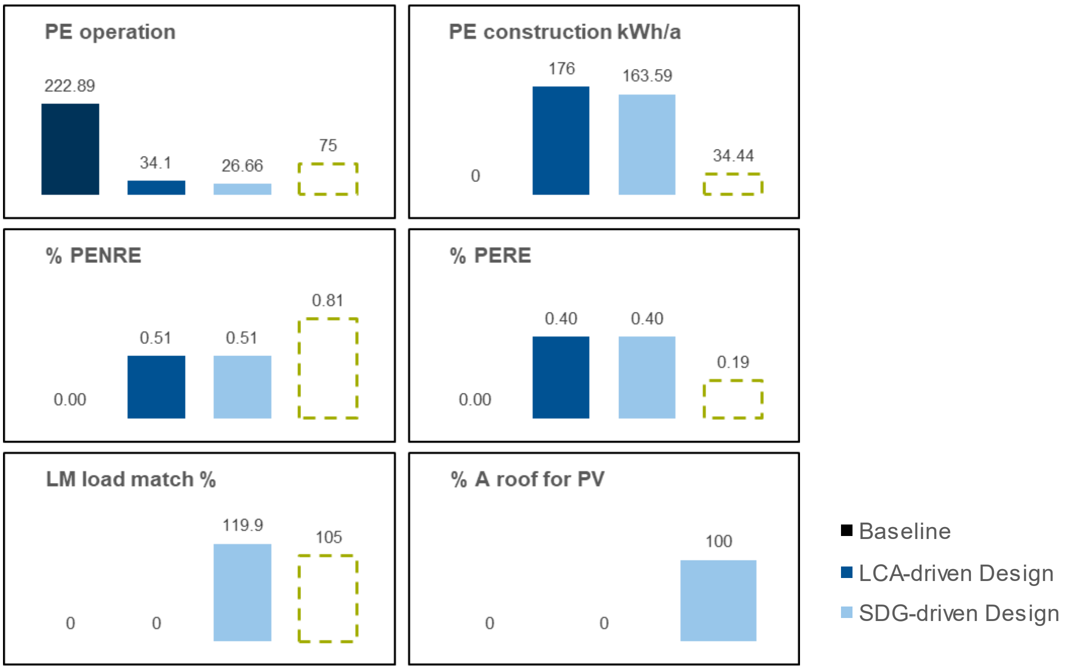


Figure 20: SDG 7 - KPIs

The minimal energy efficiency class for new buildings should be class B, which represents the GEG standard within the primary energy demand of between 50 and 75 kWh/m²a. The baseline requires an energy demand for heating of 223 kWh/m²a, requiring an immediate upgrade. In contrast, the LCA-driven and the SDG-driven proposals are planned with the passive house standard, setting them in the A+ energy efficiency class. Furthermore, the SDG-driven proposal has improved efficiency by 20 % when compared to the LCA-driven approach, even though the NFA is higher.

The embodied primary energy (PE tot), on the other hand, shows an exceedingly high demand, in both, the LCA-driven and the SDG-driven cases. They both require an optimization cycle to reduce this indicator within the recommended boundaries. The baseline scenario is not evaluated, on account that it is already built.

An indicator of a settlement´s energy resiliency is the load match, which reflects the temporal coverage ratio of total energy consumption by on-site renewable energy generation (Widén et al., 2009). The LBC recommends an energy generation on-site of 105%, which the SDG-driven design positively exceeds with almost 15 %. For this, it occupies almost 100% of the roof surface, leaving only the areas on top of the balconies for greening. The overflow of energy can be used within the boundaries of the city, reducing energy imports and dependency on external sources. The LCA-driven design approach speculates about the use of the roof for greening or photovoltaics, it is, nevertheless, not planned. The baseline case does not include on-site energy generation of any kind.

SDG 11: Sustainable cities and communities

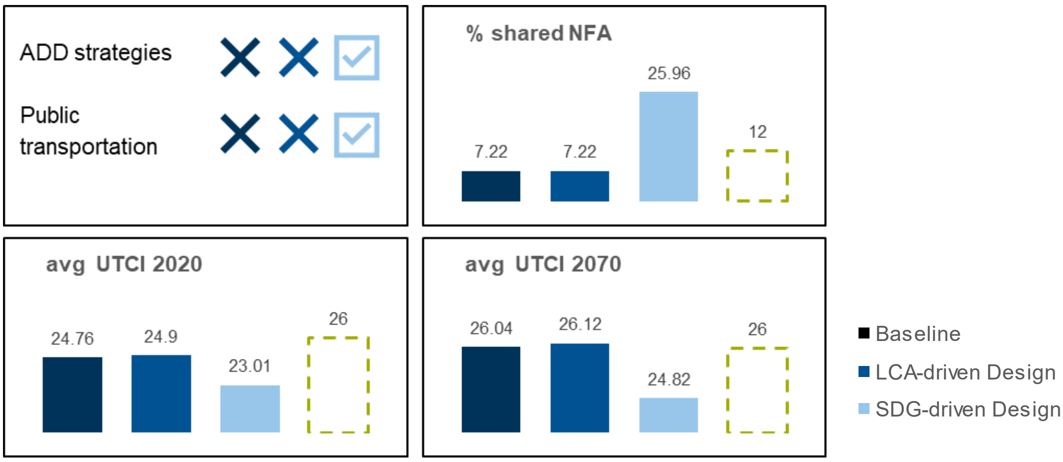


Figure 21: SDG 11 - KPIs

Mahdavinejad et al, 2012 calculated the required shared spaces for residential complexes as around 12%. This is the only source found related to a benchmark for communal spaces. The SDG-driven approach offers the inhabitants of the development a generous 26% of communal spaces when compared to the LCA-driven proposal and the baseline, with only outdoor shared spaces accounting for 7% of the net floor area.

An important indicator for regenerative design procedure is the application of animal-aided design strategies (Hauck et al., 2015). The SDG-driven design approach includes the regeneration of two widely in Europe affected species, the house sparrow and the sand lizard. By applying the life cycle requirements of this species to the design of the landscape, the survival of the species can be secured and they can thrive in situ. Furthermore, the performed adaptations are also beneficial for other species, boosting the biodiversity index of the plot.

Błażejczyk et al. 2013 created a table to classify the thermal senstaion outdoors. When the UTCI rises over 26°C the range of moderate heat stress starts. This benchmark is used to compare the different design methodologies. Both, the baseline´s and the LCA-driven approach´s average UTCI are similar and score positively for the current climate (EPW2020). Nevertheless, the results of the simulations show that climate change in 2070 (EPW 2070) compromises the integrity of outdoor comfort with a UTCI of over 26 °C, setting the inhabitants of the future in moderate heat stress. The same climate scenarios evaluated in the SDG-driven design result in comfortable UTCIs of 23 °C and 24.8 °C for the weather years 2020 and 2070 respectively. This shows the positive impact of extending the green infrastructure with deciduous trees, generating passive shading in the summer and allowing solar access in the winter.

The current state of public transportation was qualitatively controlled. There is a bus stop within 350m, cycling routes within 250m and adequate pedestrian infrastructure, which qualifies the overall urban setting. By comparing the indicators relevant to the facilities on-site, the Baseline and the LCA-driven design provide only parking spaces for bikes but do not include a mobility plan for car/bike sharing, and charging stations nor extend the capacity of the parking facilities to cover the demand derived from the extensions.

SDG 12: Responsible production and consumption

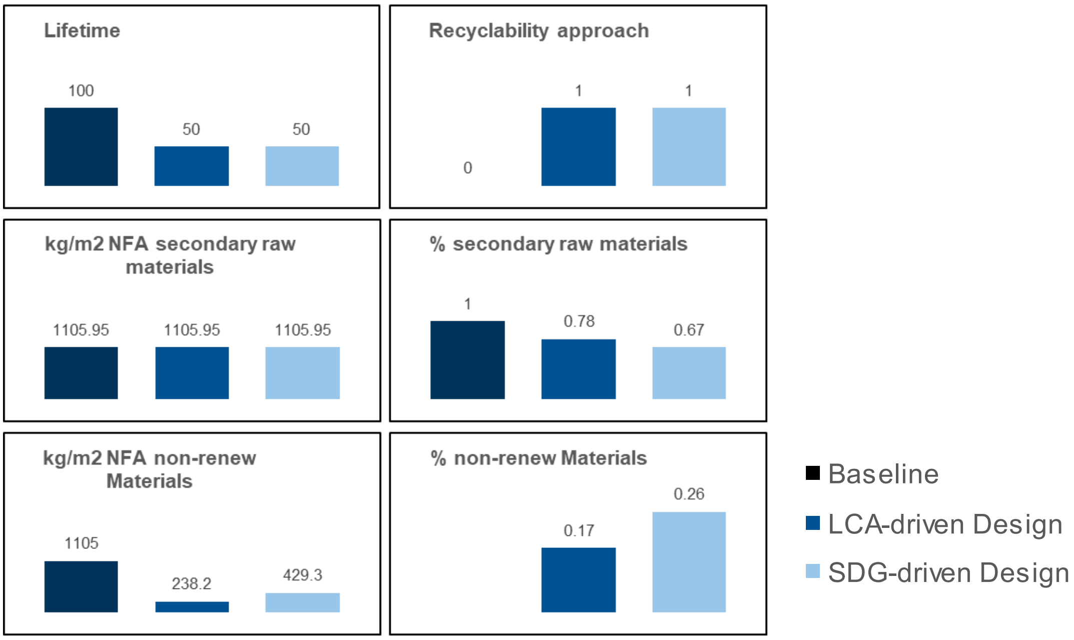


Figure 22: SDG 12 - KPIs

Both the LCA-drive design and the SDG-driven proposal show embedded recyclability approaches. Both constructions were qualitatively evaluated through the architectural drawings of their elements. The amount of non-renewable materials underwent an almost two-fold increase in the SDG-driven design when compared to the LCA-driven approach. This is mostly on account of the balconies and the horizontal extension. No benchmark related to this KPI could be found in the literature. The share of prefabrication is a difficult KPI to measure. The author analyzed the principles shown in Kaufmann et al. (2017) to quantify the prefabrication ratio possible for the LCA-driven and the SDG-driven approaches. Both qualify for a high degree of prefabrication. No benchmark regarding a minimum degree of prefabrication could be found in the literature.

SDG 13: Climate action

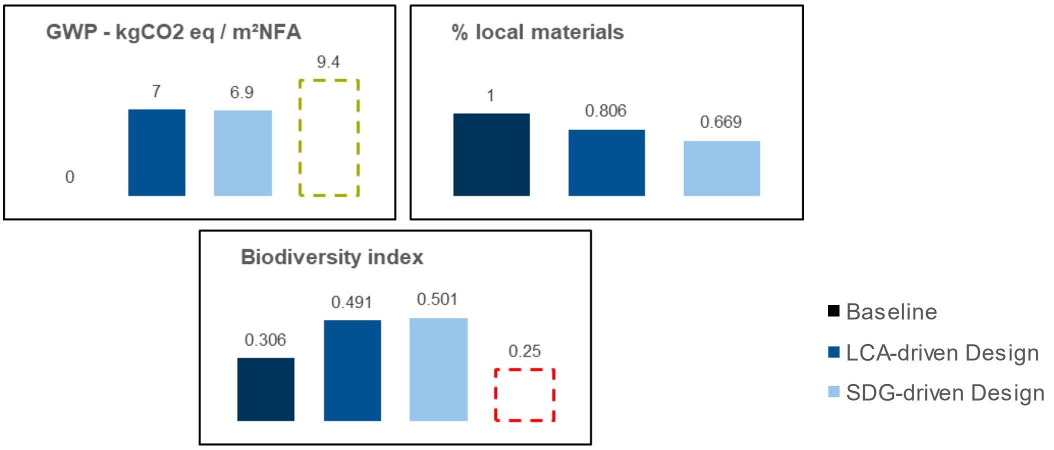
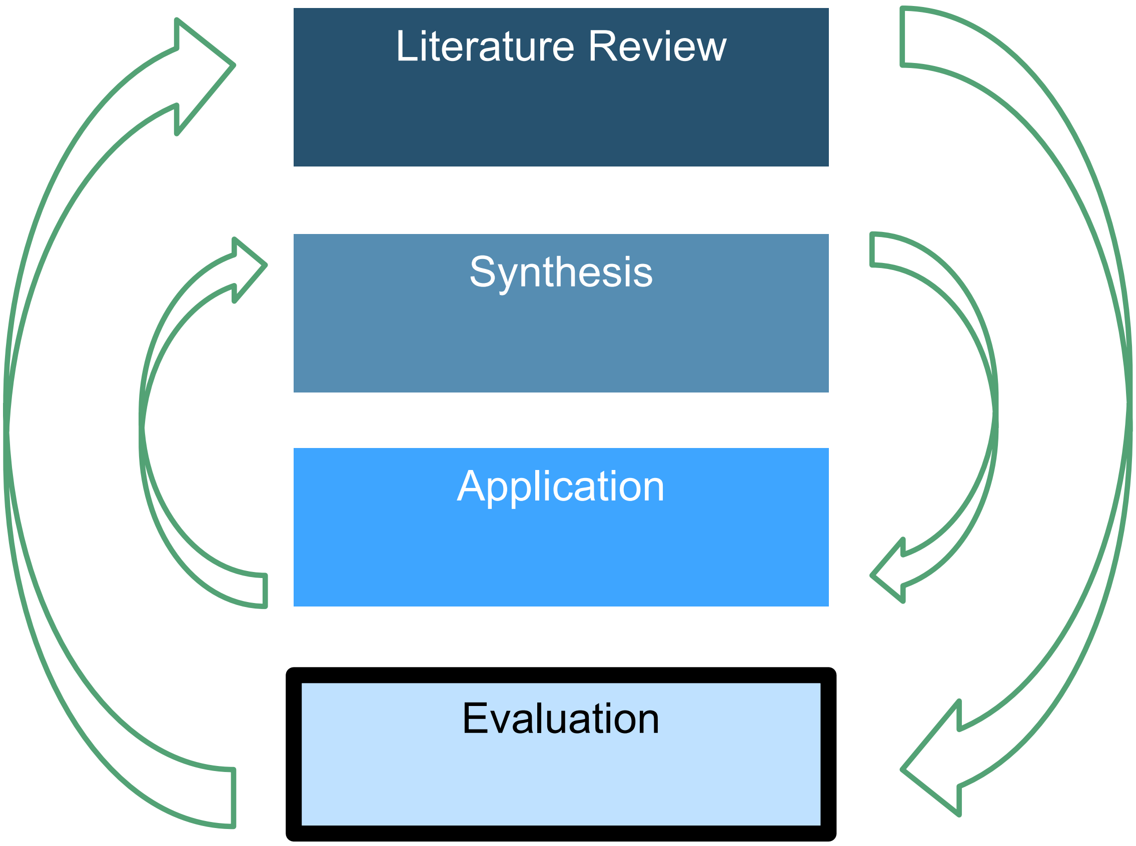


Figure 23: SDG 13 - KPIs

The results of the LCA performed in the SDG-driven design show comparable results to the ones obtained in the case of the LCA-driven approach. Both cases are within the boundaries of the recommended benchmark of 9.4 kg CO_2 eq./m²NFA a.

The share of local materials used is in all cases different but is derived from the same source. The baseline construction is conserved in all cases. Nevertheless, the LCA-driven approach and SDG-driven approach increase the density of the area, incrementing the number of materials used. This results in a decrease in the share of locally used materials to 80% and 67% in the LCA-driven case and the SDG-driven design respectively. No benchmark could be found in the literature for this KPI.

Finally, the biodiversity index quantifies the quality of the green infrastructure to host and boost the flora and fauna in situ. The starting point, set by the baseline case, fulfills already the minimum recommended by the DGNB of 0.25. The LCA-driven case envisions the implementation of green roofs, which improve the biodiversity index by 60%. The SDG-driven design includes green walls on the south facades and green roofs on top of the garage and the balconies, which improve the biodiversity index by 63 % compared to the baseline and 2 % compared to the LCA-driven case.


Literature Review
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Chapter 5: Decomposition

5.1. Allocating targets to the Early Design Phases

What are the early design phases?

The Royal Institute of British Architects (RIBA) includes not only the conceptual and schematic design phases but goes one step further to include the design development phase where elaborate drawings are created and the design details are confirmed. The German HOAI (Ordinance on Architects' and Engineers' Fees) defines the early stages similar to the RIBA, as spanning from service phases 1 to 3, which cover basic project evaluation, preliminary design, and design draft. For this thesis, the early design stages can be defined in line with the broader definitions of the RIBA and HOAI including all the design stages before construction documents are prepared and project execution begins.

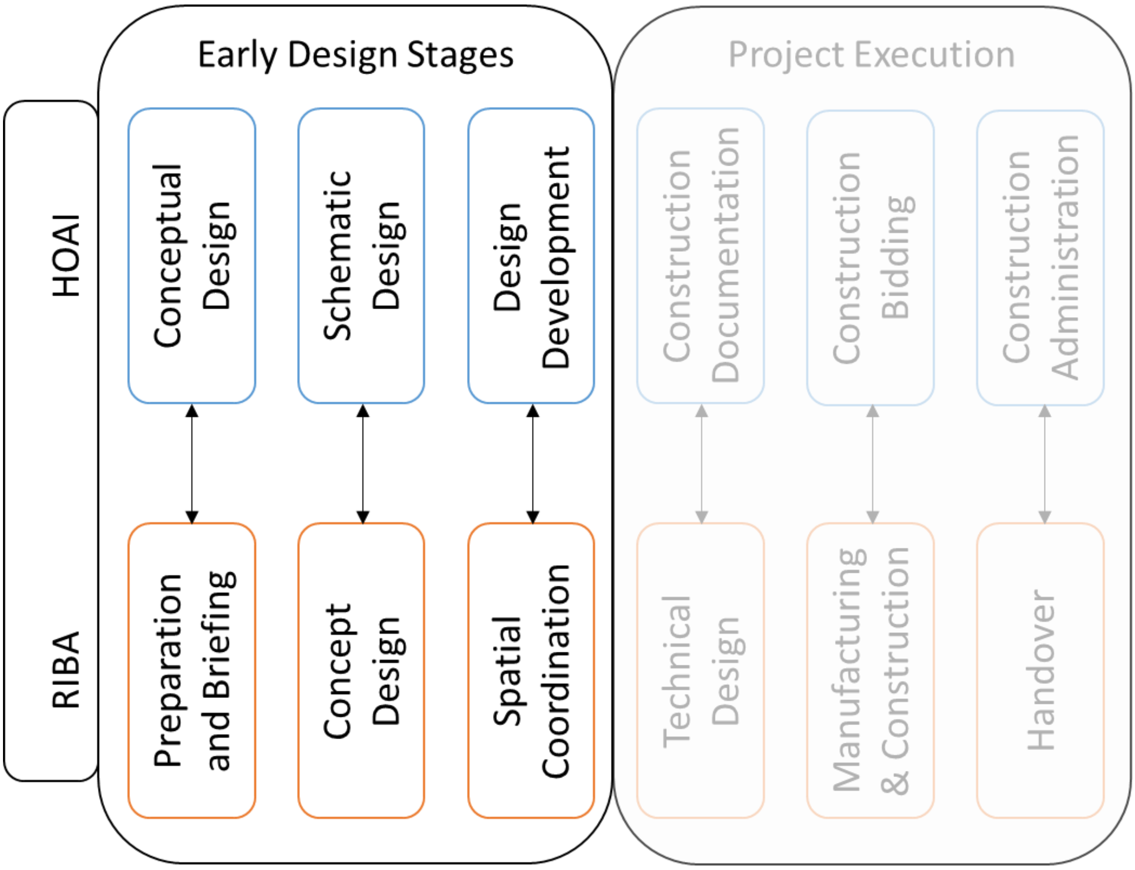


Figure 24: Early Design Stages after RIBA and HOAI. Adapted from (Patricia Schneider-Marin 2019; RIBA 2020)

Increasing complexity and specialization across all areas of planning and construction make it essential for project participants from various disciplines to be brought together at the start of a project. The early stages of the design process have a particularly important influence on the overall appearance of a building, the costs associated with the project, the performance over the total life cycle of the building, and the ability of the building to meet changing needs in the future. In these early stages, the opportunity for influencing the design is still high and the costs associated with these changes are still low. As shown in the Figure below, the earlier a change is suggested, the higher the opportunity for influence and the lower the cost of making the suggested changes. Once the design becomes finalized and the construction phase begins, the cost of making changes increases drastically and the possibilities for making changes become far more restricted.

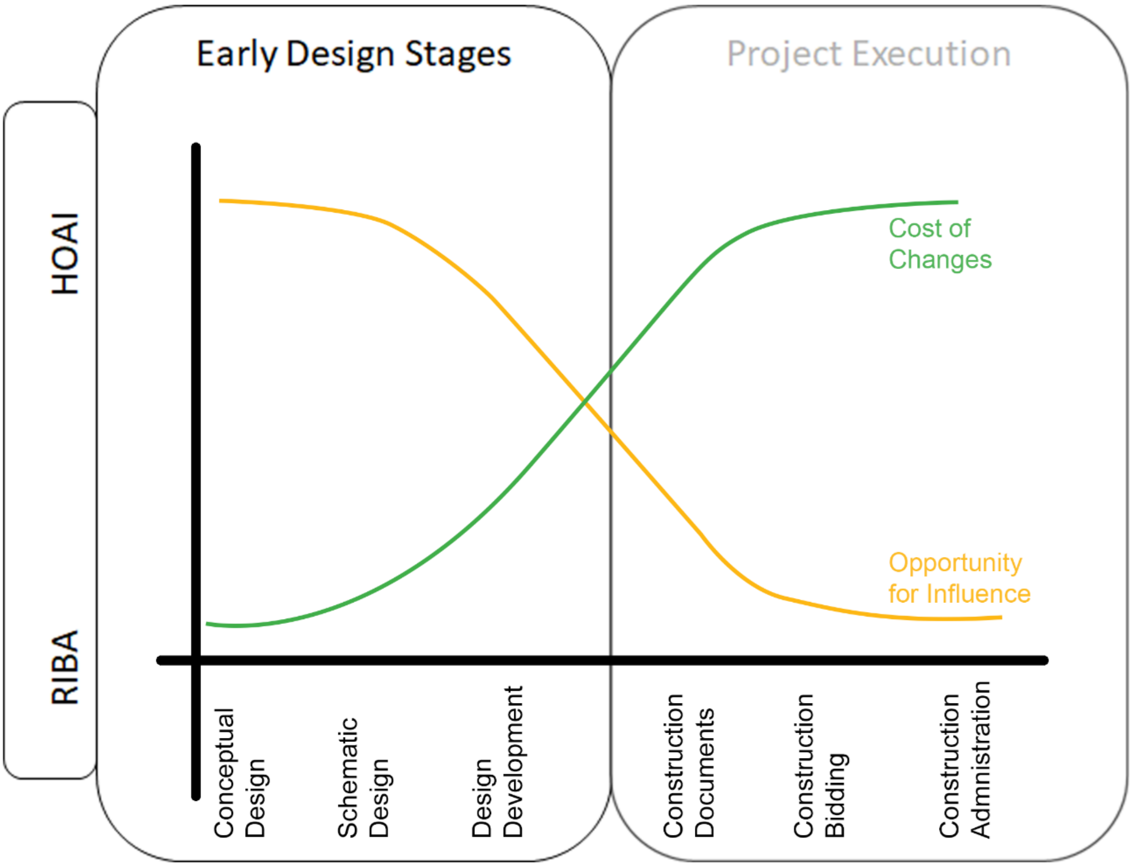


Figure 25: Opportunity of influence vs Cost of changes. Derived from (El Khouli et al 2015; Patricia Schneider-Marin 2019; RIBA 2020; Jochem and Kaufhold 2016)

Design Phases after the German HOAI

To develop this allocation, the exploration of the design phases is necessary. For this matter, this research focuses on the design phases involved in German law, the HOAI service phases, in German, Leistungsphasen (LPH). The HOAI, the Official Scale of Fees for Services by Architects and Engineers defines 9 service phases as follows (Heidenreich 2010):

LPH1: Conceptual design
LPH2: Schematic design
LPH3: Design development
LPH4: Building permission application
LPH5: Execution drawings
LPH6: Preparation of contract award
LPH7: Assisting the award process
LPH8: Project supervision
LPH9: Project control and documentation

As this research focuses on the early stages of design, only the service phases 1 to 3 are considered and described.

LPH 1: During this phase, all aspects analyzed have a significant impact on the planning. From a planning-related economic perspective, these are cost-relevant influences, e.g. the soil conditions, the building fabric to be used with any existing structural damage, and building law restrictions on the use of the property or contaminated sites (Scholz et al. 2019)

LPH2: After the basic economic considerations and the creation of the planning basis, a cost estimate according to DIN 276 must be carried out in service phase 2 - preliminary design. This is based on an area determination according to DIN 277. If necessary, a financing plan should be drawn up by the architect (Scholz et al. 2019)

LPH3: In service-phase 3 – final design or design planning, in addition to a cost calculation according to DIN 276, cost control and, if necessary, a cost steering must be carried out. Possibly a variant study for cost optimization or a profitability calculation is to be prepared. (Scholz et al. 2019)

These stages have been extended to include sustainability services extracted from literary sources handling the topic of sustainable design. These new services are highlighted for better comprehension. The allocation of targets to the design stages is based on literature (UN-Habitat 2022; Roös 2021a; United Nations 2020k; Friedman 2021b; Sassi 2006; El Khouli et al 2015; Bayerische Architektenkammer 2018; RIBA 2020) and on the insights gained during the development of the study case.

LPH1: Conceptual design

a	Clarification of the task based on the specifications or the requirements planning of the client
b	Site visit: check pollution, analyze local potentials and risks, protocol status quo
c	Advice on overall service and examination needs
d	Formulate the decision-making aids for the selection of other people involved in the planning
e	Summarizing, explaining and documenting the results
f	Initiate integral planning: create scenarios and constraints
g	Analyze local potentials: energy, climate, nature. Prioritize passive design principles and define overall goals for energy.
h	Set goals to protect local resources: comfort, energy, ecology, materials, humanity
i	Prioritize reuse of existing facilities, components or materials
j	Set ambitious goals for embodied and operational energy
k	Evaluate proximity to public transportation and elaborate an initial ecological travel plan
l	Define stormwater management and site discharge requirements
m	Define and develop strategies to minimize potable water use
n	Explore the possibility to harvest and recycle water on-site: Define sustainable drainage and surface water retention requirements.
o	Integrate aims for biodiversity, sustainable land use and improving the ecological status-quo
p	Identify potentials to improve the social infrastructure and community structure
r	Set responsible sourcing agenda for all materials
s	Analyze the impact of the construction site: possibility of prefabrication

LPH2: Schematic design

. a	Analyzing the basics, coordinating the services with those technically involved in the planning
b	Development of the preliminary planning, examination, presentation and evaluation of variants according to the same requirements, drawings on a scale according to the type and size of the object
c	Clarifying and explaining the essential relationships, specifications and conditions (e.g. urban planning, design, functional, technical, economic, ecological, building physics, energy management, social, public law)
d	Provision of the work results as a basis for the other professionals involved in the planning as well as the coordination and integration of their services
e	Pre-negotiations on eligibility
f	Cost estimate according to DIN 276, comparison with the financial framework
g	Creation of a schedule with the essential processes of the planning and construction process
h	Agreeing on the objectives, pointing out conflicting objectives
i	Summarizing, explaining and documenting the results
j	Include requirements for internal environmental conditions, including thermal comfort and overheating, visual and acoustic comfort, spatial needs, ventilation type, control strategies and relationships to external environments. Evaluate with simulations representing in-use conditions.
k	Provide environmentally friendly mobility infrastructure
l	Create quality space indoors and outdoors and plan accessibility
m	Consider place-making, privacy, social interaction, mixed-use places, community, amenity, involvement and inclusion. Include a plan for social value.
n	Optimizing comfort and security
o	Optimize building needs and land use
p	Specify resource-saving requirements: Include future deconstruction, disposal and recycling in the design.
q	Align demand planning with life cycle costs and preliminary life cycle assessment
r	Define embodied energy and carbon target outcome, including the assessment boundaries and scope
s	Define outcome targets for connectivity and transport, including active travel, minimizing car use and encouraging walking and cycling.
t	Explore on-site water recycling through rain, grey and black water harvesting.
u	Define sustainable drainage and surface water retention requirements.
v	Specify measurable outcomes and targets for whole life carbon, whole life costs, building life span, refurbishment rates, end of life and circular economy.
w	Consider strategies for climate and functional adaptation.

LPH3: Design development

a	Development of the draft plan, taking further account of the essential relationships, specifications and conditions (e.g. urban planning, design, functional, technical, economic, ecological, social, public law) based on the preliminary planning and as a basis for the further work phases and the necessary ones Public approvals using the contributions of other people involved in the planning. Drawings according to the type and size of the object to the required extent and level of detail, taking into account all technical requirements, for example, buildings on a scale of 1:100, interiors on a scale of 1:50 to 1:20
b	Provision of the work results as a basis for the other professionals involved in the planning as well as coordination and integration of their services
c	Object description
d	Cost calculation according to DIN 276 and comparison with the cost estimate,
e	Updating the schedule
f	Summarizing, explaining and documenting the results
g	Ensure space quality indoors and outdoors by evaluating the respective KPIs
h	Ensure accessibility and connectivity
i	Develop safety and comfort strategies
j	Ensure functional development
k	Validate energy benchmarks
l	Optimize building components
m	Optimize building
n	Initiate LCA: Minimize material resources, plan circularity, regenerate environmental inventory
o	Concretize objectives for pollutant-free design
p	Audit design against operational energy outcome target, including seasonal conditioning strategies, form and orientation and details for airtightness, and continuity of insulation.
q	Use embodied energy and carbon assessment to test relative impacts of design options as part of whole life costs.
r	Encourage active travel, including walking and cycling. Coordinate space for deliveries, car clubs and connections to public transport.
s	Incorporate water cycle targets into biodiversity strategy where possible.
t	Include biodiversity design enhancements to local ecosystems, habitats and productive landscaping in design documentation.
u	Review the expected building lifespan against capital and operational energy, carbon and financial costs.
v	Refine the climate adaptation strategy and make provision for future climatic and functional adaptations.

Pathway for SDGs through design phases

After evaluating the requirements for each design stage from the HOAI, different pathways for each design stage are presented below. Each pathway orients the designer during the appropriate design phase. If there are repeated targets in different phases, it means that the target possibly cannot be developed fully in only one stage and requires optimization or further development in deeper design stages. The allocation of targets was performed to display their relevance to the LPHs. It is possible to assign all targets to all phases, nevertheless, Table 3 focuses on the design phase in which the targets are most likely to be implemented and the relevance each phase has in the integration of sustainable targets. In the table shown below, the targets relevant for each LPH are shown. This serves as a filter for the pathway found in the coming section.

Table 3 Allocation of SDGs to LPHs

A-SDGs / Targets		**DESIGN STAGE**	
		LPH 1	**LPH 1**
Health and Well Being	**3**		
Provide a healthy and comfortable indoor climate	**3a**		
Support healthy and comfortable outdoor micro-climate	**3b**	**X**	Establish basic goals for urban planning, evaluate indicators for the urban realm
Avoid the use of environmentally hazardous materials and substances	**3c**	X	Establish objectives for materials
Encourage physical activity	**3d**		
Provide accessibility to all spaces	**3e**	**X**	Define accessibility objectives for the demographic target
Affordable & Clean Energy	**7**		
Reduce operational and embodied energy	**7a**	**X**	Establish energy-related goals, perform basic studies like overshadowing
Recycle and conserve energy	**7b**		
Implement resilient and adaptive energy systems	**7c**	**X**	Analyze the climate (present and future) and its potential

Use renewable energy to cover the demand	**7d**	**X**	Assess the potential of the location
Sustainable Cities and Communities	**11**		
Promote Inclusion and Community	**11a**	**X**	Bring the stakeholders together
Use regenerative design strategies	**11b**	**X**	Assess the condition of the surroundings and set objectives to regenerate them
Implement resilient and climate-adaptive measures	**11c**	**X**	Analyze the energy situation
Provide sustainable mobility	**11d**	**X**	Analyze the status quo and tendencies
Responsible Consumption and Production	**12**		
Design for a long lifetime	**12a**	**X**	Establish the long-term use requirements
Design for disassembly and circularity	**12b**	**X**	Establish strategies for the end-of-life
Reduce or restrict the use of non-renewable natural resources	**12c**	**X**	Specify resource-saving requirements and analyze possible biogenic constructions
Encourage prefabrication	**12d**	**X**	Evaluate the feasibility of prefabrication
Climate Action	**13**		
Design for carbon neutrality	**13a**	**X**	Establish environmental goals
Use local resources	**13b**	**X**	Assess and protect the local resources and structures
Integrate and expand green areas and biodiversity	**13c**	**X**	Assess the condition of the green infrastructure

Appendix G shows the rest of this categorization strategy.

5.2. Allocating targets disciplines in the early design stages

In this section, a deeper look into the integrated design process (IDP) is given. Why is it relevant? The IDP represents a method for developing high-performance buildings or urban developments. It is a collaborative process, which envisions the interdisciplinary work of a skilled team aiming for sustainable holistic solutions (Busby Perks & Will et al 2007). The objective of this section is to reveal the interdependencies of the multiple disciplines involved in the design process, answering the question of when should each discipline be integrated into the team. The Figure below shows the different disciplines necessary for a general IDP. The Core Team should work together from start, while the Supplementary team deals with tasks under one of the core team members. (Bocheńska-Skałecka and Walter 2020).

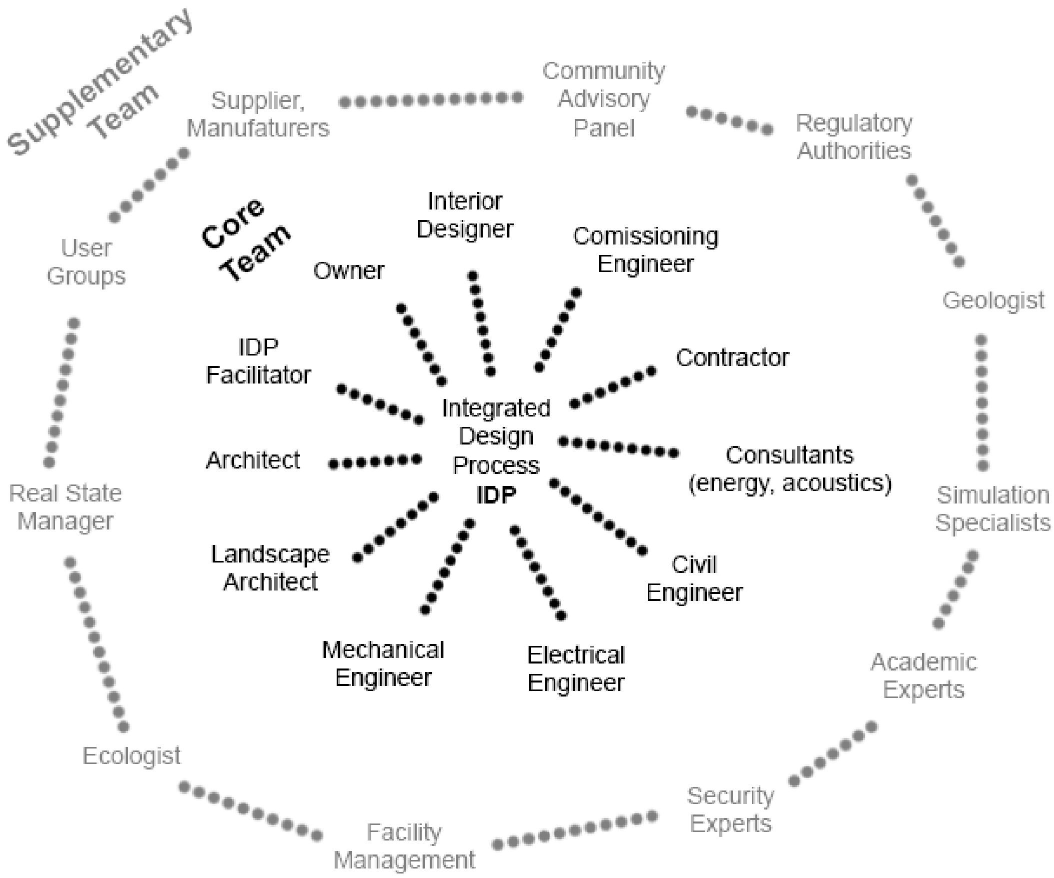


Figure 26: IDP Team. Adapted from (Busby Perks & Will et al 2007; Norbert Lechner 2015)

IDP in the LPH1: Conceptual design

The integrated design process differs from conventional design right from the outset of a project by placing a priority on establishing the goals, core objectives and direction of the project through a visioning session. Pre-design explores the relationships between the project and its surrounding environment to help reveal the optimum choices for the site, the users, and the owner. Site options or site specifics may be analyzed in light of project requirements to uncover opportunities and synergies. Sustainability targets may be set covering a full range of economic, environmental, and social performance criteria. This ambitious beginning requires many experts to be members of the design team at the outset (Busby Perks & Will et al 2007). The figure below shows the core team in charge of setting the vision and goals for the project and establishing the preliminary budget and communication pathways (Busby Perks & Will et al 2007).

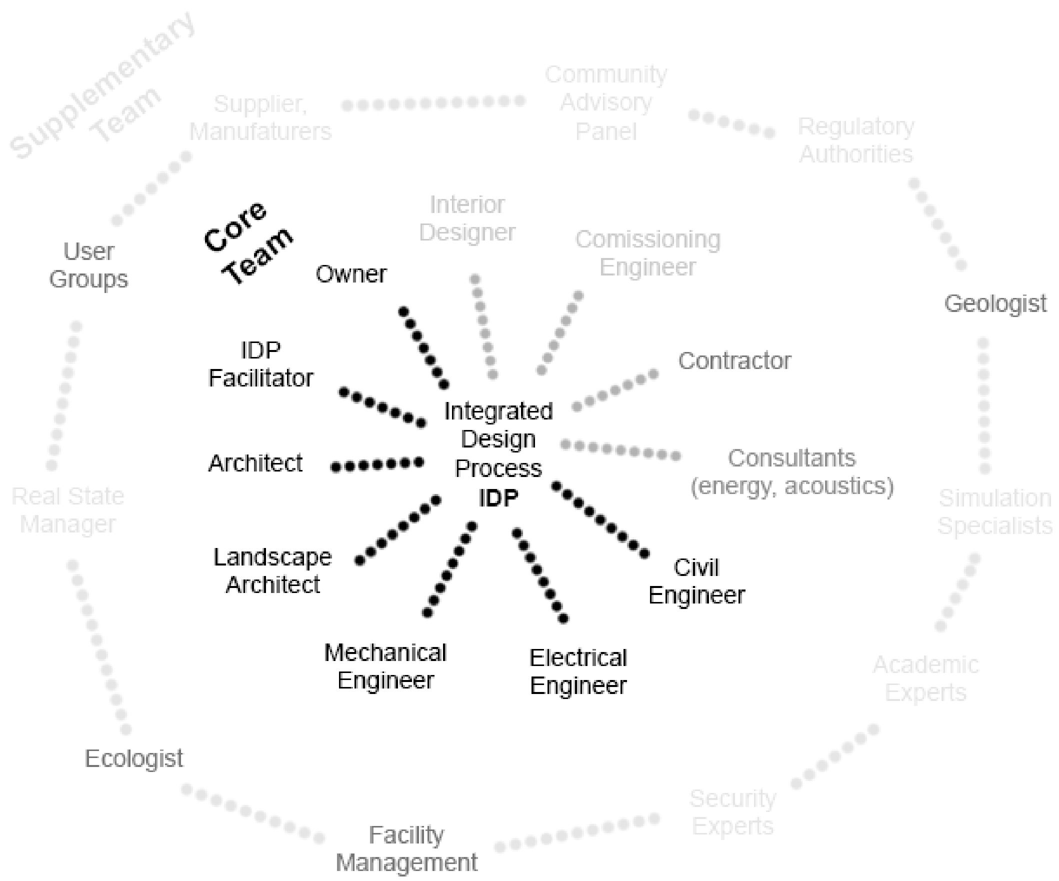


Figure 27: IDP for LPH 1 / Conceptual Design stage. Adapted from (Busby Perks & Will et al 2007; Norbert Lechner 2015)

IDP in the LPH2: Schematic design

Schematic Design builds upon the vision developed in Pre-design. It is the phase for thinking “outside the box,” for exploring innovative technologies, new ideas, and fresh application methods in working towards the broad goals and objectives set out in Pre-design. Schematic Design allows experts from all disciplines to analyze the unique opportunities and constraints of the building site and to collectively explore synergies between disciplines and with neighbouring sites. (Busby Perks & Will et al 2007). This stage contains the most involvement of disciplines. Its structure integrates all supplementary and core team individuals.

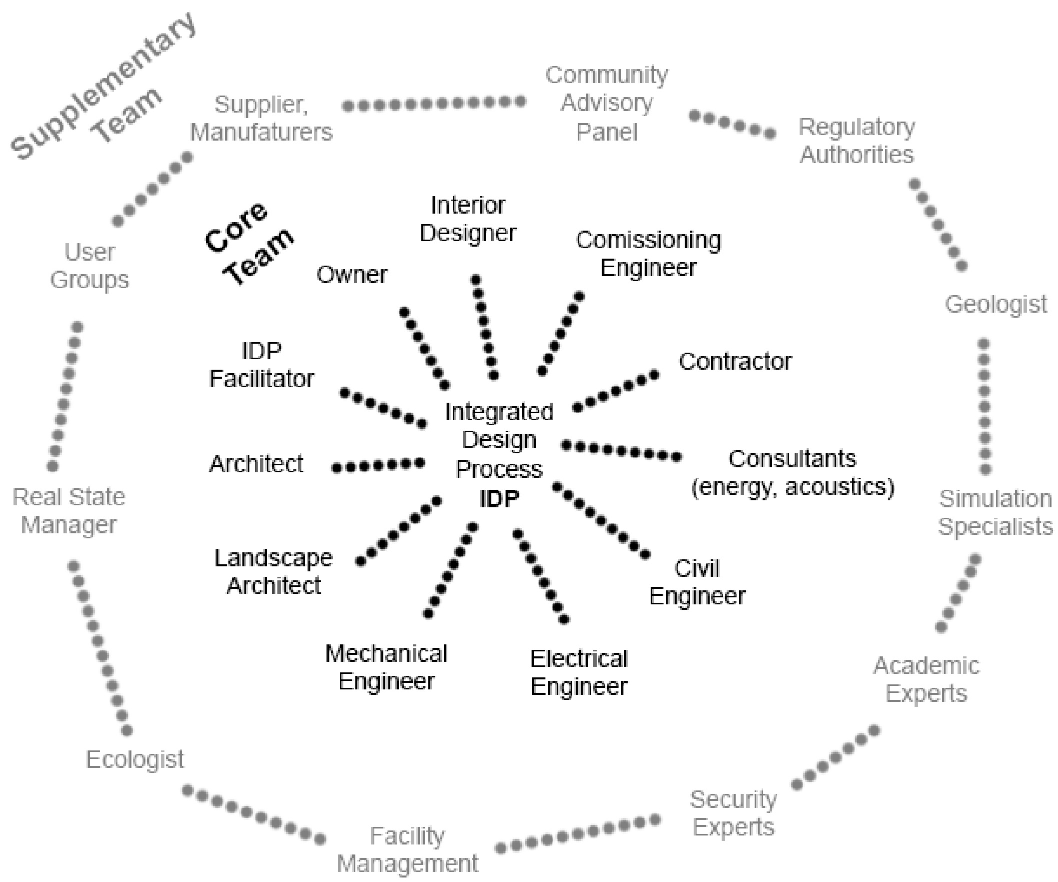


Figure 28: IDP for LPH 2 / Schematic design stage. Adapted from (Busby Perks & Will et al 2007; Norbert Lechner 2015)

IDP in the LPH3: Developed design

Design Development is a time to firm up and validate choices, resulting in a schematic design concept being selected and approved by the client. All architectural, mechanical and electrical systems are assessed for their expected performance and impact on all other systems as well as on the goals and targets. (Busby Perks & Will et al 2007)

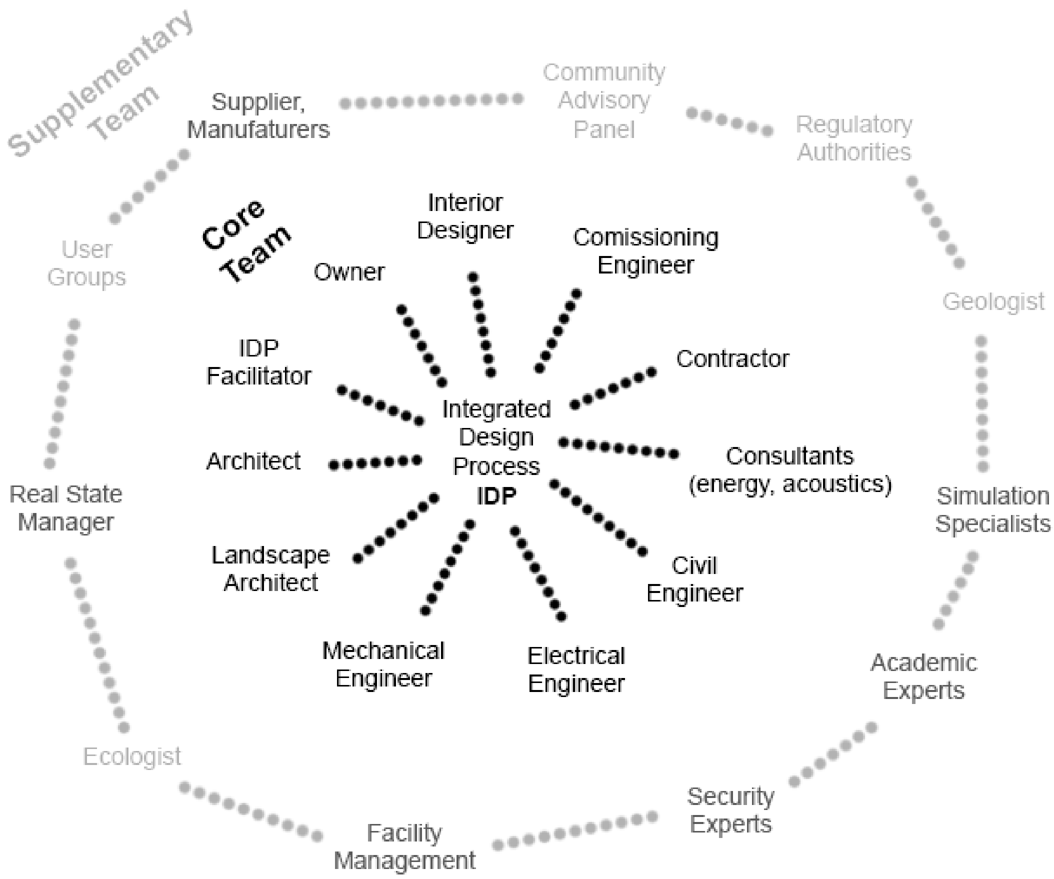
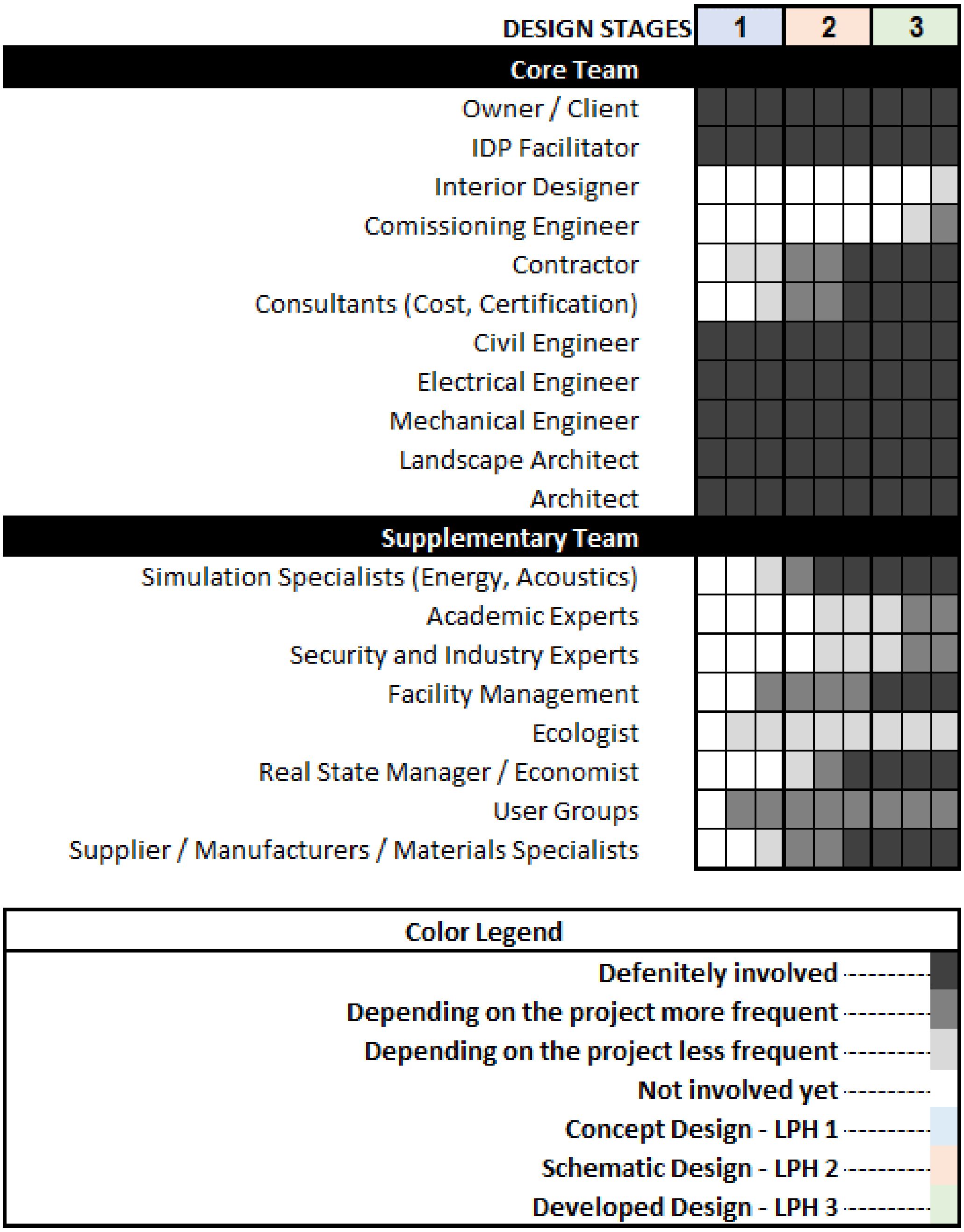
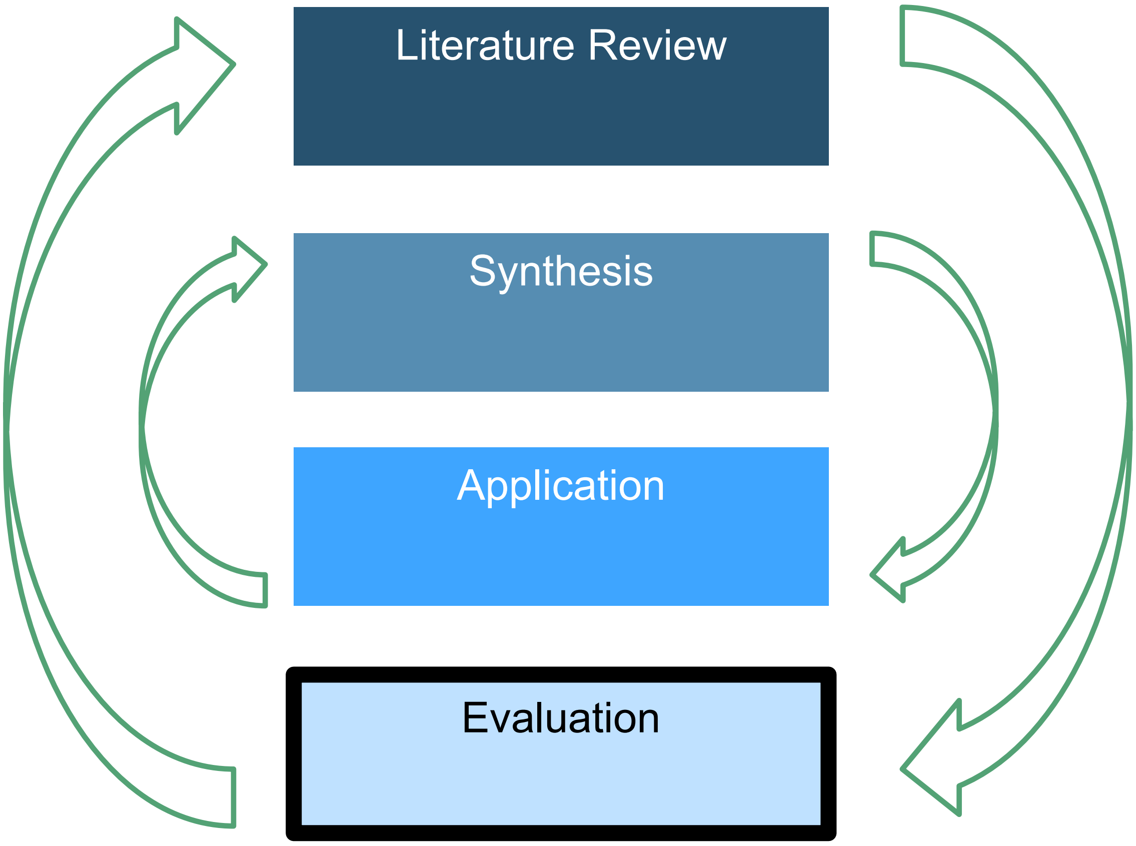


Figure 29: IDP for LPH 3 / Developed design stage. Adapted from (Busby Perks & Will et al 2007; Norbert Lechner 2015)

Overview of the disciplines involved in the IDP and their involvement

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Chapter 6: Discussion and further research

6.1. Discussion

This section covers the findings of the previous chapters reflected through the answers to the research questions proposed. The hypothesis for the theoretical and practical parts are subsequently evaluated.

This work explored the transformation of general Sustainable Development Goals (SDG) into architecture-related SDGs to incorporate the global perspective on sustainable development into the development of the architectural design. For this, the interactions among the created architecture-related SDGs were analyzed through a literature-based approach. Thus, a clear pathway for the application of the created targets was established.

Could the SDGs serve as a base to define Sustainability in urban and building developments?"

The general targets presented in the SDGs from the Agenda 2030 can be all addressed through architectural design strategies. The extent and depth of the integration of SDGs are nevertheless dependent on the local context. A general architectural design approach can be created, however, the design strategies and KPIs require context-driven adjustments.

Chapter 1 of this work evaluated the existing literature surrounding the integration of SDGs into the built environment. The results show that the theoretical and practical work is very limited. Building certification labels, like the DGNB, propose in their guidelines the inclusion of several SDGs in architectural design and planning, nevertheless, their approach tries to match the existing guidelines to the definitions of the SDGs and does not create guidelines based on the SDGs. The current trends in sustainable design are essential to extract state-of-the-art architectural targets, which can be corroborated by the ones found in the different building certification labels.

Chapter 2 explores the structurization of the synthesized architecture-related targets into design strategies and key performance indicators to facilitate their application in architectural practice. By applying contextual constraints such as the climate and the local regulations, different design strategies can be derived through a literature-based research methodology. Similarly, different key performance indicators and benchmarks could be extracted from certification labels, the standards and current theoretical approaches to evaluate the impacts of the design strategies and the fulfilment of the architecture-related targets. The KPIs represent qualitative and quantitative aspects of a design strategy. Both are necessary to properly evaluate design decisions and scenarios.

Chapter 3 answers the question How is it possible to create a road map to implement the SDGs in the design practice? and How do the targets interact with each other? The creation of a roadmap for hierarchically applying the created architectural targets is derived from the analysis of interactions among the targets. For this, the design structure matrix provides a methodology to evaluate how targets depend on each other to be fulfilled. The interactions were analyzed through literature sources, nevertheless, not all the interactions could be found in the literature. For this, a different depth for the evaluation of the interactions is recommended.

Chapter 4 explores some questions derived from the practical part of this work but also the validation of the theoretical approach. What are the main differences among the selected design methodologies? The clearest difference among the methodologies is the number of dimensions considered and evaluated in each one of the methodologies. The standard methodology, based on the existing construction, reveals only a few of the indicators used in the SDG-driven design, showing mostly regulations-based design strategies. When it comes to the main comparison in this work, between the performance-driven approach based on the Life cycle analysis (LCA-driven) and the created SDG-driven approach, the similarities regarding the environmental impact of developments are more notorious. The main difference between these two approaches is again the multidimensionality of the evaluation and integration of targets. The LCA-driven methodology accounts for environmental impacts and evaluates resources through the focus on the bill of quantities. The SDG-driven approach evaluates the same environmental indicators, nevertheless, with a reduced resolution. The results of the life cycle analysis in the SDG-driven methodology are not evaluated in depth through each material layer but at the level of whole building construction types. Thus, the evaluation of building components and materials can not be individually assessed. The SDG-driven methodology evaluates indicators referring to climate-driven and regenerative design strategies, health indoors and outdoors, comfort at the urban level, community and mobility. These indicators are not a part of the life cycle analysis and therefore not included in the LCA-driven proposal.

Is it possible to validate the application pathway for the targets through the practical approach? It was not possible to validate the theoretical results through the results of the practical approach. The hierarchical pathways derived in both cases through machine-learning clustering are different, as shown in the following figure.

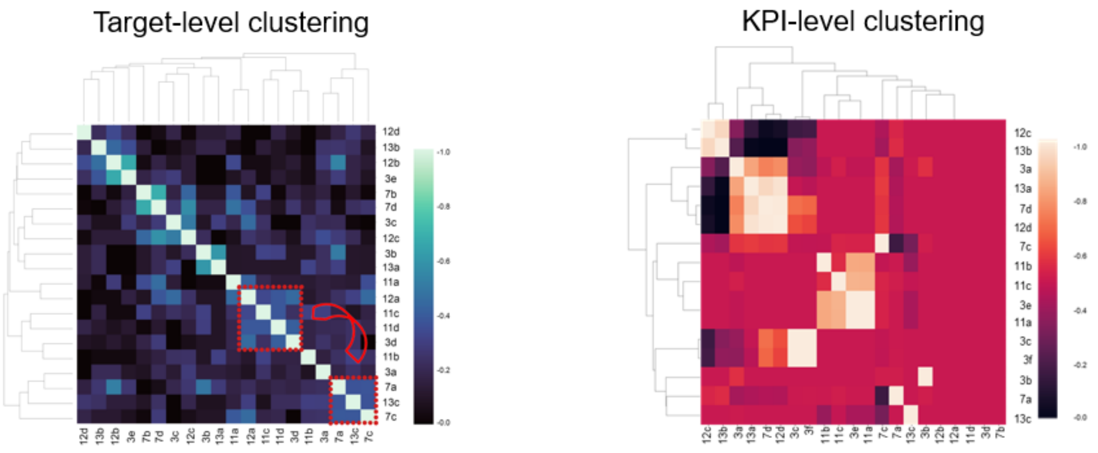

Figure 30: Target-level clustering vs KPI-level clustering

This could be the result of the simplistic methodology of assigning one key performance indicator to each one of the evaluated targets. The targets are more complex and require more than one indicator to be evaluated.

What are the main challenges in the application of an SDG-driven design? The same reason that makes the evaluated methodologies so different, is the highest challenge in the SDG-driven approach, namely the multidimensionality. The methodology is in this work powered by computational design methods, that are not common routine in general architecture practices. The current available BIM-software solutions are not equipped yet with the tools to perform the calculations for many of the key performance indicators evaluated in the SDG-driven methodology. The key performance indicators in each target require further evaluation so that the main indicators can be chosen based on robust data. Another important challenge to overcome is the sharpness in the evaluation of environmental impacts. The current methodology compromises accuracy for speed, leaving out important elements like the building´s technical equipment for the calculation of the environmental indicators.

This leads now to the validation hypothesis of this work, which states that planning guidelines extracted from the SDGs can be used to create a framework for sustainable design. The results of the case study show that the integration of SDGs into the architectural design practice is possible. The creation of design strategies is fundamental for the development of scenarios, which can be then evaluated through key performance indicators. The overall targets serve as guidance to maintaining focus on the objectives of each SDG. The proposed structure for the framework correlates to the current structure of the standard SDGs, which aids designers and planers to connect their designs to the global SDG framework.

The second hypothesis “Implementing an SDG-driven architectural design approach results in comparable outcomes for environmental impacts to an LCA-driven approach, fulfilling at the same time other dimensions of sustainability” could be verified through the key performance indicators. As previously discussed, the SDG-driven approach includes more indicators to evaluate the performance of a design than the LCA-driven approach. The results show that the SDG-driven methodology achieved similar environmental results to the LCA-driven case but a higher performance in other KPIs relevant to social quality and regenerative strategies.

6.2. Further development and research

The evaluation of the interactions among targets has been performed in a systematic literature review fashion. This approach, therefore, leaves out a more complicated form of correlation and relies only on the capabilities of the author to discern the collected data. Therefore, this work should serve as a baseline for further exploration of the interactions among goals and targets at a deeper scientifical level.

The exploration of the secondary and tertiary SDGs groups is still missing. It is recommended to evaluate their interactions accordingly to complete the full picture encapsulating all SDGs.

Further research could be set on evaluating the synergies and trade-offs based on the interactions presented. If a system of weights can be derived, a machine learning approach could be employed to optimize the interactions among targets aiming for the highest synergy ratios. This could simplify the application to targets that have the capability of positively influencing the major share of the development.

The target level has been selected to evaluate the interactions. The validation process revealed fundamental inconsistencies, which need to be further explored. Probably, the assignation of KPIs to targets does not represent the targets correctly. Each target was represented with only one KPI to prove the methodology´s concept. Nevertheless, the targets need to be described with more KPIs to create an appropriate resemblance to reality. It is recommended to explore deeper levels, like the design strategies or the KPIs to find eventually a method with stronger foundations, linking the targets in an integrated model. This deeper analysis could provide deeper insights into the validity of the selected targets, leading eventually to redefining them and creating new ones.

Computational design and BIM approaches could be further elaborated to create a seamless evaluation, simulation and documentation of the SDG-driven scenarios. For this work, Grasshopper and its plug-ins proved effective to automate the evaluation of design alternatives created in ArchiCAD. Nevertheless, a simpler approach needs to be found if more KPIs need to be evaluated.

The integration of the SDG-driven strategies to the different design scales represented in the HOAI requires further testing. The creation of a framework to collaborate among the disciplines could be useful to integrate architectural SDGs more efficiently.

The context is a very strong determinant factor for the targets, the design strategies and the selected evaluation KPIs. It is recommended to develop more scenarios regarding the geographical context and the urban/building typologies to approach the interactions holistically.

Finally, this methodology could be scalable to a global framework, creating context-based design strategies to adapt the approach to any local background.

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Appendix A: Interactions Arguments and sources

	A-SDGs / Targets	Health and Well Being	Provide a healthy and comfortable indoor climate	Support healthy and comfortable outdoor micro-climate	Avoid the use of environmentally hazardous materials and substances	Encourage physical activity	Provide accessibility to all spaces	Affordable & Clean Energy	Reduce operational and embodied energy	Recycle and conserve energy	Implement resilient and adaptive energy systems	Use renewable energy to cover the demand	Sustainable Cities and Communities	Promote Inclusion and community
A-SDGs / Targets		**3**	**3a**	**3b**	**3c**	**3d**	**3e**	**7**	**7a**	**7b**	**7c**	**7d**	11	11a
Health and Well Being	**3**													
Provide a healthy and comfortable indoor climate	**3a**			-	+	+	+		-	-	+	-		+
Support healthy and comfortable outdoor micro-climate	**3b**		+		+	+	-		+	+	-	+		+
Avoid the use of environmentally hazardous materials and substances	**3c**		-	-		-	-		+	+	+	+		+
Encourage physical activity	**3d**		-	+	+		+		-	-	-	-		+
Provide accessibility to all spaces	**3e**		-	-	-	-			-	-	-	-		+
Affordable & Clean Energy	**7**													
Reduce operational and embodied energy	**7a**		-	+	-	+	-			+	-	-		-
Recycle and conserve energy	**7b**		-	-	+	+	-		-		-	+		-
Implement resilient and adaptive energy systems	**7c**		-	-	-	-	-		-	+		+		+
Use renewable energy to cover the demand	**7d**		-	+	+	+	-		-	-	-			+
Sustainable Cities and Communities	**11**													
Promote Inclusion and community	**11a**		+	+	+	+	+		-	-	-	-		
Use regenerative design strategies	**11b**		-	+	+	-	-		+	+	+	+		+
Implement reslient and climate-adaptive measures	**11c**		-	-	-	-	-		+	-	+	-		+
Provide sustainable mobility	**11d**		-	+	+	+	+		-	-	+	+		+
Responsible Consumption and Production	**12**													
Design for long lifetime	**12a**		+	+	+	-	+		-	-	+	+		+
Design for disassembly and circularity	**12b**		-	-	+	-	+		-	-	-	-		-
Reduce or restrict the use of non-renewable natural resources	**12c**		-	-	+	+	+		+	+	-	+		-
Encourage prefabrication	**12d**		-	-	-	-	-		-	-	-	-		-
Climate Action	**13**													
Design for carbon neutrality	**13a**		-	+	+	+	+		+	+	-	+		+
Use local resources	**13b**		-	-	-	-	-		-	-	+	-		-
Integrate and expand green areas and biodiversity	**13c**		-	-	-	-	-		+	+	-	-		+
INFLUENCE			3	8	12	9	8		7	8	7	9		13

Structure of the DSM before sequencing

This Appendix is delivered partially in digital form.

Implement resilient and adaptive energy systems	Use renewable energy to cover the demand	**Sustainable Cities and Communities**	Promote Inclusion and community	Use regenerative design strategies	Implement reslient and climate-adaptive measures	Provide sustainable mobility	**Responsible Consumption and Production**	Design for long lifetime	Design for disassembly and circularity	Reduce or restrict the use of non-renewable natural resources	Encourage prefabrication	**Climate Action**	Design for carbon neutrality	Use local resources	Integrate and expand green areas and biodiversity	**DEPENDENCY**	
7c	7d	**11**	**11a**	**11b**	**11c**	**11d**	**12**	**12a**	**12b**	**12c**	**12d**	**13**	**13a**	**13b**	**13c**		**A-SDGs** / Targets
																	Health and Well Being
+	-		+	-	+	-		-	+	+	-		+	+	+	11	Provide a healthy and comfortable indoor climate
-	+		+	+	+	-		-	+	+	-		+	+	+	14	Support healthy and comfortable outdoor micro-climate
+	+		+	-	+	+		+	-	+	-		+	+	-	11	Avoid the use of environmentally hazardous materials and substances
-	-		+	-	+	+		-	-	+	-		+	-	-	8	Encourage physical activity
-	-		+	-	+	+		-	-	+	-		+	-	-	5	Provide accessibility to all spaces
																	Affordable & Clean Energy
-	-		-	+	+	-		+	+	+	+		+	+	+	12	Reduce operational and embodied energy
-	+		-	+	+	-		-	+	-	-		-	-	-	6	Recycle and conserve energy
	+		+	-	+	+		-	+	-	-		-	+	+	8	Implement resilient and adaptive energy systems
-			+	+	-	-		-	-	+	-		-	+	-	7	Use renewable energy to cover the demand
																	Sustainable Cities and Communities
-	-			-	-	+		+	-	-	-		-	+	+	9	Promote Inclusion and community
+	+		+		-	-		-	-	-	-		+	-	+	9	Use regenerative design strategies
+	-		+	-		-		-	-	-	-		-	+	+	5	Implement reslient and climate-adaptive measures
+	+		+	-	+			-	-	+	-		+	+	+	12	Provide sustainable mobility
																	Responsible Consumption and Production
+	+		+	+	+	+			+	-	-		-	-	-	11	Design for long lifetime
-	-		-	-	-	-		-		+	-		-	-	-	3	Design for disassembly and circularity
-	+		-	-	+	+		+	+		-		+	-	-	11	Reduce or restrict the use of non-renewable natural resources
-	-		-	-	-	-		-	+	-			-	-	-	1	Encourage prefabrication
																	Climate Action
-	+		+	+	+	+		+	+	+	-			+	+	16	Design for carbon neutrality
+	-		-	-	-	-		-	-	-	-		-		+	2	Use local resources
-	-		+	+	+	+		+	-	+	-		-	-		8	Integrate and expand green areas and biodiversity
7	9		13	7	13	9		6	9	11	1		9	10	10		**INFLUENCE**

Interaction	
+	Yes
-	No

Structure of the DSM after sequencing

	A-SDGs / Targets	Encourage prefabrication	Use local resources	Design for disassembly and circularity	Implement reslient and climate-adaptive measures	Provide accessibility to all spaces	Recycle and conserve energy	Use renewable energy to cover the demand	Integrate and expand green areas and biodiversity	Encourage physical activity	Implement resilient and adaptive energy systems	Promote Inclusion and community	Use regenerative design strategies	Avoid the use of environmentally
A-SDGs / Targets		**12d**	**13b**	**12b**	**11c**	**3e**	**7b**	**7d**	**13c**	**3d**	**7c**	**11a**	**11b**	**3c**
Encourage prefabrication	**12d**		-	+	-	-	-	-	-	-	-	-	-	-
Use local resources	**13b**	-		-	-	-	-	-	+	-	+	-	-	-
Design for disassembly and circularity	**12b**	-	-		-	+	-	-	-	-	-	-	-	+
Implement reslient and climate-adaptive measures	**11c**	-	+	-		-	-	-	+	-	+	+	-	-
Provide accessibility to all spaces	**3e**	-	-	-	+		-	-	-	-	-	+	-	-
Recycle and conserve energy	**7b**	-	-	+	+	-		+	-	+	-	-	+	+
Use renewable energy to cover the demand	**7d**	-	+	-	-	-	-		-	+	-	+	+	+
Integrate and expand green areas and biodiversity	**13c**	-	-	-	+	-	+	-		-	-	+	+	-
Encourage physical activity	**3d**	-	-	-	+	+	-	-	-		-	+	-	+
Implement resilient and adaptive energy systems	**7c**	-	+	+	+	-	+	+	+	-		+	-	-
Promote Inclusion and community	**11a**	-	+	-	-	+	-	-	+	+	-		-	+
Use regenerative design strategies	**11b**	-	-	-	-	-	+	+	+	-	+	+		+
Avoid the use of environmentally hazardous materials and substances	**3c**	-	+	-	+	-	+	+	-	-	+	+	-	
Reduce or restrict the use of non-renewable natural resources	**12c**	-	-	+	+	+	+	+	-	+	-	-	-	+
Design for long lifetime	**12a**	-	-	+	+	+	-	+	-	-	+	+	+	+
Provide a healthy and comfortable indoor climate	**3a**	-	+	+	+	+	-	-	+	+	+	+	-	+
Provide sustainable mobility	**11d**	-	+	-	+	+	-	+	+	+	+	+	-	+
Reduce operational and embodied energy	**7a**	+	+	+	+	-	+	-	+	+	-	-	+	-
Support healthy and comfortable outdoor micro-climate	**3b**	-	+	+	+	-	+	+	+	+	-	+	+	+
Design for carbon neutrality	**13a**	-	+	+	+	+	+	+	+	+	-	+	+	+
INFLUENCE		**1**	**10**	**9**	**13**	**8**	**8**	**9**	**10**	**9**	**7**	13	7	12

Interaction	
+	Yes
-	No

Encourage physical activity	Implement resilient and adaptive energy systems	Promote Inclusion and community	Use regenerative design strategies	Avoid the use of environmentally hazardous materials and substances	Reduce or restrict the use of non-renewable natural resources	Design for long lifetime	Provide a healthy and comfortable indoor climate	Provide sustainable mobility	Reduce operational and embodied energy	Support healthy and comfortable outdoor micro-climate	Design for carbon neutrality	DEPENDENCY
3d	7c	11a	11b	3c	12c	12a	3a	11d	7a	3b	13a	
-	-	-	-	-	-	-	-	-	-	-	-	1
-	+	-	-	-	-	-	-	-	-	-	-	2
-	-	-	-	+	+	-	-	-	-	-	-	3
-	+	+	-	-	-	-	-	-	+	-	-	5
-	-	+	-	-	+	-	-	+	-	-	+	5
+	-	-	+	+	-	-	-	-	-	-	-	6
+	-	+	+	+	+	-	-	-	-	+	-	7
-	-	+	+	-	+	+	-	+	+	-	-	8
	-	+	-	+	+	-	-	+	-	+	+	8
-		+	-	-	-	-	-	+	-	-	-	8
+	-		-	+	-	+	+	+	-	+	-	9
-	+	+		+	-	-	-	-	+	+	+	9
-	+	+	-		+	+	-	+	+	-	+	11
+	-	-	-	+		+	-	+	+	-	+	11
-	+	+	+	+	-		+	+	-	+	-	11
+	+	+	-	+	+	-		-	-	-	+	11
+	+	+	-	+	+	-	-		-	+	+	12
+	-	-	+	-	+	+	-	-		+	+	12
+	-	+	+	+	+	-	+	-	+		+	14
+	-	+	+	+	+	+	-	+	+	+		16
9	7	13	7	12	11	6	3	9	7	8	9	

Appendix B: KPIs

Selected list of KPIs

	A-SDG & Targets	KPI	Unit	Bench-mark	Source	Calcula-tion
3	**Health and Well Be-ing**					
3a	Provide a **healthy** and **comfortable** indoor cli-mate	Toxic materi-als / Pollutants checklist	[-]	See Ta-bles in Ap-pendix C	El Khouli et al (2015) Theilig et al (2021) Ece (2018)	Re-search about Materials in i.e WECO-BIS, Na-turePlus, Blauer Engel
		PMV (Predicted Mean Vote)	[-]	Category B -0.5 to +0.5	DIN 7730	LBT / Simula-tion En-ergy +
3b	Support **healthy** and **comfortable** outdoor micro-climate	UTCI (Universal Thermal Com-fort Index)	°C	9°C – 26°C No heat stress	Jen-dritzky et al. (2008)	Simula-tion La-dybug Tools (LBT)
3c	Avoid the use of **envi-ronmentally hazard-ous** materials	AP	kg SO2 equiv./(m²NFAs*a)	≤ 0,037	DGNB	eLCA
3d	Encourage physical ac-tivity	Bike sharing planned / Sport parks?	True / False	None found in the litera-ture	DGNB	Archicad / GH
3e	Provide **accessibility to all** spaces	Barrier-free accessibility ratio	%	30 % of all apart-ments	BayBo, Art. 48, Para-graph 1, statement 2	Archicad / GH
3f	Avoid any contribution to **air, water** and **soil** contamination	EP (Eutrophica-tion Potential)	kg PO43 equiv./(m² *a)	≤ 0,0047	DGNB	eLCA
7	**Affordable & Clean Energy**					
7a	Reduce **operational** and **embodied** energy	PE operation	kWh/m²a PE op.	50-75	DGNB	Honey-Bee / Simula-tion En-ergy +
		PE construc-tion	kWh/m²a PE co.	34.44	DGNB	eLCA / GH
		% PENRT const.	%		DGNB	eLCA / GH
		% PERT const.	%		DGNB	eLCA / GH
7b	Recycle and conserve energy	Eff. heat recov-ery	% / [-]	None found in the litera-ture	----	Honey-Bee /

						Simulation Energy +
7c	Implement **resilient** and **adaptive energy** systems	LM (Energy Load Match)	%	105	Attia et al. (2017) / LBC	Simulation Ladybug Tools (LBT)
7d	Use renewable energy to cover the demand	Share of renew. PE construction	%	None found in the literature	----	eLCA
11	**Sustainable Cities and Communities**					
11a	Promote Inclusion and **community**	Share of communal NFA	%	12	Mahdavinejad et al (2012)	Archicad / GH
11b	Use **regenerative design** strategies	Animal Aided Design Strategies	True/ False	None found in the literature	Hauck et al (2015)	Archicad / Species portraits
11c	Implement **resilient and climate-adaptive** measures	Climate Analysis	[-]	None found in the literature	----	LBT / Climate Consultant / EPW
11d	Provide **sustainable mobility**	Checklist sustainable mobility	True/ False	several	DGNB	Archicad / GH
12	**Responsible Consumption and Production**					
12a	Design for **long lifetime**	Projected Lifetime of edification	a	50	El Khouli et al (2015)	
		Mass index for secondary raw materials	kg/m² NFA	None found in the literature	DGNB System – New buildings criteria set VERSION 2020 INTERNATIONAL	eLCA / GH
12b	**Design for disassembly** and circularity	Recyclability concepts	True/ False	None found in the literature	----	Archicad / Documentation / Research
12c	**Reduce** or restrict the use of **non-renewable** natural resources	Amount of used non-renewable materials	kg/m²NFA non-renewable	None found in the literature	DGNB System – New buildings criteria set VERSION 2020 INTERNATIONAL	
12d	Encourage **prefabrication**	Share of prefabrication	%	None found in the literature	Kaufmann et al (2018)	Documentation / Research

13	Climate Action					
13a	Aim for **carbon neutrality**	GWP	kg CO2 equiv./m^{2}a	9.4	DGNB	eLCA / GH
13b	Use **local resources**	Share of locally reused materials	%	None found in the literature	DGNB	
13c	Integrate and **expand green areas and biodiversity**	Biodiversity Index	[-]	0.25	DGNB System – New buildings criteria set VERSION 2020 INTERNATIONAL	DGNB / GH

An extended list of KPIs

Description: This section presents the SDGs with more possible targets and all their relevant KPIs decided into general groups							
Energy	Total Primary Energy	kWh/m^{2}a PE		**Ecological Footprint**	Global Warming Potential (GWP)	kg CO2-e/m^{2}a	
	Total Primary Energy non-renewable	kWh/m^{2}a PENRE			GWP per User Operation Phase	kg CO2-e/person*a Operation	
	Total Primary Energy renewable	kWh/m^{2}a PERE			GWP Construction Phase	kg CO2-e/m^{2}a Construction	
	Total Exported Energy	kWh/m^{2}a Exported Energy			GWP per User Construction Phase	kg CO2-e/m^2*a Total	
	Heat transfer coefficients, differentiated by different exterior components	W/m^2*K			LCA Modules	-	
	Thermal heat bridge correction factors	W/m^2*K			LCA Scope	-	
	Air exchange rate	1/h			Ozone depletion potential (ODP)	kg R11 equiv./(m^{2}NFAs*a)	
	SHGC: Solar heat Gain Coefficient	-			Ozone depletion potential Photochemical ozone creation potential (POCP)	kg C2H4 equiv./(m^{2}NFAs*a)	
	Orientation	degrees			Acidification potential (AP)	kg SO2 equiv./(m^{2}NFAs*a)	
	WWR: Window-to-wall ratio	-			Eutrophication potential (EP)	kg PO43 equiv./(m^{2}NFAs*a)	
	LM: Energy Load Match	%					

	EUI: Energy use intensity	kWh/m² a		Local Pollution	Amount of used biogenic materials	kg biogenic	
					Use of halogenated refrigerants?	True / False	
Acoustic Comfort	Average reverberation time	s			Concentration of Pollutants in the room (VOC, Formaldehyde)	µg/m³	
	The average equivalent sound absorption area	%			Frequency of maximum CO_2-Concentration	%	
	Airborne sound insulation against other rooms	dB			Radon or other factors of contamination on site	True / False	
	Footfall sound insulation for dividing ceilings	dB			The concept of Light Pollution outdoors	True / False	
	Airborne sound insulation against external noise	dB					
	Airborne sound insulation against building technology	dB		Biodiversity	Biodiversity index	-	
					Invasive species planned	True / False	
Resources	Total Amount of each used Material	kg		Land and space use	Soil sealing factor of the total developed and undeveloped area	%	
	Lifetime each Material/Component	years			Soil sealing types with infiltration coefficients	%	
	Lifetime building	years			BCR: Building coverage ratio	-	
	Amount of waste produced	kg waste/m²			Aspect Ratio	-	
	Amount of used non-renewable materials	kg CO_2-e/a non-renewable			GFA: Gross Floor Area	m²	
	Mass index for certified raw materials	kg/m² GFA			FAR: Floor Area Ratio	-	
	Mass index for secondary raw materials	kg/m² GFA					
	Recyclability share	%		Psychological Comfort	Ventilation can be controlled by users	True/False	
	Disassembly share	%			Shading can be controlled by users	True / False	
	Life cycle scenarios	-			Room temperatures can be controlled individually for particular rooms	True / False	
					Artificial light can be controlled by users	True / False	
Market-	Occupancy rate	%					
	The proportion of exterior glass surfaces that can be cleaned without aids	%		Com-	Share of provisions designed to promote communication	%	

	The proportion of floor coverings (interior) with high tolerance to contamination	%			Share of additional provisions for users	%	
	Life Cycle Cost	EUR/m^2 GFA*a			Share of facilities for families, children and senior citizens	%	
					Nearby social infrastructure facilities	True / False	
Water	Total water consumption including rainwater use	m^3/a			Nearby commercial infrastructure facilities	True / False	
	Water demand	m^3/a*person			Social or commercial infrastructure inside the building itself	True / False	
	Rainwater collection	m^3/a			Assessment of Urban Demographics (population growth, family size, income, rate of urbanization, rate of new household formation and the amount that households are able/willing to spend on housing)	True / False	
	Greywater reuse	m^3/a			Range of housing tenure typologies (rental accommodation, cooperative housing, lease, owner occupied, emergency housing, among others)	True / False	
	Wastewater occurrence	m^3/a					
	Potable water use	m^3/a					
Flexibility	Space Efficiency: Usable area/GFA	m^2/m^2		Mobility	Car Parking Capacity for habitants/owners	Parking space/unit	
	Room Height	m			Car Parking Capacity for visitors/public	Parking space/unit	
	Building Depth	m			Bicycle parking capacity	Bicylce / unit	
	flexible non-load bearing internal wall system	True / False			Nearby parking spaces for car sharing	True / False	
					Nearby parking spaces for bike sharing	True / False	
Thermal Comfort	Frequency of uncomfortable time: heating and cooling period	%			Car charging stations	True / False	
	Frequency of uncomfortable space: heating and cooling period	%			Car Parking spaces coupled with charging stations	%	
	PMV: Predicted Mean Vote	Number			Bike parking coupled with charging stations	%	
	PPD: Predicted percentage of dissatisfied	%			Nearby cycle paths available	True / False	
	Comfort-temperature range: Heating and cooling period	°C			Nearby public transport routes available	True / False	

	Maximum and minimum interior surface temperatures	°C			Nearby pedestrian path networks are available	True / False	
	Frequency of uncomfortable indoor humidity	%			Barrier-free public transport stops	True / False	
	UTCI: Universal Thermal Climate Index	°C			Innovative mobility elements planned	True / False	
	OTCA: Outdoor Thermal Comfort Autonomy	%					
				Accessibility	Proportion of barrier-free units in the building	%	
Visual Comfort	Illuminance	Lux			Proportion of barrier-free shared indoor areas	%	
	Spatial Daylight Autonomy (sDA)	%			Barrier-free access concept available	True / False	
	DF: Daylightfator for 50% of the usable area	%			Proportion of barrier-free outdoor areas	%	
	Relative annual useful exposure	%					
	The proportion of rooms with a direct visual link to the outside	%		**Climate adaptation**	Weather data for future climate	True / False	
	Artificial light qualities: Colour rendering index, illuminance and rate of adjustment, light colour	-			UHI considered	True / False	
	Colour rendering index of the glazing	%			Flooding safety		
	Duration of exposure to daylight (17th January and at the equinox) and proportion of rooms to which this information applies	h			Water storage		
					Local Tree and plant species		

Note: Future research should try to create a clearer definition of the targets including all relevant KPIs to their evaluation.

Appendix C: Checklists

Materials red list LBC

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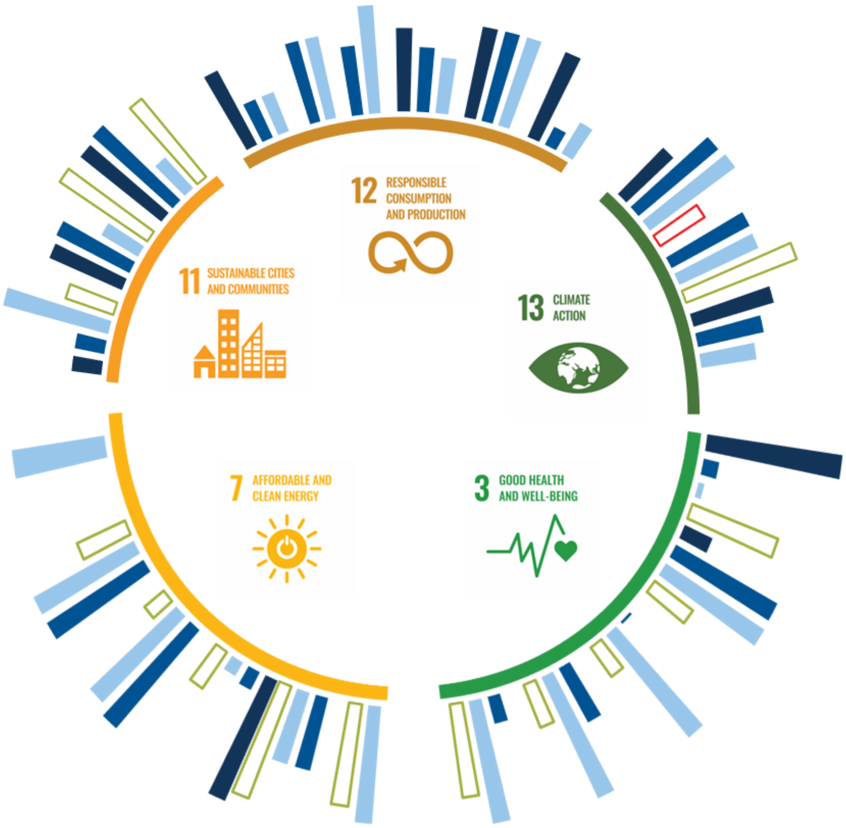
2022 RED LIST CHEMICAL CLASS CHANGES (SINCE JANUARY 2021) CHEMICAL CLASS	RED LIST	PRIORITY FOR RED LIST INCLUSION	WATCH LIST
Alkylphenols and related compounds	No changes.	No changes.	No changes.
Antimicrobials (marketed with a health claim)	No changes.	No changes.	No changes.
Asbestos compounds	No changes.	No changes.	No changes.
Bisphenol A (BPA) and structural analogues	2 CASRNs added from Priority List, 1 moved to Chlorinated Polymers.	25 CASRNs added from Watch List.	25 CASRNs added to Priority List.
California-banned solvents	No changes.	No changes.	No changes.
Chlorinated Polymers	No changes.	No changes.	No changes.
Chlorobenzenes	1 moved from Bisphenol A (BPA) and structural analogues.	No changes.	No changes.
Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)	No changes.	No changes.	No changes.
Formaldehyde (added)	No changes.	No changes.	No changes.
Monomeric, polymeric, and organophosphate halogenated flame retardants (HFRs)	No changes.	No changes.	No changes.
Organotin Compounds	No changes.	No changes.	No changes.
Perfluorinated and Polyfluorinated Alkyl Substances (PFAS) / Perfluorinated compounds (PFCs)	4,844 CASRNs added from Priority List.	5,947 CASRNs added directly.	No changes.
Phthalates (orthophthalates)	No changes.	No changes.	No changes.
Polychlorinated biphenyls (PCBs)	No changes.	No changes.	No changes.
Polycyclic aromatic hydrocarbons (PAHs)	No changes.	No changes.	No changes.
Short-chain and medium-chain chlorinated paraffins	No changes.	No changes.	No changes.
Toxic heavy metals	No changes.	No changes.	5 CASRNs added directly.
Volatile organic compounds (VOCs) in wet-applied products*	No changes.	No changes.	No changes.
Wood Treatments containing creosote or pentachlorophenol	No changes.	No changes.	No changes.

*Volatile organic compounds (VOCs) in on-site wet-applied products are not banned, but must have VOC levels below the South Coast Air Quality Management District (SCAQMD) Rule 1168 for Adhesives and Sealants or the CARB 2007 Suggested Control Measure (SCM) for Architectural Coatings, as applicable.

Sustainable mobility checklist

Checklist for sustainable mobility	TRUE	FALSE
Availability of public transit		
Intermodality		
The proximity of bus stops to homes		
Adapted transport for barrier-free access		
Bus shelters		
Display of bus schedules		
Bike rental station		
Bicycles on bus		
Car sharing		
Connectivity between clusters of homes		

Appendix D: Architectural design comparison



The details of the numerical values and arguments can be found digitally in the attached Excel file under the sheets “Compare data” and “Compare Charts”.

Appendix E: Design Project preliminary analysis

Analysis to select scenarios

Identify key characteristics of the location: potentials and threats

Analyzing the weather can help unveil hidden unused potentials to generate energy with passive measures.

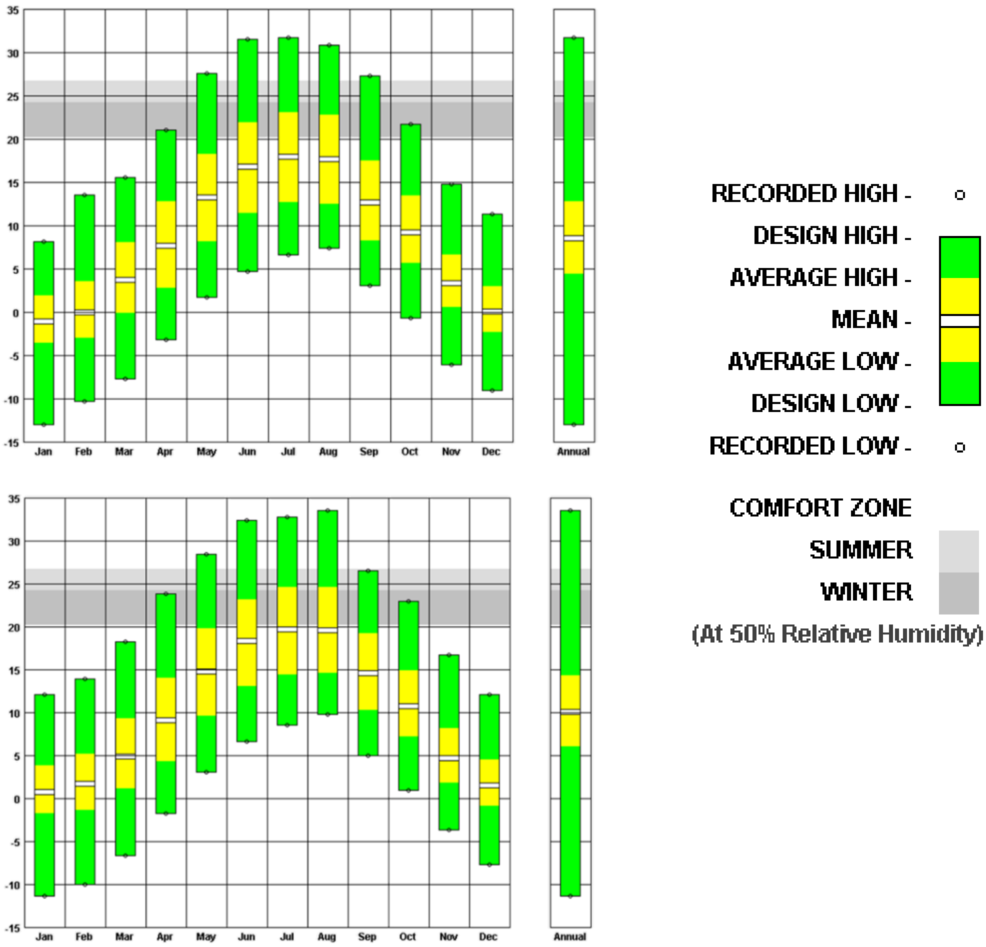


Figure 31: Dry-bulb temperature for EPW 2020 (Top) and EPW 2070 (Bottom)

The temperature in the year 2020 shows that the comfort areas marked with grey are limited to a few hours in the year. The local weather prevailed with cold temperatures the whole year with peaks of hot temperatures between May and September. The evaluation of the temperature in the year 2070 shows an increase in the monthly average temperatures, reducing the cold temperatures but increasing the hot temperatures as well. This poses a threat to the comfort of the inhabitants of the future and has implications on the energy systems that could be optimally used in this location, especially on the active heating system. The buildings, due to their program will not integrate active cooling systems, nevertheless, the comfort of its inhabitants must be secured.

Figure 51 shows the ground temperatures at the depth of 1m. These graphics reveal the potential to use the ground´s temperature in the winter to reduce preheat the medium used in the heating system.

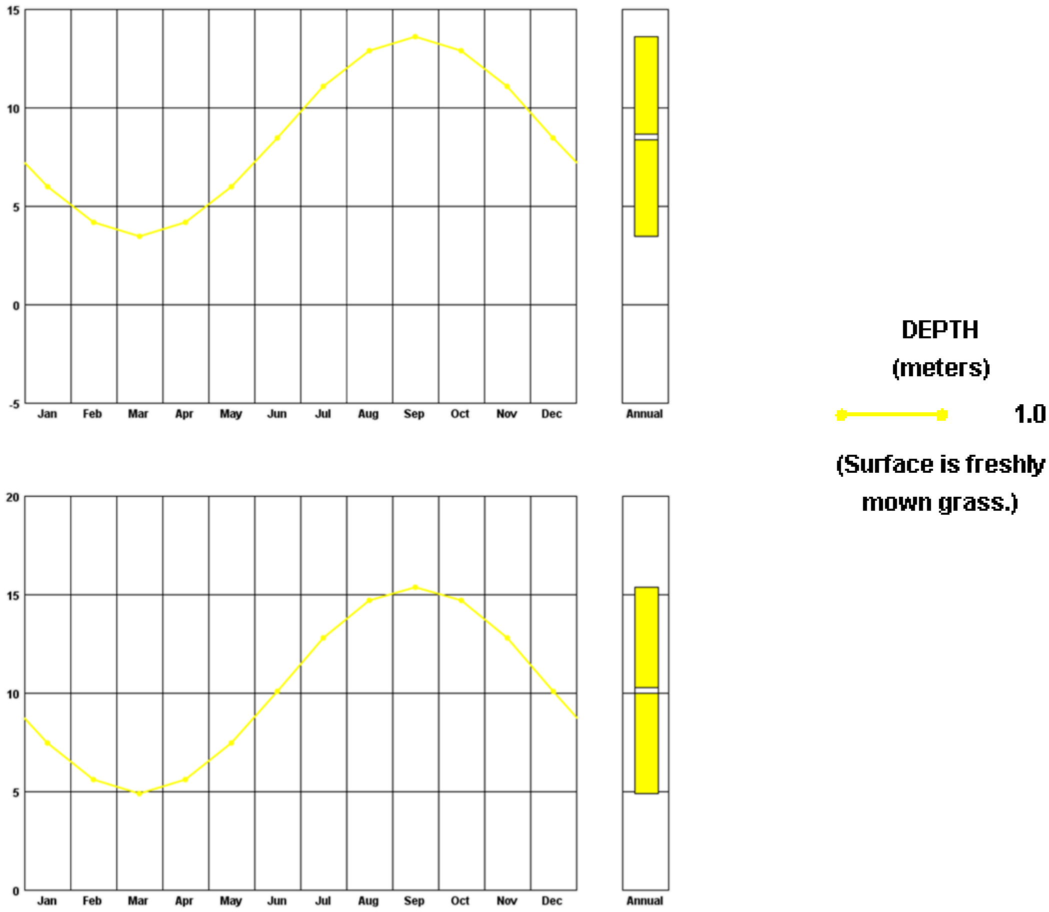


Figure 32: Ground surface temperatures for EPW 2020 (Top) and EPW 2070 (Bottom)

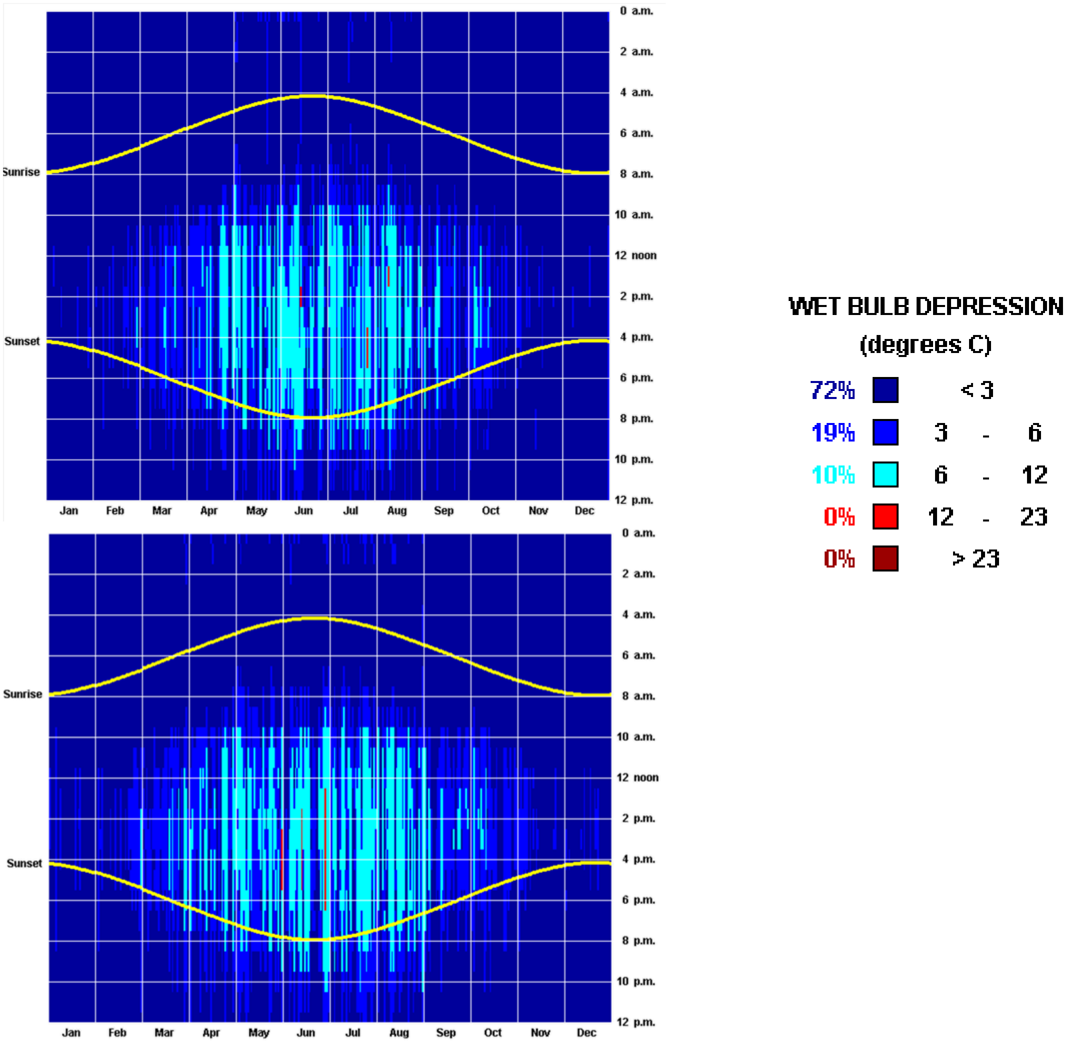


Figure 33: Wet-bulb depression for EPW 2020 (Top) and EPW 2070 (Bottom)

Figure 52 shows the wet-bulb depression for both of the analyzed weather files. There is a great potential to reduce the temperature using evaporative cooling in the summer. Although there is no active system to be planned for the cooling of the buildings, the use of indirect evaporative cooling by properly selecting the hours to water the green infrastructure can reduce the temperature of the immediate surroundings, creating more comfortable temperatures for the inhabitants of this development.

Figure 53 shows the potential to use solar radiation to generate energy, especially in the summer months for both weather files. The sun can also be used to reduce energy consumption for heating in the winter.

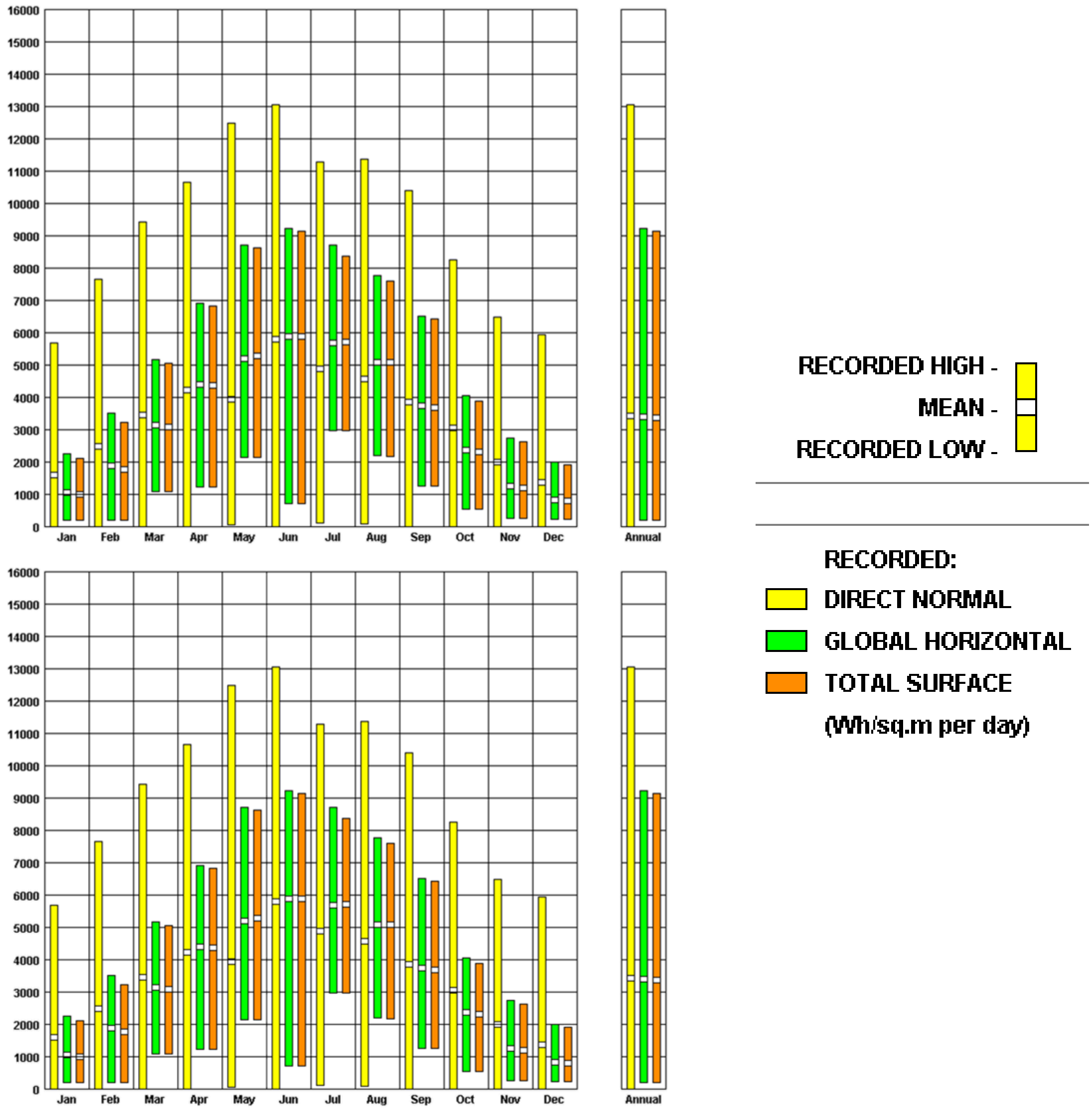


Figure 34: Radiation range for EPW 2020 (Top) and EPW 2070 (Bottom)

The main characteristics of the location are listed below:

- Potentials: Ground temperature, sun radiation, evaporative cooling
- Threats: Air temperature, climate change

Establish the baseline case

The baseline is set by the existing structures and their current envelope´s energetic standard as their current energy consumption.

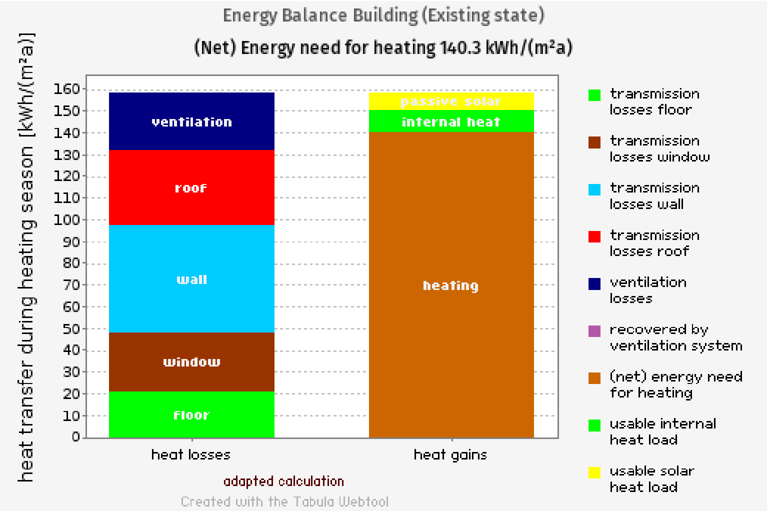


Figure 35: Baseline case. From https://webtool.building-typology.eu

This information can be extracted from the TABULA (Typology Approach for Building Stock Energy Assessment) for Germany for the construction year class 1949-1957 and the multiple family dwellings (DE.N.MFH.04.Gen).

- Heat Supply system:
  - Gas central heating system, rather poor efficiency (low-temperature boiler, poor insulation of pipes)
  - Heat generation combined with heating system (low-temperature boiler), poorly insulated circulation loop
- U-Values for the envelope
  - Roof: 1.08 W/(m2K)
  - Floor slab: 1.33 W/(m2K)
  - Wall: 1.20 W/(m2K)
  - Window: 3.00 W/(m2K)

Evaluate HVAC-system alternatives

Up to this point, no simulation was required, but to evaluate different energy systems, the use of simulation models is required. For this, a virtual model of the existing infrastructure was created and different energy systems with different energy standards were evaluated for the two existing weather files (EPW 2020 and EPW 2070). The results are shown in the following Figure:

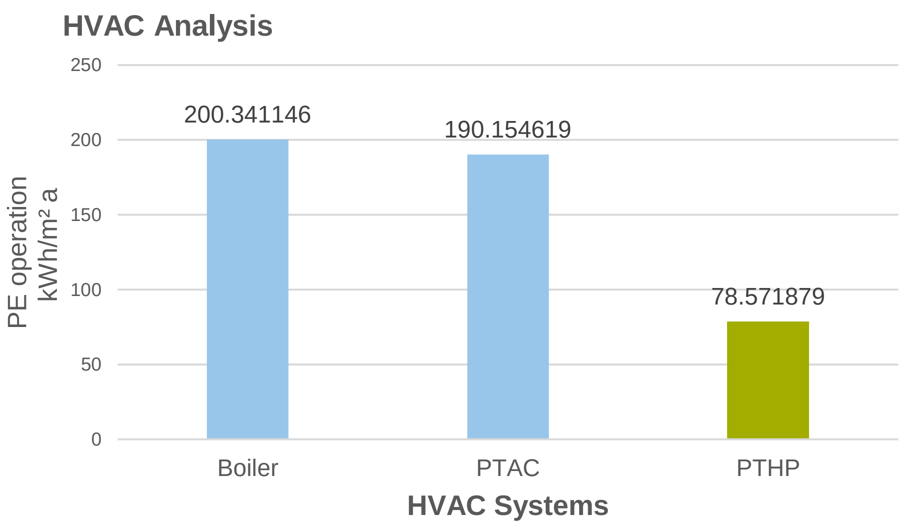


Figure 36: Evaluating HVAC systems

The first design decision is to move forward with a heat pump system, which can reduce the energy demand to more than 50% of the conventional HVAC systems.

Define goals and constraints

The energetic goals can be derived from the overall A-SDGs.

- Net-zero or nearly zero energy standard
- Prosumer state preferable
- Energy production on site: renewable and reliable

The constraints for some of the goals are mainly derived from the characteristics of the location:

- Existing constructions impede the use of the underground to extract heat
- The green infrastructure must be conserved, therefore, the space for expanding earth collectors is limited

Create scenarios for future climate

The weather files used for this design project represent the average expected useful life of a building, i.e. 50 years, therefore, the EPWs for the years 2020 and 2070 were selected. By evaluating different energy standards such as the Baseline, the GEG (German Energy Act for Buildings or Gebäudeenergiegesetzt in German) and the PHPP (Passive House Design Package or Passivhaus-Projektierungspaket in German), a renovation scheme for the envelope can be derived. The following Figure illustrates the results of this comparison:

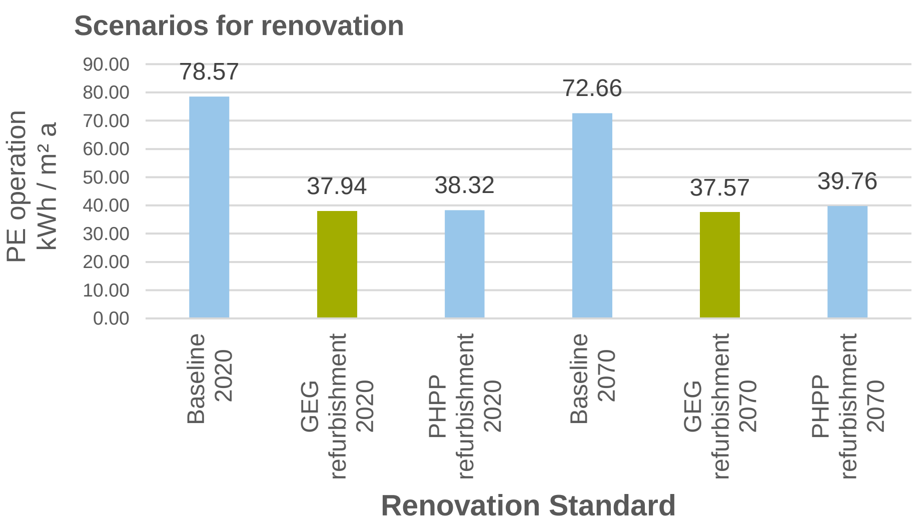


Figure 37: Evaluating scenarios for renovation

A refurbishment under the GEG standards results in the lowest energy demand and its investments are probably considerably lower than the ones required to fulfil the PHPP. The second design decision is to move forward with the GEG standard. Perhaps in a higher more detailed stage of the design, the PHPP can be re-evaluated.

Integrate renewable energy generation systems

The following Figure 57 shows the coverage of 100% of the existing roof with PV and the result of the load matching for each one of the previous scenarios.

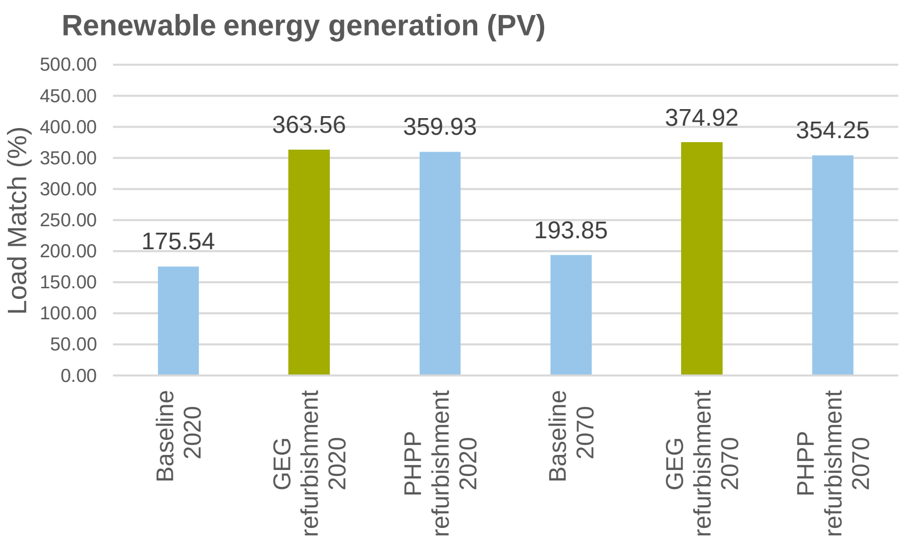


Figure 38: Energy generation PV

The selected GEG standard shows a load match of approximately 363% (2020) and 374% (2070), meaning that the photovoltaic arrangement has a surplus of more than 2,5 times the energy necessary to satisfy the energy demand of the buildings. In a later stage, this surplus will be optimised to fit the requirements of the expansion.

General design goal intervention

Before stepping into the next target (13c), which handles the green infrastructure and landscape, it is necessary to develop the design goals which conflict with the green areas. The vertical extension is not directly conflicting with the landscape but is necessary to develop the horizontal extension. Therefore, it is initially planned.

Vertical Extension

The decision of extending the existing buildings on one more floor is defined by the potential of the existing infrastructure (mainly walls and foundations) to support the new loads. The tendency in the buildings between the years 1949-1957 was to build cheap and light. The constructions were characterized by hollow stone bricks and hollow stone ceilings to reduce the number of utilized materials.

Figure 39 shows the most relevant impacts of the vertical expansion and the GEG refurbishment compared to the baseline:

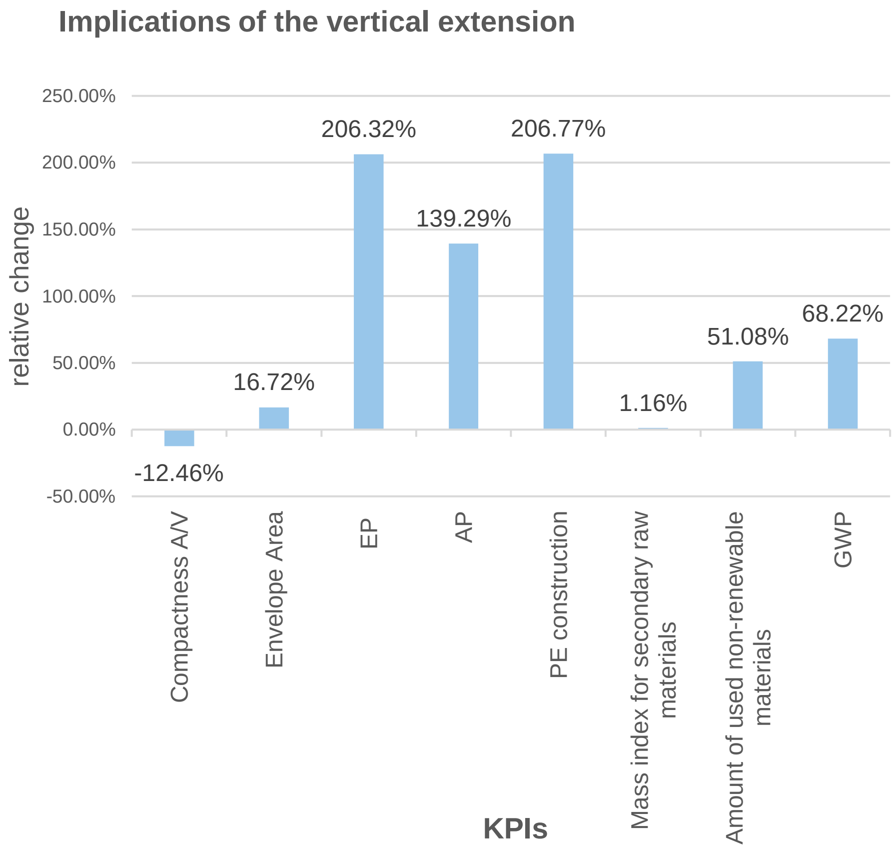


Figure 39: Vertical extension

A decrease in the compactness of 12% results from the increase of 16% of the envelope area. The most affected indicators are the EP (Eutrophication potential) and the AP (Acidification potential) with an increase of 206% and 139% respectively. The primary embodied energy increases twofold, due to the new materials necessary for the refurbishment and the extension. In the same manner, the amount of secondary raw materials and non-renewable materials increase by 1% and 51%. Lastly, the embodied carbon increases by almost 70%. These results will serve as the new baseline for further optimization strategies.

Horizontal Extension

Figures 59-62 show the impact of the horizontal expansion on three different alternative constructions for stairs: steel, concrete and wood. The BayBO allows the use of flammable materials for the second escape route under the condition that the design integrates two secondary escape routes in different directions. Therefore, the amount of staircases doubles compared to concrete or steel constructions. To properly evaluate this design choice, the following parameters are analyzed: non-renewable materials, GWP, EP and AP.

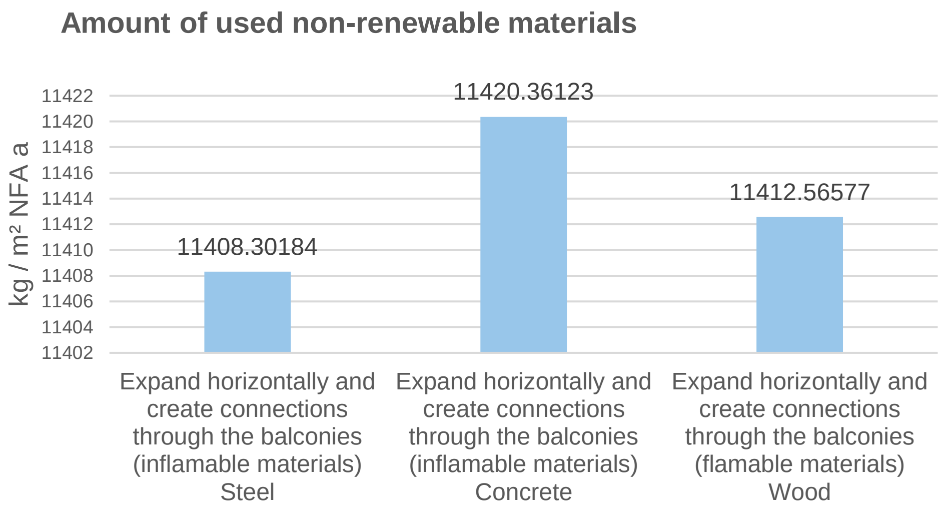


Figure 40: Horizontal expansion´s non-renewable materials

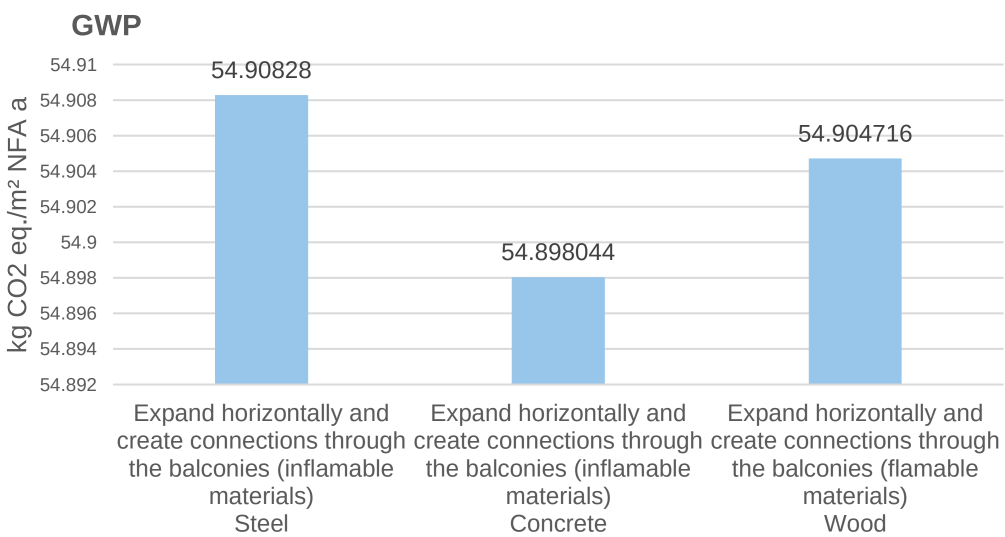


Figure 41: Horizontal expansion´s GWP

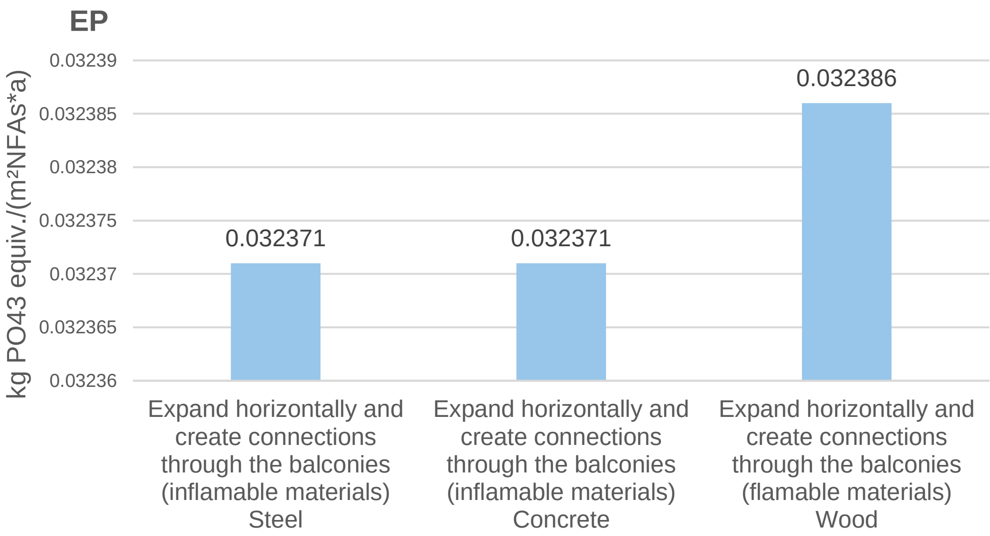


Figure 42: Horizontal Expansion´s EP

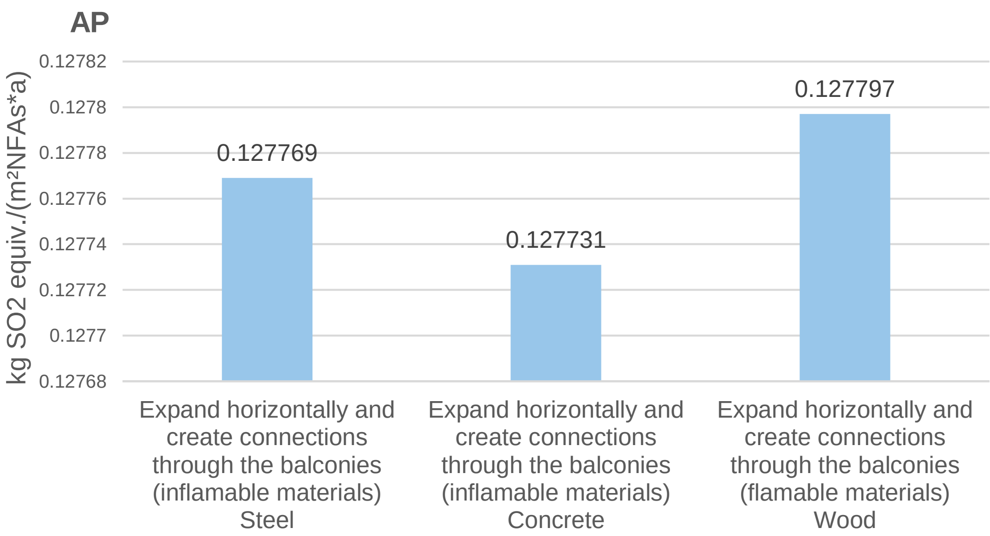
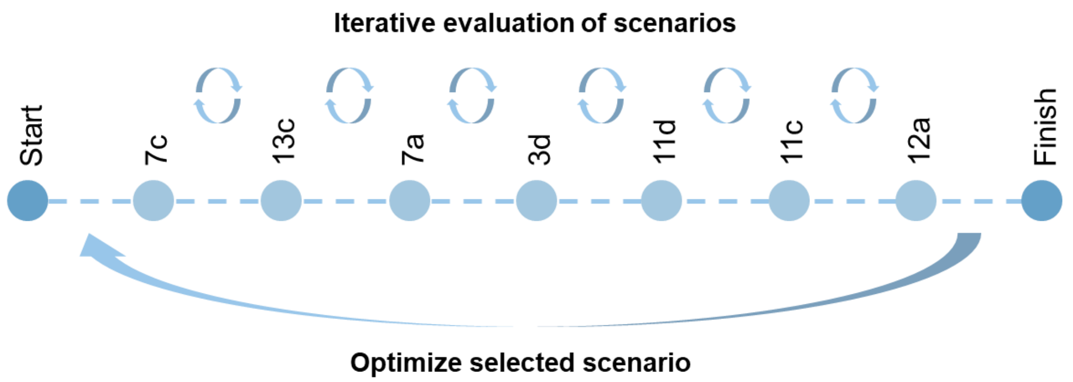


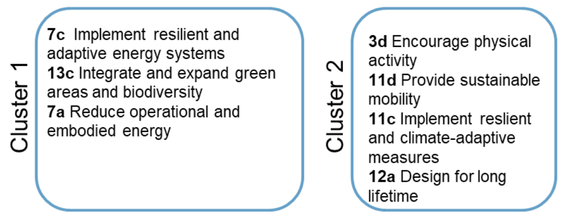
Figure 43: Horizontal expansion´s AP

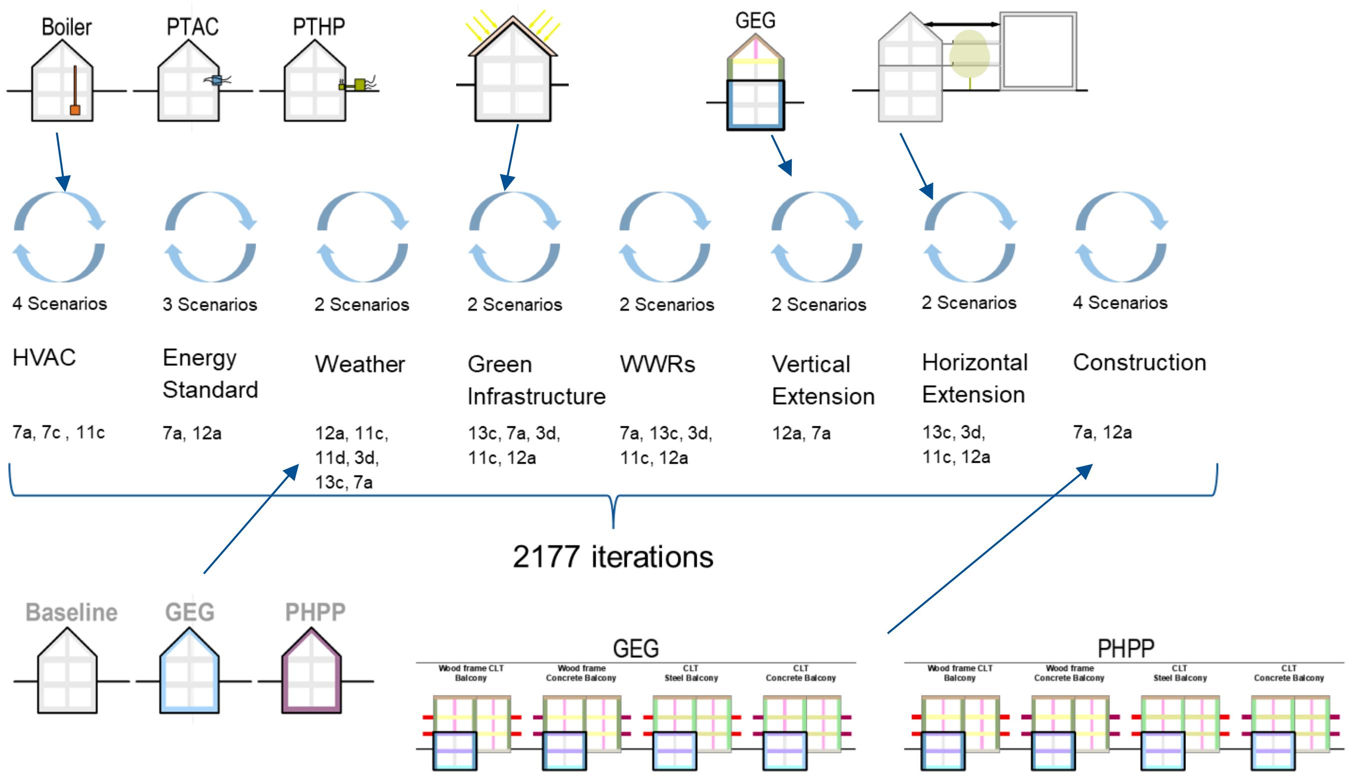
The parameter with greater deviation is the mass index for used non-renewable materials.

Scenarios

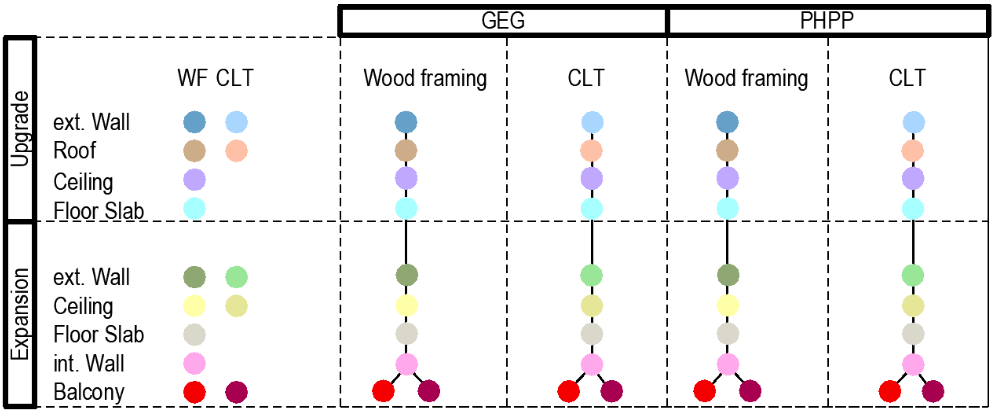


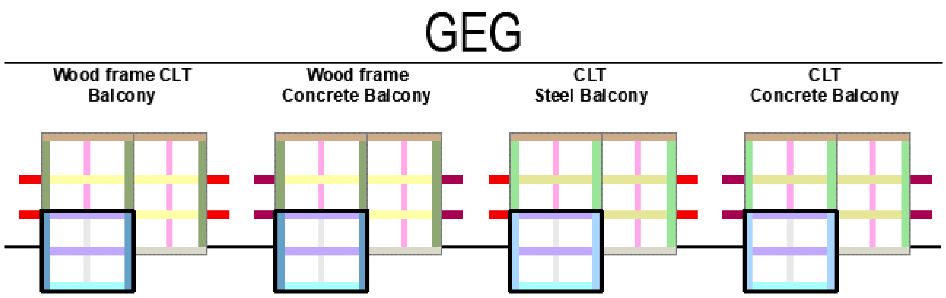
Most dependent = highest impact

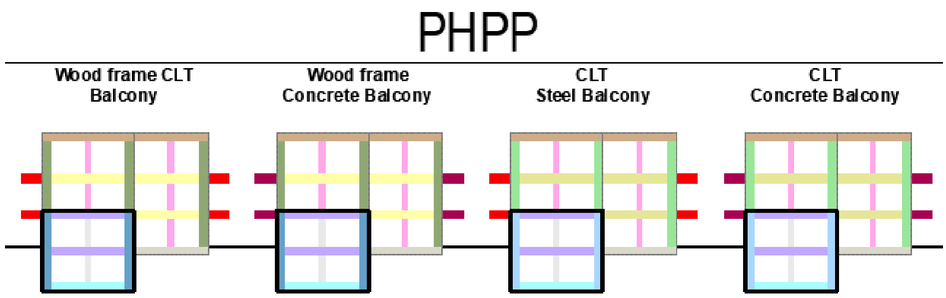




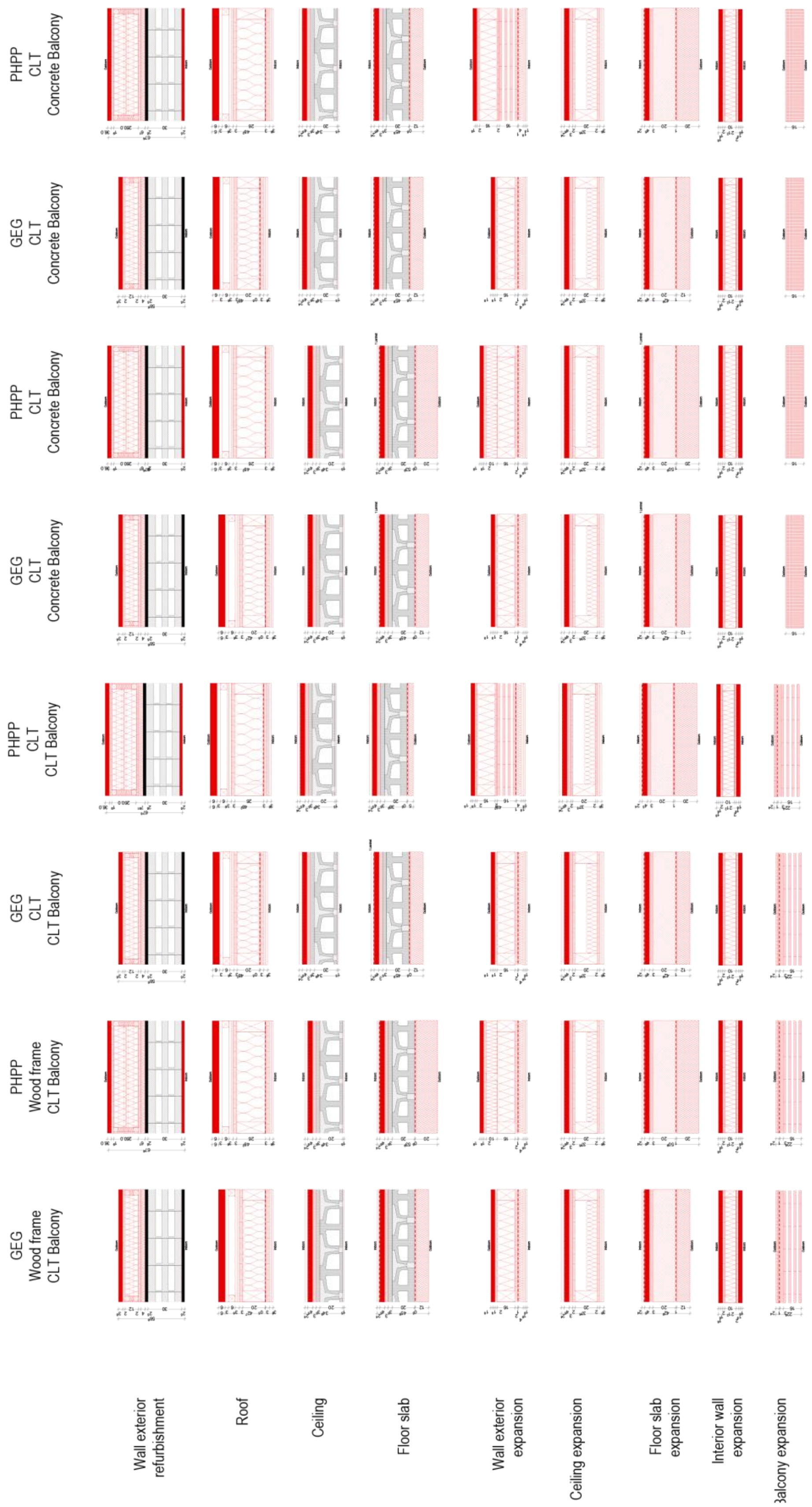
Appendix F: Construction alternatives







In total, 16 different éléments were analyzed and logically combined to create 16 different construction proposals. The following details show a summary of the most relevant differences.


PHPP
CLT
Concrete Balcony
GEG
CLT
Concrete Balcony
PHPP
CLT
Concrete Balcony
GEG
CLT
Concrete Balcony
PHPP
CLT
CLT Balcony
GEG
CLT
CLT Balcony
PHPP
Wood frame
CLT Balcony
GEG
Wood frame
CLT Balcony
Wall exterior refurbishment
Roof
Ceiling
Floor slab
Wall exterior expansion
Ceiling expansion
Floor slab expansion
Interior wall expansion
Balcony expansion

Appendix G: Design Strategies in Design Phases

A-SDGs / Targets		DESIGN STAGE	
		LPH 2	LPH 2
Health and Well Being	3		
Provide a healthy and comfortable indoor climate	3a	X	Evaluate the regulations and requirements. Exclusion criteria concerning building biology and environmental aspects
Support healthy and comfortable outdoor micro-climate	3b	X	Analyse the topographie in depth. Assess the impact of selected materials on the outdoor comfort
Avoid the use of environmentally hazardous materials and substances	3c	X	Perform a GWP sensitity anlaysis for rough components and spaces
Encourage physical activity	3d		
Provide accessibility to all spaces	3e	X	Analyze the accessibility outdoors
Affordable & Clean Energy	7		
Reduce operational and embodied energy	7a	X	Perform a PEI sensitity anlaysis for components and spaces
Recycle and conserve energy	7b	X	Prepare a draft for the enrgy concept including recycling and conserving energy
Implement resilient and adaptive energy systems	7c	X	Extend the climate analyses to propose measures for water cycles, sewage and treatment
Use renewable energy to cover the demand	7d	X	Perform rough energy simulations or calculations to estimate the availability of renewable energy generated in the location
Sustainable Cities and Communities	11		
Promote Inclusion and community	11a	X	
Use regenerative design strategies	11b	X	Rainwater harvesting and greywater reuse
Implement reslient and climate-adaptive measures	11c	X	Plan the use of environmental energy sources
Provide sustainable mobility	11d	X	Develop a mobility concept, including structural and organisational measures to control mobility behaviour
Responsible Consumption and Production	12		
Design for long lifetime	12a	X	Plan multifunctional spaces and components
Design for disassembly and circularity	12b	X	Evaluate methodlogies for dissassembly
Reduce or restrict the use of non-renewable natural resources	12c	X	Define requirements for low emisions and define bio-based construction elements
Encourage prefabrication	12d	X	
Climate Action	13		
Design for carbon neutrality	13a	X	Integrate goals to dephase Emissions
Use local resources	13b	X	Investigate pollution and risks in the inventory
Integrate and expand green areas and biodiversity	13c	X	Assess the local flora and fauna to adapt to the design to their conditions

A-SDGs / Targets		DESIGN STAGE	
		LPH 3	LPH 3
Health and Well Being	3		
Provide a healthy and comfortable indoor climate	3a	X	Perform a building biology assessment, optimze comfort, integrate biophilic design
Support healthy and comfortable outdoor micro-climate	3b	X	Integrate measures to strengthen the previous processes and ensure comfort and biophilia
Avoid the use of environmentally hazardous materials and substances	3c	X	Perform a GWP sensitity anlaysis for detailed components and spaces
Encourage physical activity	3d	X	Plan accessibility indoors and outdoors
Provide accessibility to all spaces	3e	X	Evaluate accessibility and barrier-free condition indoors
Affordable & Clean Energy	7		
Reduce operational and embodied energy	7a	X	Optimize the floor plans and building envelope
Recycle and conserve energy	7b	X	Optimize the building envelope to recycle energy and reduce heat losses
Implement resilient and adaptive energy systems	7c	X	Integrate efficient buiding technology
Use renewable energy to cover the demand	7d	X	Integrate renewable and passiv-diven approaches
Sustainable Cities and Communities	11		
Promote Inclusion and community	11a	X	
Use regenerative design strategies	11b	X	Evaluate the regeneration strategies applied
Implement reslient and climate-adaptive measures	11c	X	Proyect the performance of the design into the future
Provide sustainable mobility	11d	X	Evaluate the strategies applied
Responsible Consumption and Production	12		
Design for long lifetime	12a		
Design for disassembly and circularity	12b	X	Define more accurate details
Reduce or restrict the use of non-renewable natural resources	12c	X	Evaluate and optimize the design to include more renewable resources
Encourage prefabrication	12d	X	
Climate Action	13		
Design for carbon neutrality	13a	X	Calculate the CO2-Balance for the whole lifecylcle
Use local resources	13b		
Integrate and expand green areas and biodiversity	13c	X	Evaluare and strengthen synergyes

Appendix H: Architectural Documentation

- Floor plans in resolution 1 :100 (rescaled):
    - Ground Floor
    - First floor
    - Second floor
    - Third floor
    - Fourth floor
- Floor plans in resolution 1 :200 (rescaled):
    - ADD strategies
- Floor plans in resolution 1 :100 (rescaled):
    - Ground floor: H1-H7
    - Standard floor H1-H2
    - Standard floor H3-H7
- Elevations and Sections in resolution 1:100 (rescaled):
    - West + East with an included section for the reference building
    - North + South for the whole complex
    - South Elevation with included longitudinal section through the whole complex
- Façade Elevation Section in resolution 1:20 (rescaled)
- Layout with conceptual design and visualizations

First Floor
22 Units
14 Apartments non-barrier-free
4 communal areas
- Kindergarden
- Event area
- Gym indoors
- Co-working
2 multifunctional rooms
2 Technical rooms

Project: SDG-driven design

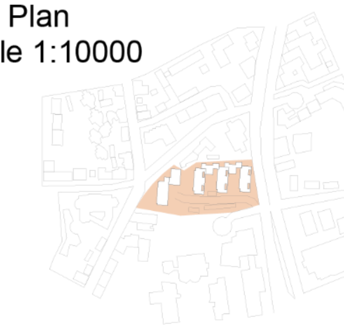
Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: Ground floor for all houses on site plan
Scale: 1:100 (Scaled dow to 1:500)
Date: 04.10.2022

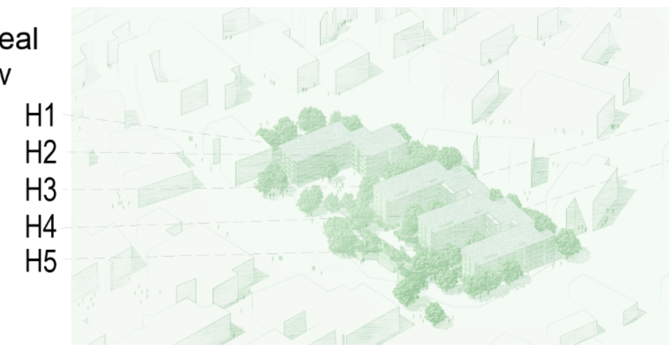
N

10 20 30 40 50 meters

Site Plan
Scale 1:10000

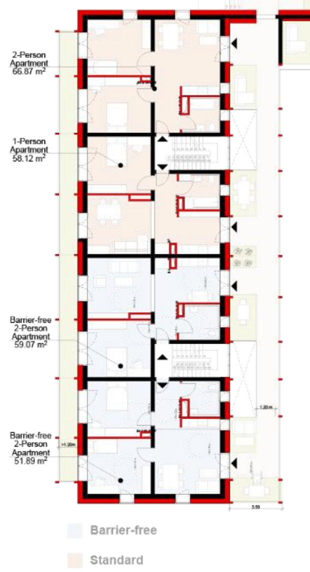


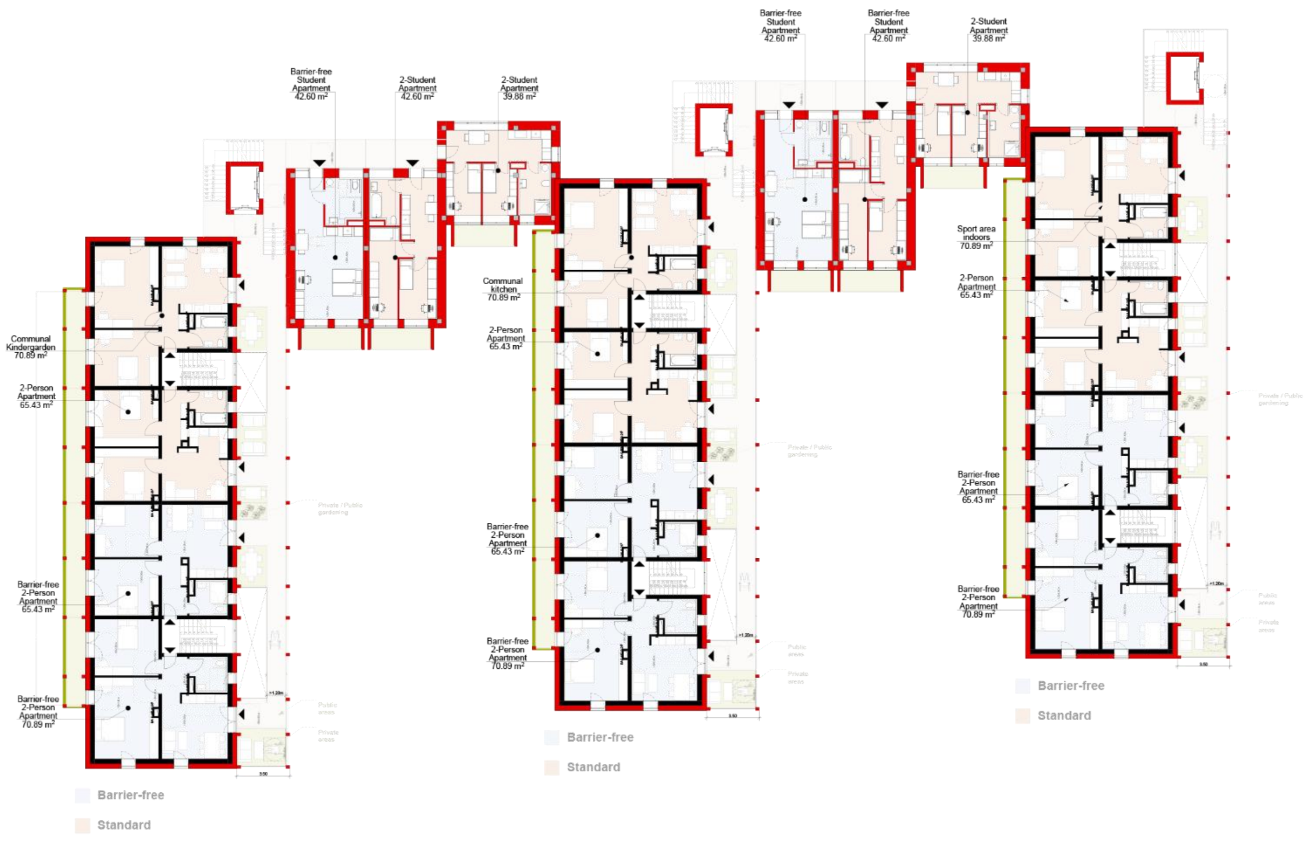
Aereal view

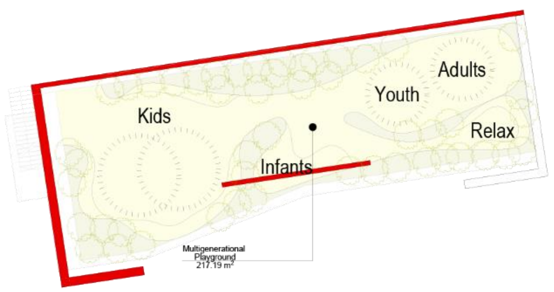


Second Floor
24 Units
- *18 Apartments for regulars*
  - *9 standard*
  - *9 barrier-free*
- *6 Apartments for students*
  - *4 standard*
  - *2 barrier-free*

1 outdoor shared space on top of the garage





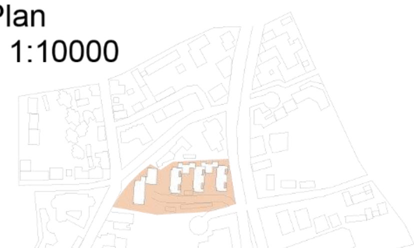


Project:	SDG-driven design
Author:	Carlos Andres Espinosa Romero
Institute:	Institute of Energy Efficient and Sustainable Design and Building
Supervisors:	Roland Reitberger, Carsten Schade
Contents:	1st floor for all houses
Scale:	1:100 (Scaled dow to 1:500)
Date:	04.10.2022

N

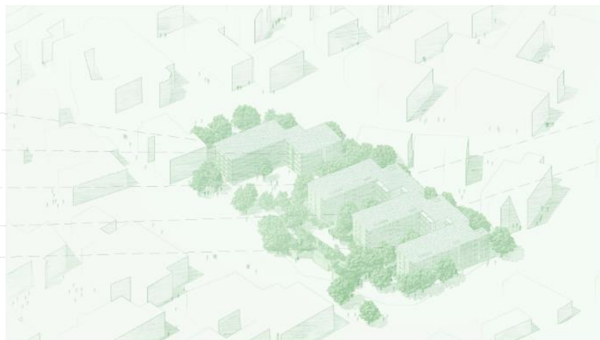
10 20 30 40 50 meters

Site Plan
Scale 1:10000



Aereal view

H1
H2
H3
H4
H5



H6
H7

Third Floor

24 Units

- *18 Apartments for regulars*
  - *9 standard*
  - *9 barrier-free*
- *6 Apartments for students*
  - *4 standard*
  - *2 barrier-free*

Project: SDG-driven design

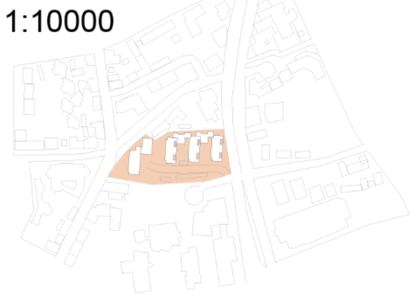
Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: 3rd floor for all houses
Scale: 1:100 (Scaled down to 1:500)
Date: 04.10.2022

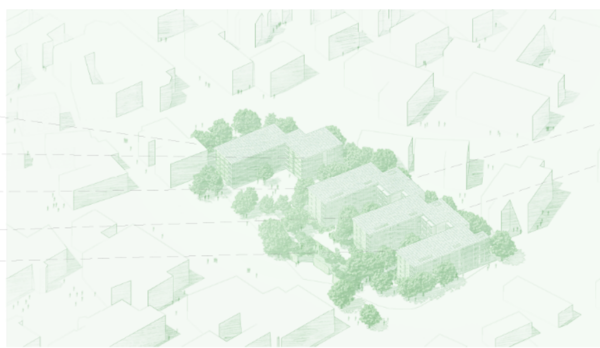
10 20 30 40 50 meters

N

Site Plan
Scale 1:10000



Aereal view



H1
H2
H3
H4
H5
H6
H7

Fourth Floor
24 Units
- *18 Apartments for regulars*
  - *9 standard*
  - *9 barrier-free*
- *6 Apartments for students*
  - *4 standard*
  - *2 barrier-free*

Project: SDG-driven design

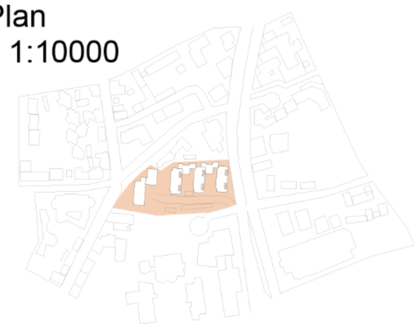
Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: 4th floor for all houses
Scale: 1:100 (Scaled dow to 1:500)
Date: 04.10.2022

N

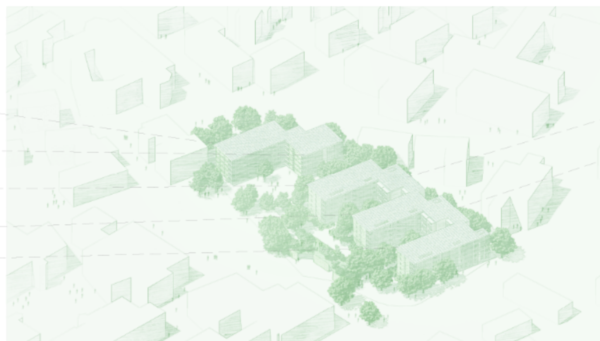
10 20 30 40 50 meters

Site Plan
Scale 1:10000



Aereal view

H1
H2
H3
H4
H5



H6
H7

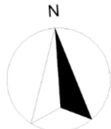
Fifth Floor
18 Units
- *18 Apartments for regulars*
  - *9 standard*
  - *9 barrier-free*

Project: SDG-driven design

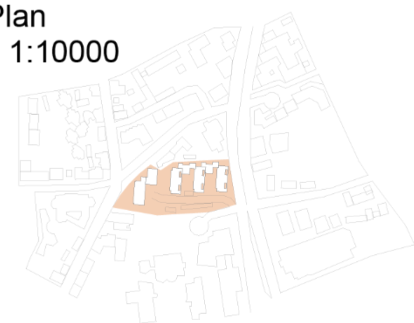
Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: Fifth floor for all houses
Scale: 1:100 (Scaled dow to 1:500)
Date: 04.10.2022

10 20 30 40 50 meters

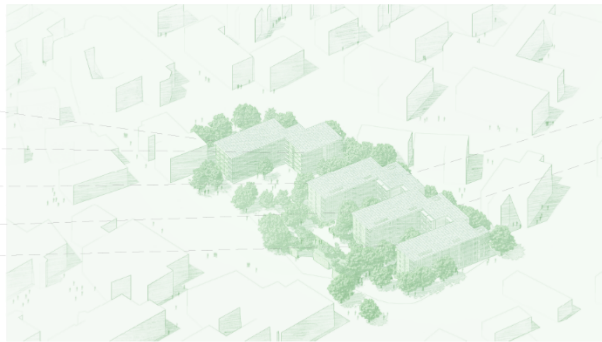


Site Plan
Scale 1:10000



Aereal view

H1
H2
H3
H4
H5

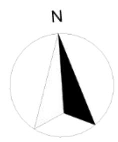


H6
H7

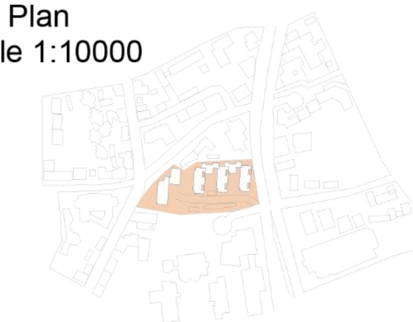
Project: SDG-driven design

Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

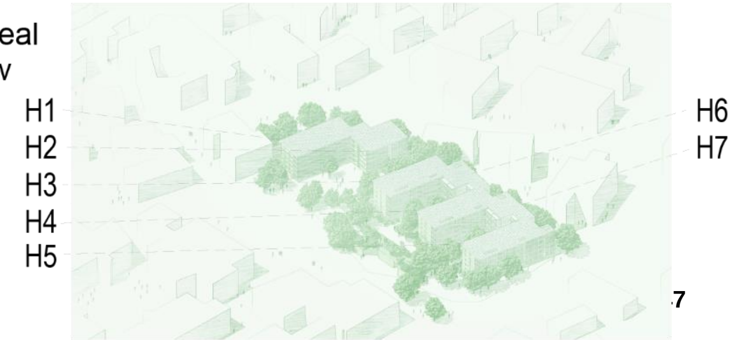
Contents: Ground floor - Animal Aided Design
Scale: 1:200 (Scaled down to 1:750)
Date: 04.10.2022

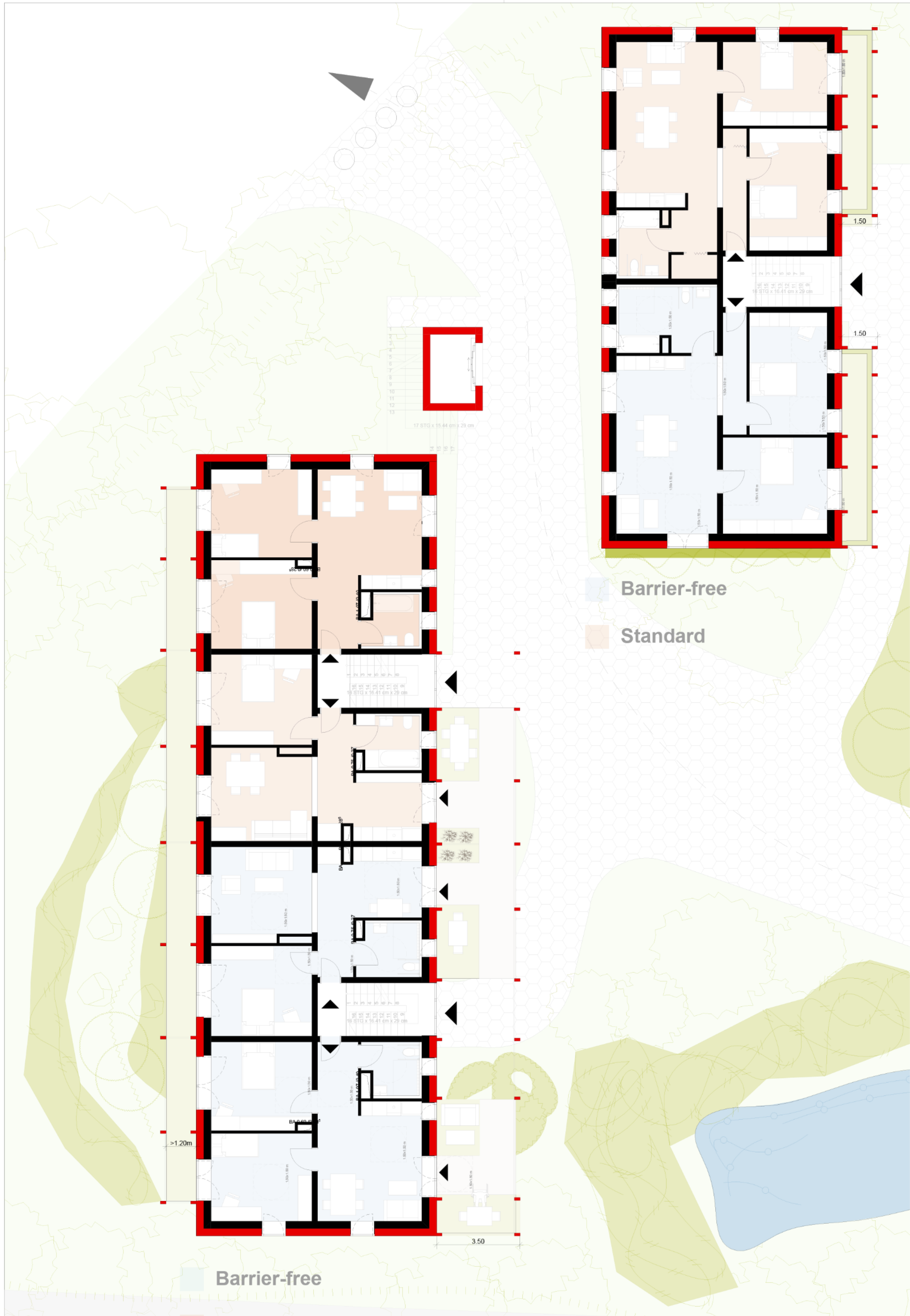


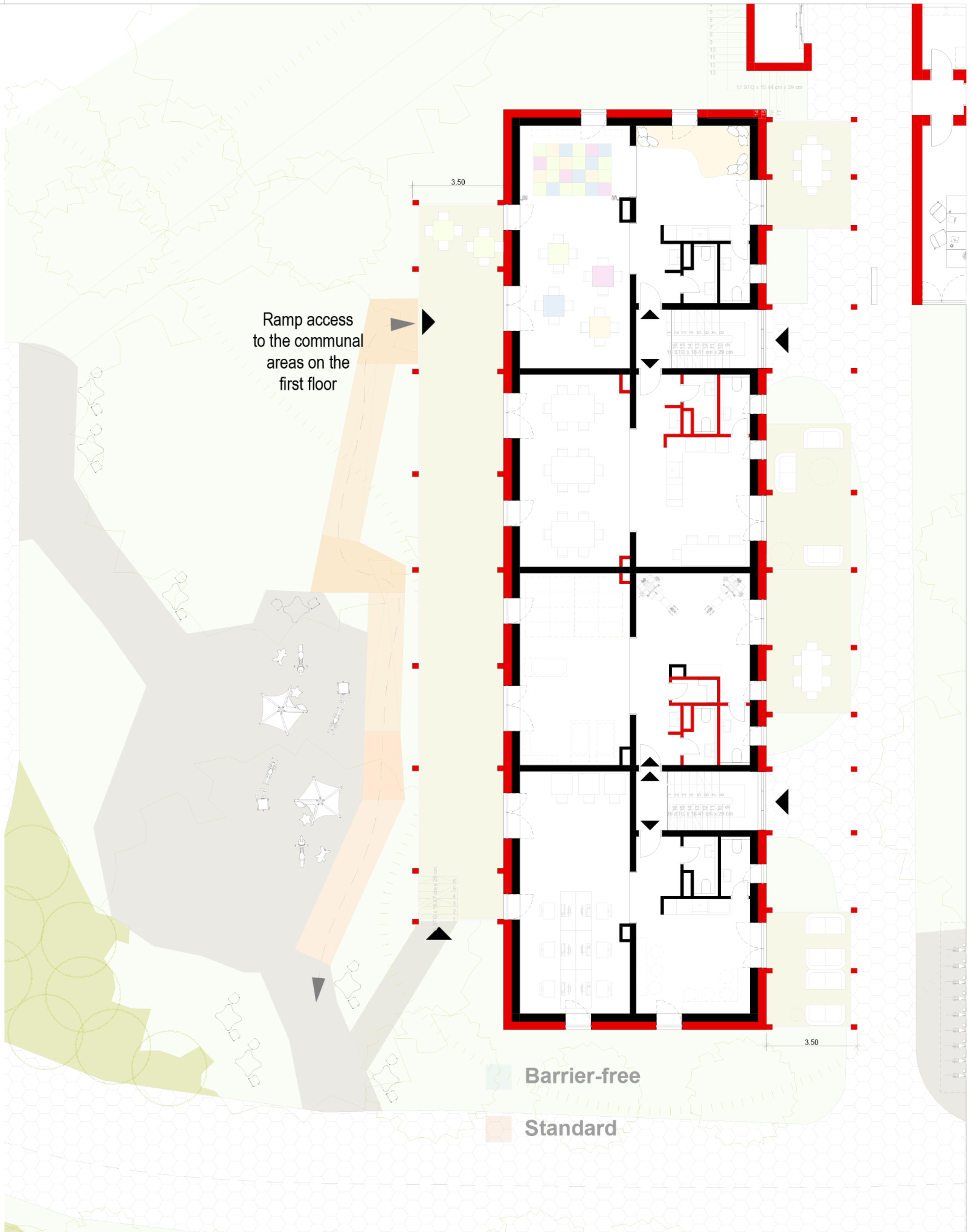
Site Plan
Scale 1:10000



Aereal
view



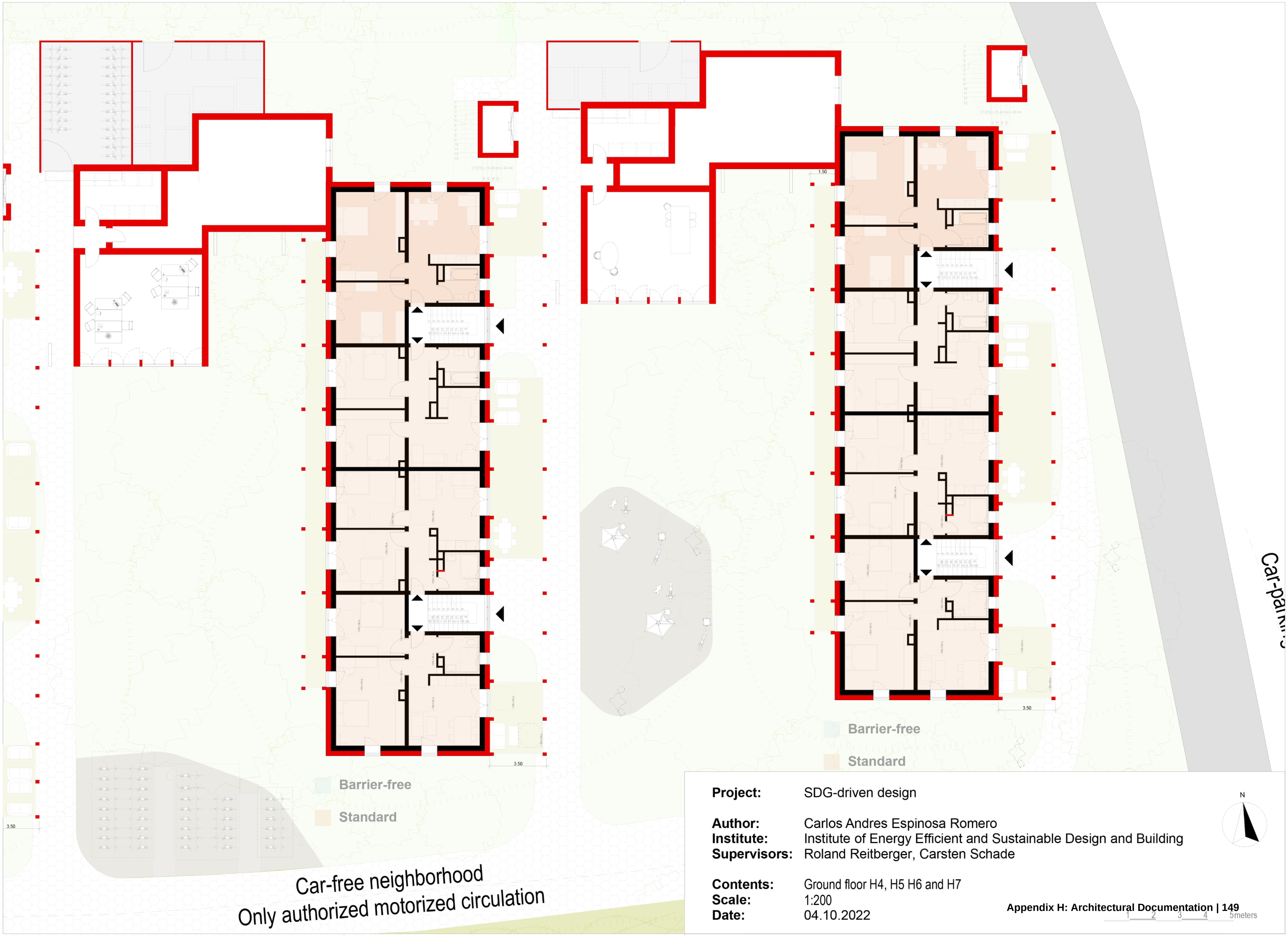




Project: SDG-driven design

Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: Ground floor H1, H2 and H3
Scale: 1:200
Date: 04.10.2022



Project: SDG-driven design

Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: Ground floor H4, H5 H6 and H7
Scale: 1:200
Date: 04.10.2022

Standard floor layout

This floor plan shows the standard layout for the floors above the first level. The conversion of standard into barrier-free apartments can be adapted if necessary, providing the opportunity to adjust to the population.

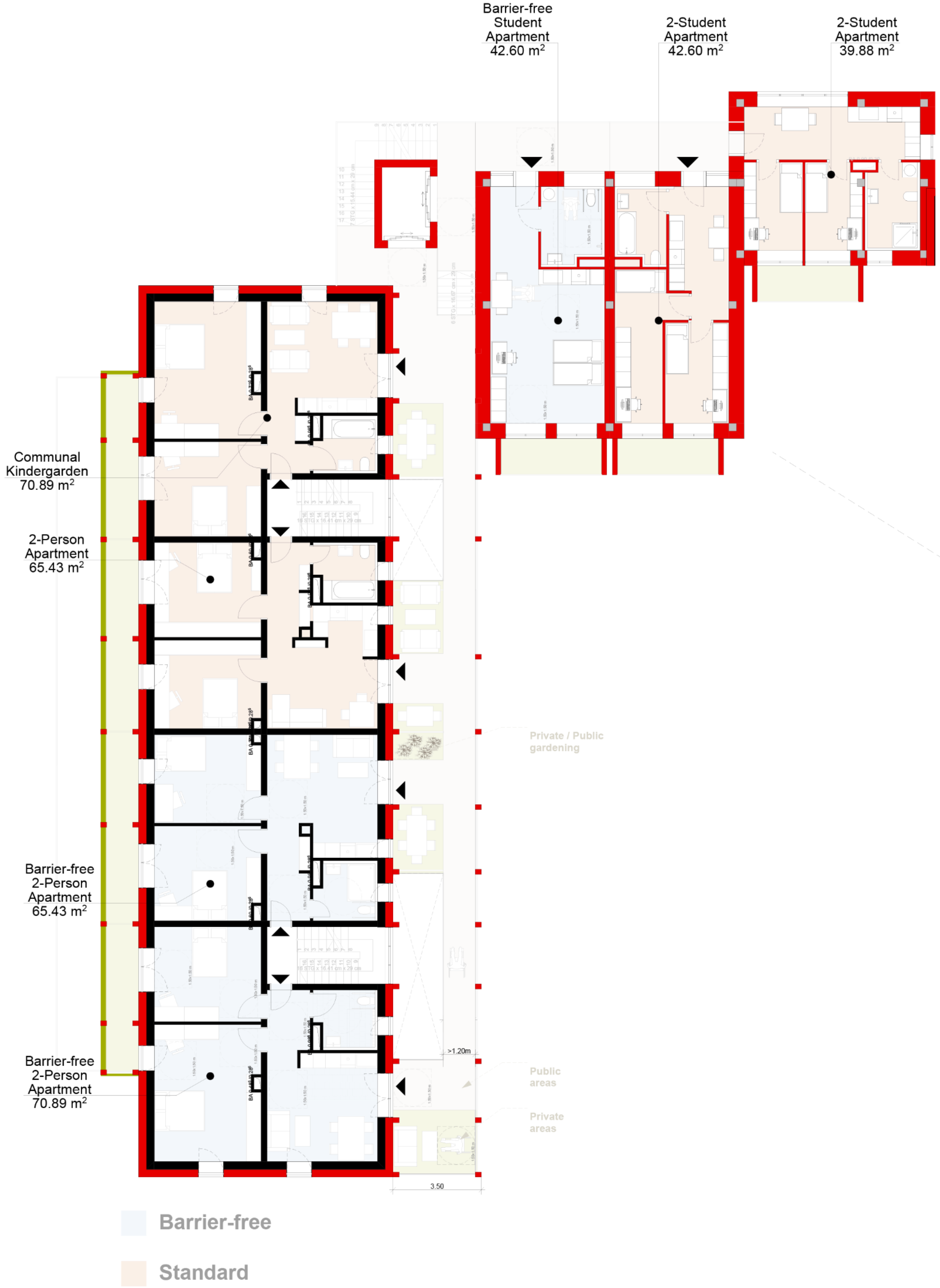
Project: SDG-driven design

Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: Standard floor for H1 and H2
Scale: 1:200
Date: 04.10.2022

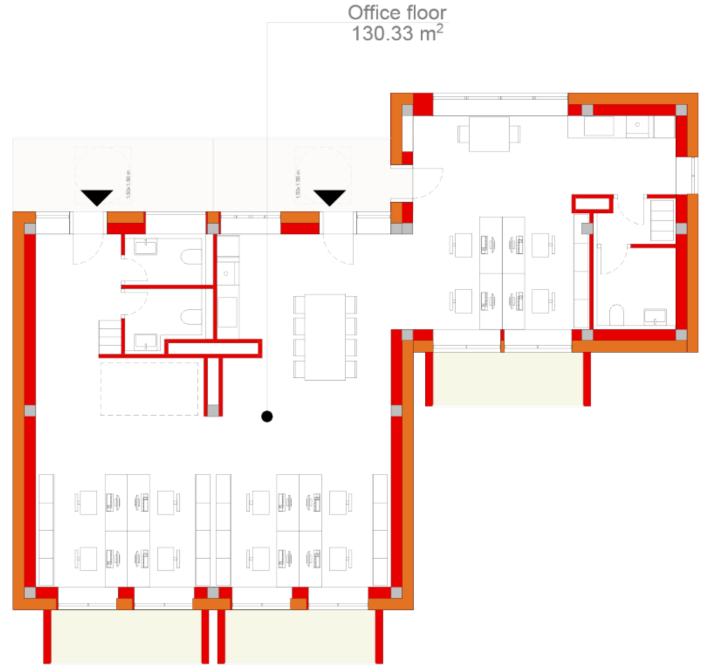
N

1 2 3 4 5meters



Standard floor layout

This floor plan shows the standard layout for the floors above the first level. The conversion of standard into barrier-free apartments can be adapted if necessary, providing the opportunity to adjust to the population.



Office floors

Flexibility

The layout of the new horizontal expansion can be readapted to new programs in case the district requires it.

The layout of the offices can be divided into 1, 2 or 3 rooms, allowing different sizes and requirements.

Project: SDG-driven design

Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: Standard floor for H3,H4,H5,H6,H7
Scale: 1:200
Date: 04.10.2022

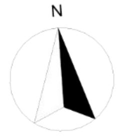
West Elevation

East Elevation

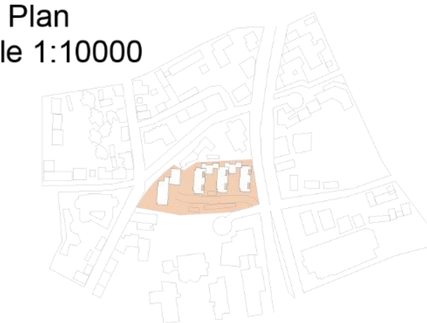
Project: SDG-driven design

Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

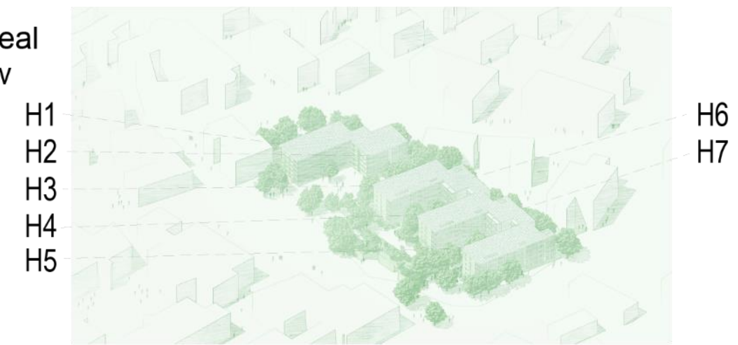
Contents: West and East Elevation of the referential building (H3)
Scale: 1:100 (scaled down to 1:200)
Date: 04.10.2022



Site Plan
Scale 1:10000



Aereal view



North Elevation

South Elevation

Longitudinal section

Project: SDG-driven design

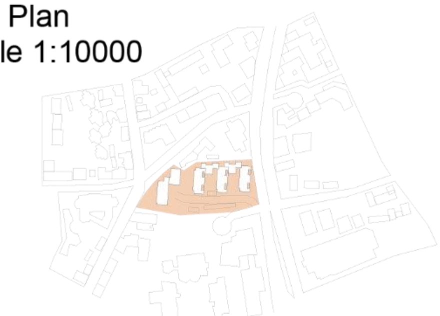
Author: Carlos Andres Espinosa Romero
Institute: Institute of Energy Efficient and Sustainable Design and Building
Supervisors: Roland Reitberger, Carsten Schade

Contents: North and South Elevation + Longitudinal section of the whole complex
Scale: 1:100 (scaled down to 1:500)
Date: 04.10.2022

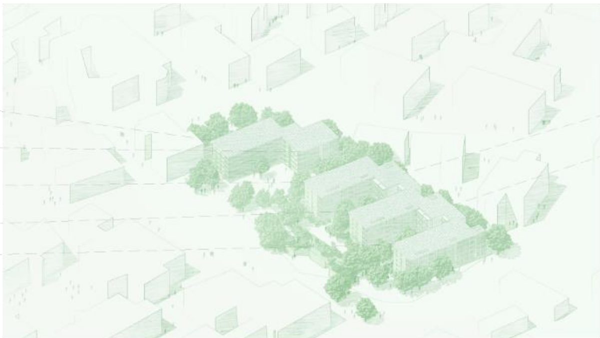
10 20 30 40 50 meters

N

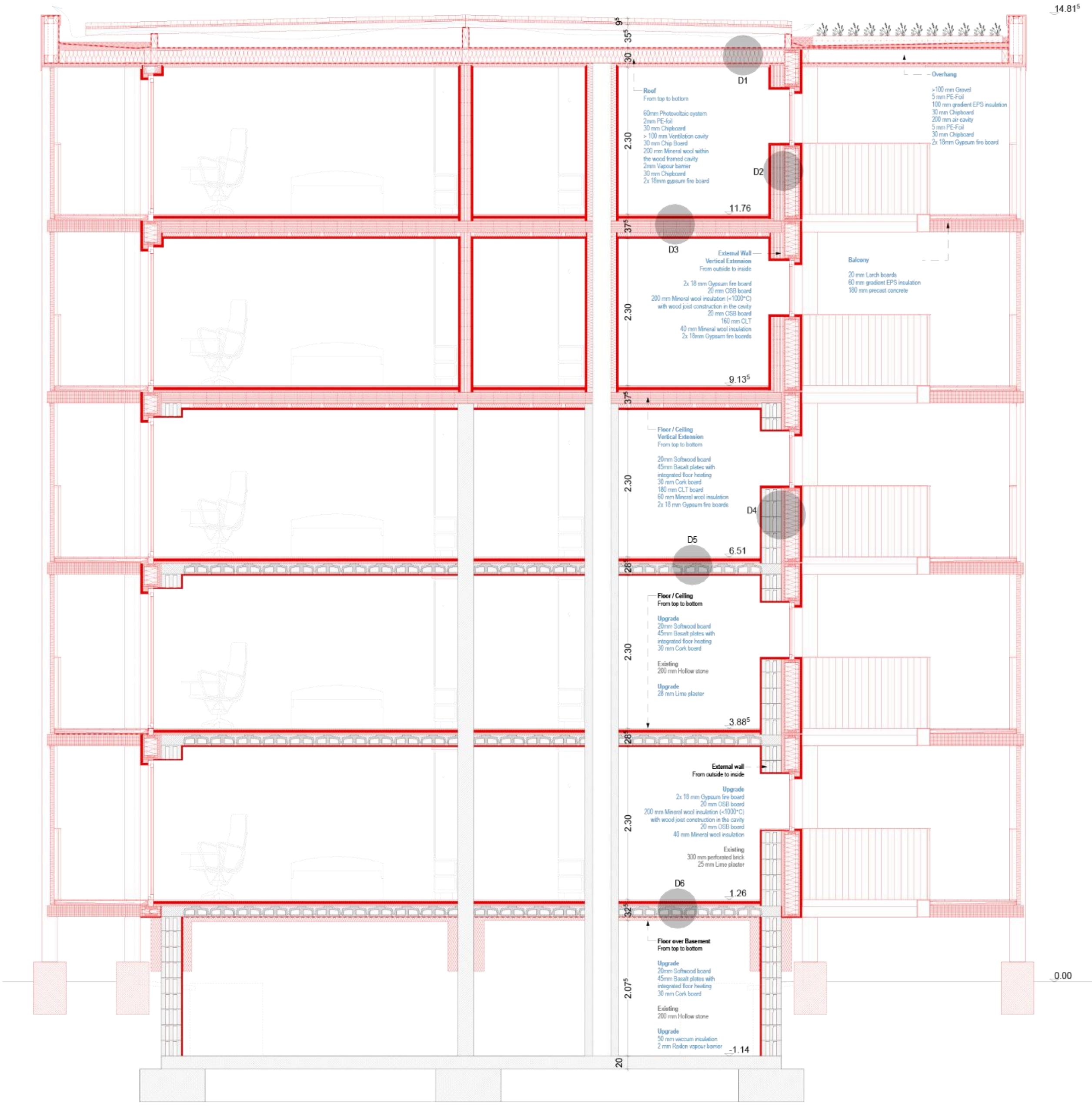
Site Plan
Scale 1:10000



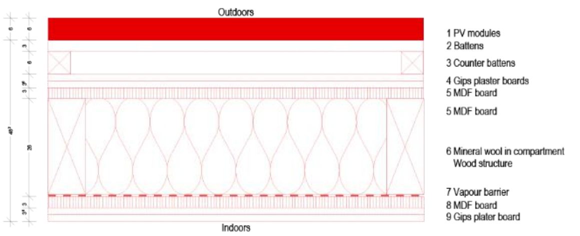
Aereal view



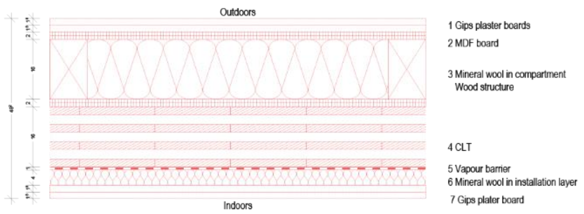
3



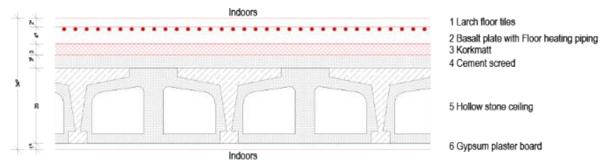
Detail D1 - Roof for extension



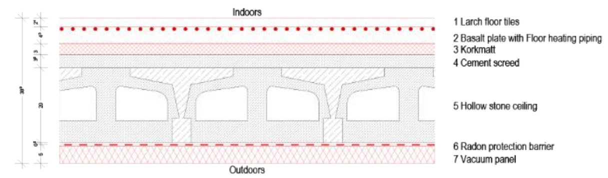
Detail D2 - Exterior wall for extension



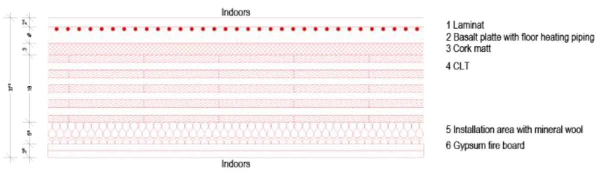
Detail D5 - Ceiling slab for refurbishment



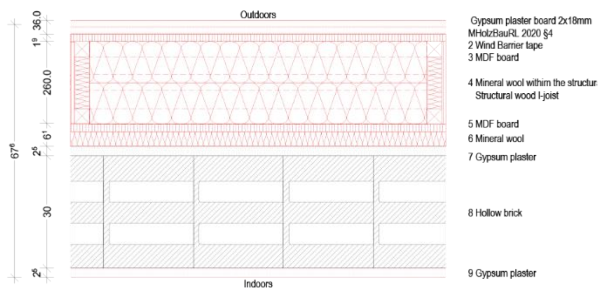
Detail D6 - Floor slab for refurbishment



Detail D3 - Ceiling slab for extension



Detail D4 - Exterior wall for refurbishment

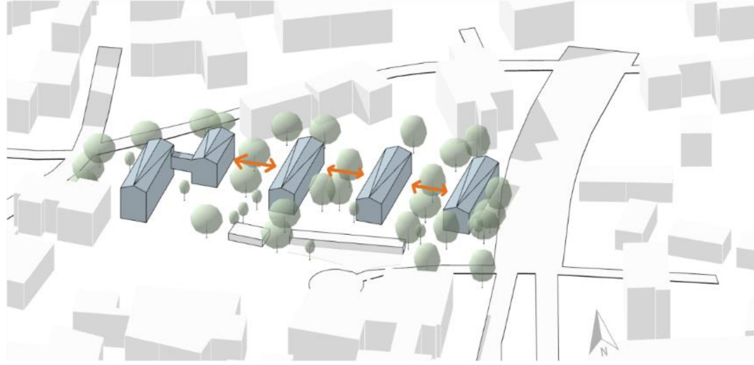


Project:	SDG-driven design
Author:	Carlos Andres Espinosa Romero
Institute:	Institute of Energy Efficient and Sustainable Design and Building
Supervisors:	Roland Reitberger, Carsten Schade
Contents:	Facade section with main cnstruction details
Scale:	1:20 (Facade scaled down to 1:100) - 1:5 (Details scaled down to 1:20)
Date:	04.10.2022

N

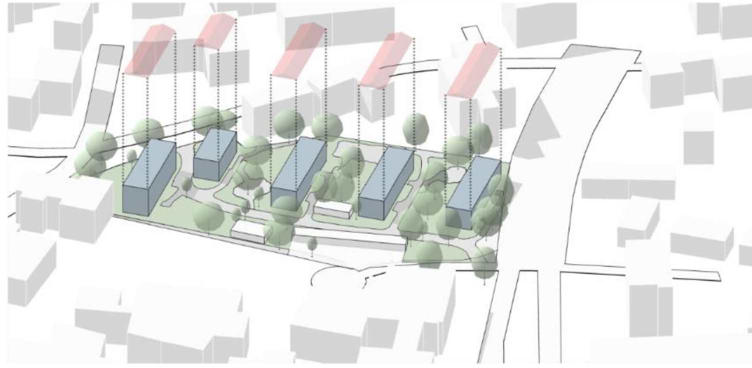
Perspective from the roof-top of the parking lot

Perspective from the courtyard



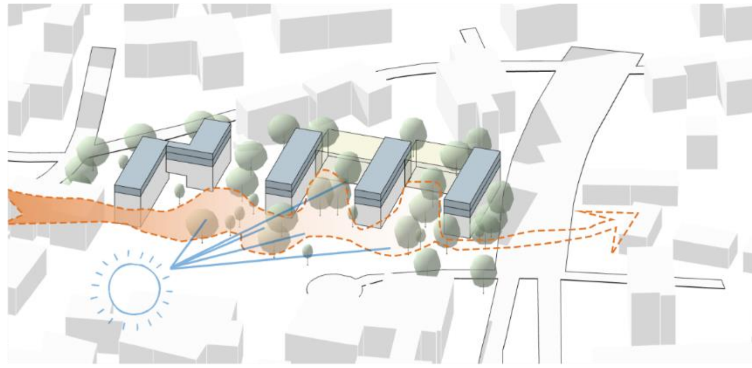
1. Assessment of the status-quo
- Nord-South orientation
- Green infrastructure serves as buffer-zone

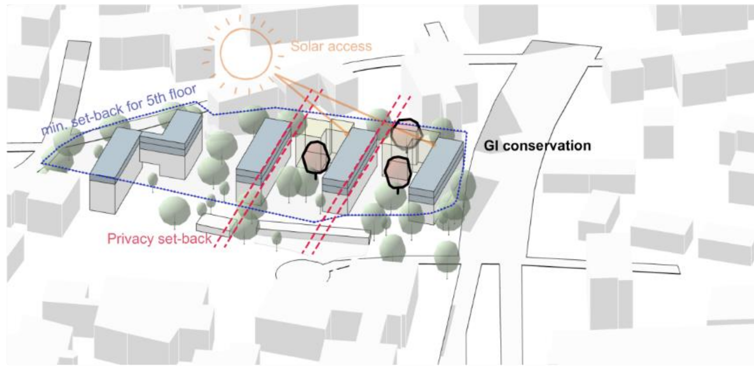
2. Preparation for vertical extension
- Roof´s weight allows for the extension of two floors without further structural enhancements



3. Vertical extension
- Urban context and urban building heights considered

4. Horizontal extension
- Creation of courtyards through to the south
- Enhanced wind circulation
- Enhanced solar access





6. Set-backs
- The maximal vertical and horizontal expansion lies within the boundaries of the plot
- Set-backs betwenn the old and the new construction enhance the quality of the views and the privacy

7. Connectivity
- Inclusion and community created thorugh the balconies
- Interactions and scenery as driver of physical activity

Project: SDG-driven design

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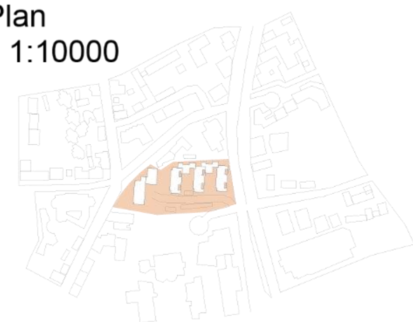
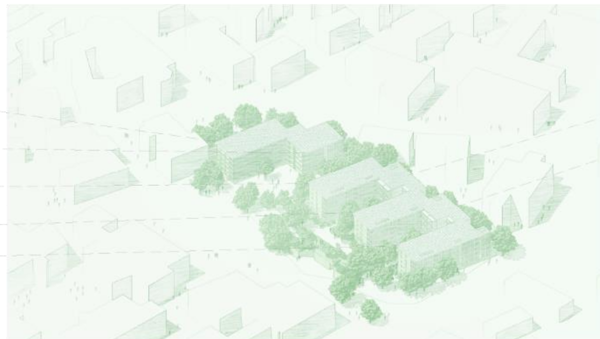
Contents: Conceptual design and visualizations
Scale: N.A.
Date: 04.10.2022

Site Plan
Scale 1:10000



Aereal view

H1
H2
H3
H4
H5



H6
H7

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