Institute of
Digital and Autonomous Construction
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TUHH
Hamburg University of Technology

Master Thesis

for the degree program of Civil Engineering

Design of a smart apartment building with special focus on digital, sustainable and social aspects

Entwurf eines Mehrfamilienhauses als Smart Building
unter besonderer Berücksichtigung digitaler, nachhaltiger und sozialer Aspekte

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Introduction:

Particularly in populous cities, people need room for their personal development. Sufficient room is not only important for shared activities, but also for basic living requirements, such as reasonable and adequate spatial divisions of rooms and technical equipment of buildings. For example, in case of apartment buildings, all residents must have sufficient space and essential equipment, including water supply and heating facilities. Further important aspects include supply of fresh air through ventilation, noise protection, and access to sufficient daylight. It is also crucial to provide humane living conditions for the inhabitants. Specifically in small apartments, it is important to ensure enough space for activities, self-development, or storage. The aforementioned requirements also raise the question of minimum standards: What is absolutely necessary and what is considered luxury? Within the process of planning and managing basic and sustainable living conditions, digitalization can make a significant contribution through intelligent links between different databases and diverse information.

Tasks:

1. At the beginning of the master thesis, a detailed research on socially oriented building measures is to be carried out. In addition to examining historical concepts (e.g. *Unité d'Habitation*, *DDR-Plattenbauten*, *Bauhaus*), modern projects should also be inspected (e.g. *Christiania*, *HafenCity*, *Prinz-Eugen-Park*). As an initial approach, it needs to be determined how social housing can be understood in modern times (housing shortage). In addition to the minimum size and the equipment of apartments (mainly water, heating, and electrical supply), building materials (e.g. concrete, masonry, or timber) and, above all, digital aspects must be considered. The focus should be placed on smart buildings as multi-family dwellings, which can be regarded digital twins – not only during planning, but also in facility management. In the course of the research, particular attention should also be paid to the *Life Cycle Assessment (LCA)* and the sustainability of buildings. Fundamental aspects of the *Universal Declaration of Human Rights (UDHR)* must be considered, as well as basic building design factors (*Neufert*). With regard to the current climate crisis, the focus should be also placed on the *Sustainable Development Goals (SDGs)* of the *UN*. Since a smart building can help ensure health and increase the well-being of its residents, investigations are to be conducted in the direction of public health services as well. In this context, the potential of personalized *Conscious Apartments* should be discussed.

2. From the results of the research of item 1, aspects are to be highlighted for further processing that mainly relate to the maintenance of ecological factors and the consideration of life cycle analyses. In this regard, additions to existing certification systems (e.g. *DGNB*, *BNB*, *BREEAM*, *LEED*) and existing software (e.g. *Autodesk Tally*, *ÖKOBAUDAT*, *CALAA*) must be examined. In particular, the aim of further processing is to analyze processes that are necessary for constructing of apartment houses. Essential parameters for designing the smart building in item 3 are to be defined. In the course of further processing, it should also be determined which programs are oriented towards socially acceptable aspects, not only in terms of basic features of software, but also of product-specific features. The question, how socially acceptable minimum standards can be considered in a planning process, in addition to technical attributes, must be discussed. Deficits should be pointed out and suggestions for improvements should be made in the sense of questioning existing processes.

3. By designing an apartment building, ideally with several parties or intergenerational living conditions, the knowledge previously gained from items 1 and 2 should be used within a practical example. The basic parameters of the project are not only to be applied to general construction rules, but also to be justified with regard to digital, sustainable and social aspects. In addition to a detailed description of the apartment building, various decisions within the design processes must also be documented. A building information modeling program (e.g. *Revit*, *Allplan*, *ArchiCAD*) is to be used to create the apartment building. The implementation of the programs identified in item 2 should be discussed and presented in detail. When designing the apartment building, structural aspects as well as aspects of social housing identified in item 1 need to be considered.

4. To generate a sustainable and living-friendly smart building, it is necessary to determine, in addition to the basic design parameters in item 3, which digital assets can be used for the apartment building. When determining the assets, special focus should be placed on sensor technology, so that future residents can live in an economically and ecologically oriented manner with the help of digital support. In this regard, attention must be paid to the exchange of information: The question of maintenance of data and information (*Data Science*) in a smart building with multiple residents must be addressed.

5. The findings that emerged during the design of the smart apartment building are to be presented in a concise and comprehensible manner. All general aspects must be brought together with the definitions listed in item 1 and discussed in comparison with similar projects with regard to digital, sustainable and social factors. Advantages and disadvantages must be explicitly mentioned. A guideline should be created, describing the process steps mandatory for designing smart apartment buildings.

6. The master thesis will conclude with a summary and an outlook. In addition to the concise presentation of the core results, the outlook must show how living in apartment buildings can evolve, especially with the help of digital equipment.

Start:	22.11.2021
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2nd examiner and supervisor:	Dr.-Ing. Thomas Kölzer

Abstract

Recent phenomena like urbanization, climate change and digitalization are influencing the way we dwell today and in the future. Designing buildings from a social, environmental and digital perspective is therefore part of the societal challenge of providing adequate housing. This research aims to bridge the gap between these design objectives and to find out what a future-proof residential building can look like in practice. A building assessment methodology is presented that first evaluates social and environmental building requirements. Additionally, it is investigated how a *smart building* can be implemented to realize a human-centered, ecological and future-oriented design. First, the enshrinement of adequate housing as a human right, possible problems and contemporary developments related to housing are elaborated. Together with an analysis of the enormous environmental impact of the construction industry, essential requirements for the design of residential buildings from a social and environmental perspective are identified and compared with common building sustainability assessment methods.

Based on these findings, a practical building example is modeled using *Building Information Modeling* and optimized by means of the EU *Level(s)* framework and selected *life cycle assessment* tools. The design result is an apartment building made of predominantly biobased materials with twelve residential units and spacious common areas. In addition, a *smart building* system is integrated with consideration of data security and protection using an *Internet of Things-fog-cloud* architecture. The use of smart devices enhances the predetermined objectives for building design and allows for a dynamic reaction to various future scenarios, such as extreme weather events and pandemics, for the benefit of the residents. The findings of this research provide a guideline for addressing social and environmental requirements for building design and highlights the benefits of implementing a *smart building*.

Statutory Declaration

I, *Hong Diem My Pham*, hereby declare that this thesis *Design of a smart apartment building with special focus on digital, sustainable, and social aspects* has been written only by the undersigned and without any assistance from third parties. Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those specified in the thesis itself. This thesis, in same or similar form, has not been available to any audit authority yet.

Hamburg, November 27, 2022

Location, Date

Signature

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List of Abbreviations

AP	Acidification Potential
BCS	Building Certification Systems
BIM	Building Information Modeling
BLE	Bluetooth Low Energy
BOM	Bill Of Materials
BOQ	Bill Of Quantities
BREEAM	Building Research Establishment Environmental Assessment Method
BSAM	Building Sustainability Assessment Method
CLT	Cross-Laminated Timber
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
dRBAC	Dynamic Role-Based Access Control
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EPS	Extruded Polystyrene
FM	Facility Management
GDR	German Democratic Republic
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air conditioning
IDAC	Institute of Digital and Autonomous Construction
IoT	Internet of Things
IoTFC	Internet of Things-Fog-Cloud
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LOD	Level Of Detail
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
SDG	Sustainable Development Goal

UN United Nations

XPS Expanded Polystyrene

1 Introduction

Dwelling is a fundamental need that concerns every person without exception and is one of the essential things and precondition for humans to thrive and lead a dignified life. However, dwelling comes in many forms and there is a variety of potential issues and obstacles that can occur. For instance, difficult access to housing especially in urban areas or low building quality hamper adequate housing and compromise humans' physical and mental health. Because we live in a market-based system, the occurrence of these problems depends on personal financial wealth in interaction with other forms of marginalization. Therefore, the less privileged part of the population is particularly vulnerable to these issues. In recent times, the COVID-19 pandemic has forced people to spend more time inside their homes making dwelling even more critical. It is a societal challenge to provide adequate housing to everyone so that dwelling is not a privilege but a matter of course. At the same time, dwellings have a strong connection to climate change due to their emitted greenhouse gases throughout their lifetime. These contribute to negative effects such as extreme weather events, which threaten human existence. Hence, the building sector has a great responsibility to change the conventional methods of construction and operation to mitigate their impact on the environment and to create green buildings.

Keeping all these issues in mind, it becomes evident that the design of dwellings has to combine both social and environmental objectives in order to be truly sustainable for future generations to come. The question then arises: How can buildings be designed to ensure that humans live dignified and simultaneously have the least possible impact on the environment? Additionally, the advancing digitalization is bringing a whole new perspective and possibilities concerning dwelling. New technologies like the *Internet of Things* create *smart homes* that have the potential to change the way we live and interact with a building. The next question becomes: How can we take advantage of digitalization and use it to enhance quality of life, environmental building performance and adaptability to future conditions?

Aim of the thesis

This research aims to investigate how both social and environmental aspects can be taken into account in the design of residential buildings by using traditional building assessment methods and, in addition, smart technologies. By exploring thoroughly the relationship of humans to dwellings and the impacts of constructing and operating buildings, design requirements are to be determined. Available building assessment methods to evaluate both objectives are investigated to present state of the art, show possible shortcomings and deduce a strategy for best practice in building design. Based on these outcomes, a practical example of an apartment building is designed. Finally, a proposal is made on how certain digital assets of a *smart building* system can be integrated so that both objectives are met.

Structure of the thesis

The thesis begins in Chapter 2 with the investigation of social and green aspects of living. Current societal issues regarding dwelling in interaction with the phenomena of urbanization are elaborated, including the right to adequate housing, past examples of social housing concepts in Europe and takeaways from today's perspective (section 2.1). Then, environmental issues caused by the building industry as well as societal and political measures to counteract these are presented (section 2.2). Investigating both social and green perspectives on dwelling allows for determining building design requirements that are considered indispensable to achieving sustainability (section 2.3). Afterwards, recent developments in urban housing are elaborated, including the topics housing market, *home office*, modern housing concepts, *smart homes* and the implementation of green buildings (section 2.4).

In Chapter 3, common building sustainability assessment methods are discussed. First, the concept of *life cycle assessment* (section 3.1) and its connection to *Building Information Modeling* (section 3.2) are shown. Then, building sustainability assessment methods in Europe are introduced and compared with the determined building design requirements to give recommendations for possible improvements (section 3.3). On this basis, the most suitable method is selected and an appropriate workflow for building assessments, using certain tools, is determined (section 3.4).

Following the proposed workflow, a practice-oriented example of an apartment building is designed in Chapter 4. The basic design concept is described, including assumptions about location and structural analysis (section 4.1). Then, the determined building design requirements and conducted optimizations are implemented (section 4.2, section 4.3, section 4.4). After the basic properties of the building are elaborated, a smart building system is designed while investigating data maintenance and security, deployed smart devices and their link to the design requirements (section 4.5). The building design, that resulted from the previous steps, is evaluated by comparing it to exemplary modern building concepts. Finally, a guideline for designing green, social and smart buildings is proposed (section 4.6).

2 Basics of Social and Green Housing

This chapter investigates the challenges in urban housing and aims to give an overview of different social (section 2.1) and environmental perspectives (section 2.2) on residential buildings. Basic building design requirements are defined (section 2.3) and recent developments elaborated (section 2.4).

2.1 Urbanization and the societal challenge of providing adequate housing

2.1.1 Unequal preconditions in urban environments

In the history of humankind, people have been agglomerating over time from small settlements to cities and even to mega-metropolises with millions of inhabitants. In 2008 the urban population exceeded the rural population and is expected to make up about two-thirds of the world's population by 2050 (UN-Habitat 2015, p. 1). Meanwhile the global population is instantly growing and is expected to reach a number of about 9.8 billion by 2050 (DESA 2019, p. 11). Connecting both prognoses, about 6.5 billion people will live in urban environments in the future. This large quantity of people inhabiting a limited space entails opportunities but also remarkable challenges, where inequalities on many societal levels become visible.

On the positive side, urban areas portray advances in technological development and potential for economic growth and therefore are attractive for people seeking opportunities for economic prosperity. This applies to both educated professionals with high-paying jobs and low-skilled workers, more likely to have a low income. The congregation of large numbers of people with differing capital and the importance of good urban location have increased competition and contention over urban land. Normally in capitalist systems, the more wealthy part of a population have better opportunities to claim land, leading to spatial hierarchies, dividing cities by residential segregation depending on the assets of their inhabitants and ultimately lead to exclusion of the poor (McGranahan et al. 2016, pp. 15-16). The result and the outcome are large inequalities in "access to opportunities, income, consumption, location, information and technology" (UN-Habitat 2015, p. 2) within society. As a result, an increasing number of urban inhabitants "experience or are at risk of poverty or social exclusion" (UN-Habitat 2015, p. 3), pushing people into precarious situations and creating a growing gap between the rich and poor. According to the *Global Wealth Data Report* in 2020 about 1 % of the adult population owned about 44 % of the world's net wealth (Davies et al. 2021, p. 17), implicating that the vast majority of the world population only holds about half of the world wealth while a tiny elite holds the other half. It is worth mentioning that the economic segregation interacts with dynamics of marginalization of different social groups, including race, religion and gender identity, which are mutually impacting each other in complex ways (McGranahan et al. 2016, p. 15). Intersections of these categories can amplify economic and social disadvantages even more.

Ultimately, the divergence of high- and low-income disparity becomes evident and visible in terms of housing. While the high-income class can afford to buy houses with an oversupply of many amenities and luxuries, the more disadvantaged part of the urban population has limited access to housing, poor housing conditions and as a result degraded living conditions. With an increasing number of people living in an urban environment and the contestation of urban land, the question of how people, especially with low income, can live in populous regions has to be addressed. In the following section problems regarding housing units are further investigated.

2.1.2 The housing right – Ideal and reality

The notion that housing is a crucial necessity has been around ever since humans settled and has manifested in modern times in international law. In Article 25 of the *Universal Declaration of Human Rights* the United Nations (UN) stated that "[e]veryone has the right to a standard of living adequate for the health and well-being of [themselves] and of [their] family, including food, clothing, housing and medical care and necessary social services" (UN 1948), making *adequate housing* an explicit human right. In 1991, the UN Committee on Economic, Social and Cultural Rights attempted in their *General Comment No. 4* to outline essential aspects: Housing right needs to ensure that a person can "live somewhere in security, peace and dignity" (CESR 1991), hence provided shelter by simply having a roof over the head is not sufficient to fulfill adequate housing requirements. Apart from the mere construction, a house has to include basic facilities for health and security such as potable water, proper sanitation and energy for cooking. In order to make a house habitable, adequate space and protection against weather and other natural threats to health or life threats must also be provided. Another point is that the amount of costs caused by housing, such as energy costs, should not compromise other basic needs of the residents. Furthermore, a house should allow its residents to live and express their cultural identity and the needs that are related with it (CESR 1991).

The right to adequate housing is also linked with the UN's adaption of the *2030 Agenda for Sustainable Development*. With this historic agenda, the UN framed 17 *sustainable development goals (SDGs)* in 2015, which can be applied partly to adequate housing as shown in Figure 2.1. All previously described housing requirements can be an asset to cities and communities (11). They promote health and well being (2), clean water and sanitation (6) and affordable energy (7). Providing adequate housing helps to reduce socioeconomic inequality (10) and hence can be a measurement to alleviating poverty (1).

Figure 2.1: Sustainable development goals related to adequate housing (UN 2020)

Although adequate housing is a human right, it does not display the lived reality for all people. Especially the less affordable class is the most vulnerable to live under precarious housing conditions or even homelessness (Akinluyi et al. 2014). When living in a house a wide range of problems can occur that are directly linked with the quality of building materials and housing equipment. Ultimately, these conditions impact human health and well-being.

One of the most common housing problem that residents face are inadequate temperatures below or above comfort level, which mainly occurs due to insufficient insulation of the building envelope, including walls, roof, floor, windows and doors. Poor thermal insulation causes overheating in hot seasons and insufficient warmth levels in cold seasons, requiring more energy to maintain an adequate room temperature. In combination with a household's inability to afford the high energy demand this leads to a so-called *energy poverty* (Kolokotsa et al. 2015; Bosch et al. 2019). In hot seasons costs of fans and air-conditioning have to be considered whereas in cold seasons energy for heating systems have to be paid. The energy efficiency of these devices also play a major role in energy poverty. The fact that energy prices are constantly rising exacerbates the problem even more (Grösche 2010).

The impact of inadequate room temperatures for health are severe: Overheating in hot seasons unbalances body temperature and can result in hyperthermy or even to death (Holmes et al. 2016). On the other side, exposure to low temperatures in cold homes are associated with increasing cardiovascular diseases, reducing resistance to infections, and the risk of influenza, asthma and mortality. Low indoor temperatures are also linked with dampness and condensation which set optimal conditions for mold and funghi contamination causing asthma and other respiratory diseases (Boomsma et al. 2017). Additionally, the lack of proper air ventilation and overcrowding increase interior moisture, enhancing the above mentioned effects of cold and dampness and causing a greater risk of respiratory infectious diseases (Krieger et al. 2002). In times of the COVID-19 pandemic, this becomes of particular importance.

Besides thermal issues of building materials, their toxicity is of major importance for the residents' health as well. Some building materials release indoor pollutants such as volatile organic compounds, formaldehyde or nanoparticles contaminating indoor air or tap water. Exposure to these lead to various health issues such as skin irritation, headaches, cancer and many more (Torgal et al. 2012).

Living in inadequate housing not only impacts the physical integrity of human beings but also mental health and well-being. The poor conditions lead to constant worries about the housing situation, paying high bills for energy and physical health (Bosch et al. 2019). The severe stress to which residents in precarious housing are exposed can cause psychological problems such as depression, anxiety or irritability (Krieger et al. 2002). In addition, noise pollution due to poor sound insulation and lack of windows for natural daylight contribute as serious stressors (Kolokotsa et al. 2015). As space in low-income households is usually very limited, little space has to be shared with many people and can amplify feelings of stress. According to UN-Habitat (2018, p. 10), if in a household more than three people share the same habitable room, the living space is not considered sufficient but overcrowded. All these experiences create constant disruptions in daily lives and prevent residents to identify with their housing as a place of self-expression and recuperation. The inability to establish a sense of home therefore compromise the level of well-being (Garnham et al. 2021).

In summary, inadequate housing conditions lead to increasing exposure to biological, chemical and physical hazards for the residents causing physical and mental health issues (Krieger et al. 2002). Given the current pandemic situation, people are spending even more of their life-time indoors and are thus more exposed to interior hazards.

The housing situation even deteriorates when proper maintenance cannot be performed. As most people with low income are unable to afford buying their own home, they mostly have no choice but live in rented housing. The drive and the budget to invest in a rented house are both therefore very low. The tenants are fully dependent on their landlord to renovate and preserve a certain standard. As maintenance is cost-intensive landlords from experience have low incentive to invest in improvements (Grösche 2010; Palacios et al. 2021).

Investigating the main housing problems, it becomes evident that housing quality is primarily dependent on budget that enables a person to buy or rent a high-quality, energy-efficient residence in well-located areas and to pay their housing bills. Therefore low-income households are tremendously more at risk for any kind of housing problem. Especially in urban areas, it is crucial for society to make adequate housing for the most vulnerable and deserving group possible. In practice, this translates to the provision of social housing.

2.1.3 Social housing in Europe in the 20th century

Between and after the World Wars in the 20th century, Europe was facing a tremendous lack of housing for the population due to the destruction of many cities. The measurement for governments—both in Western and in Eastern countries—to counteract the housing shortage was to build as much accommodation in the shortest time as possible. Therefore, the decades after World War II were also called the “golden age of social housing” (Wassenberg 2018). Social housing by definition includes any kind of dwelling provided and managed by the state or by a nonprofit-organization (Sisson et al. 2020). The aim is to ensure affordability of accommodation for tenants with low income, following the idea of creating living space for the entire population. Through the years architects and urban planners have designed different urban dwelling constructions that mostly focus on large housing estates (Wassenberg 2018). Accommodating and fitting as many people in a living space as possible has been the most effective way to meet requirements of low budget, limited urban space and ensuring accommodation for many. In the following, the housing concept *Unité d'habitation* and *Plattenbau*, as examples from West and East Europe, are further presented.

Unité d'habitation – a Western example

The architect Le Corbusier attempted to give a solution to mass housing demand and created the *Unité d'habitation* (French for housing unit). The modern residential building, built in skeleton structure out of reinforced concrete, was first constructed between 1947 and 1952 in Marseille and later in different variations also in other French cities and in Berlin (Stillers 2014). The buildings still exist today. The giant cuboid, revealing bare concrete surface, has 15 stories, including 337 apartments for up to 1700 residents (s. Figure 2.2) (FLC 2019).

Figure 2.2: *Unité d'habitacion* in Marseille (FLC 2019)

Le Corbusier's main motive was to unite individual refuge with shared spaces to strengthen community spirit. Furthermore, the building's design should be reduced to only essentials of human needs. The results of these considerations are housing units executed as duplex apartments and with a floor area of 98 m^2 each, enough space to accommodate a traditional family of four. The living room including a dining area and the kitchen are placed on the smaller one of the two floors. A set of stairs leads to the second floor, with a large bedroom for a couple, two smaller rooms for children and a bathroom (Stillers 2014). Due to the skeleton structure of the building the spatial division is variable. Depending on the living structure and needs of the residents, room combinations are adaptable (FLC 2019).

In the building's design, extra attention on sun lighting was given: Most apartments extend along the width of the building which is also the east-west axis. By this, residents are able to enjoy both sunrises and sunsets inside their own homes and on their balconies. For the same reason apartments were placed on the south side but not on the north side, leaving the entire wall without windows (Stillers 2014).

On the 7th and 8th floor Le Corbusier placed a shopping street with supermarkets, restaurants, bars, hotels and more services. The roof was executed as a terrace with a kindergarten and cultural and sports facilities. Together with the apartments distributed on all the other floors, the building represented a *vertically stacked city*, that was functioning to some extent autonomously (Stillers 2014).

GDR Plattenbau – a former Eastern bloc example

The *Plattenbau* (German for panel construction) was the most dominant form of housing financed by the German Democratic Republic (GDR) government and sets a marker for industrialized construction in the 20th century. The goverment's goal was to increase the quality of living and to reach a uniform housing system beyond social classes. Between 1973 and 1990, 1.3 million apartments were constructed to counteract the severe housing shortage using large, prefabricated concrete slabs (Scheffler 2009, p. 18). Settlements were built consisting of multi-story apartment buildings, with the *WBS 70* version being the most prevalent (s. Figure 2.3).

Figure 2.3: *WBS 70* buildings in Berlin Marzahn, 1984 (Rubin 2016)

The floor plans for the apartments were mostly standardized and identical for all stories of one building. By utilizing a minimum variety of building components with little alternations, it was possible to gain cost savings. The apartments were designed based for the socialist nuclear family and had very similar size as well as space utilization. An average apartment with a floor area of 59 m^2 consisted of a kitchen, a bathroom, a large living room, a parents bedroom and a childrens' room (Hannemann 1996, p. 91). The design was to intended to be functionalist to meet basic human needs, the way they were interpreted in this era. The buildings also had modern heating systems and sanitation equipment inside the apartments, which were a new amenity in the time (Scheffler 2009, p. 18).

Criticism of the former housing concepts from today's perspective

The presented housing concepts followed the idea of egalitarian dwelling as a step towards a more just and equal society. Providing buildings and equipment with a high standard for the time, allowed residents to elevate their living conditions and set an example for implementing social and modern housing ideas for adequate living in reality. A one-size-fits-all ideal of what dwelling is supposed to be, was created, inducing a standard in planning and enabling the possibility to provide mass housing at high speed and low budget.

As good and noble as the intentions of the architects and planners may have been, considering the time and care they invested in their concepts, time has revealed a multitude of problems that can arise from large building designs, political ideologies, and the perception of the residents:

The buildings in both examples are characterized by giant grey rectangular blocks made out of concrete with little alternations and give the visual impression of monotony, often making the neighborhood look less appealing to most people. The recurring patterns of the facade and the impersonal design inside the apartments left little room for residents to live out individuality or even establish a sense of home.

The designs of the apartments were determined on the basis of what the planners thought residents should want from a top-down perspective, considering mostly one reality of how living should look like (Wassenberg 2018). The most common assumption about the residents as a unit was the expectation that an apartment is inhabited by a traditional family. As Hillier et al. (2020, p. 159) argue, planning has historically privileged and reinforced heteronormative and cisnormative structures, totally excluding other possible forms of communal living. This is reflected in the structure of the floor plans that included a bedroom for a cis couple and smaller rooms for children. However, in Le Corbusier's design it must at least be credited that it is flexible in terms of spatial division. Nevertheless, it is hardly questionable that residents of social housing can seize the opportunity financially to change any structures before they move in. Therefore different forms of communal living should preferably be considered beforehand in the design stage.

Regarding the individual resident, further inaccurate assumptions were made. Le Corbusier, for instance, developed a *Modulor*, a 183 cm tall white non-disabled man, that was used to adjust all room proportions and to gear everything to its needs (Stillers 2014). The attempt to define a standard person seems rational at first glance as it was based on the average male size. On closer inspection, however, such definition is a blunt generalization of human beings and fails to mirror the complexities of how people might live beyond norms. People with physical or mental disabilities were genuinely disregarded as well as white males prioritized in being the measure in all design decisions (Rahemtulla 2021).

Accessibility had been mostly neglected and was, if implemented, more a side effect than a result of genuine consideration of physical human impairment.

These possible outcomes for individuals and the made assumptions do not come surprisingly as both examples are highly motivated by political ideologies. The *Plattenbau*, for example, followed the idea of social equity, which meant, on the one hand, that all members of society should live in the same housing under same conditions as a traditional nuclear family, the smallest cell in the state (Hannemann 1996, p. 98). On the other hand the ideology implied giving up personal individuality and cultural identity for a higher communal interest, only satisfying basic human needs. Le Corbusier followed similar motivations, but was idealistically more ambiguous. As Hall (2001, p. 210) argues, the *Unité d'habitacion* was designed for the bare necessary minimum to fulfill the idea of efficient human existence, truly a housing machine with emphasis on *machine*. Although often undermined by classic architectural literature, which celebrates Le Corbusier as a pioneer, it is worth noting that he strongly sympathized with fascist and eugenic ideologies (Brott 2017, p. 209)[1]. It becomes evident that the interpretation of basic human needs in both concepts is not acceptable from today's perspective as they view people rather as functioning objects than as human beings.

In practice, however, beyond idealist theories, a variety of problems regarding physical construction and maintenance occurred, complicating the residents' relation with the buildings even more and indicating the disparity between ideas and lived reality. These problems involved poor sound insulation, issues with waste disposal systems or aggravated accessibility due to small-sized apartments and lead to troubles in daily life (Decker et al. 2009, p. 76).

Generally, even if there weren't issues in the beginning of the habitation, the quality of a building decreases over time through physical deterioration and sooner or later the dwelling demands maintenance, especially under harsh climate conditions (Wassenberg 2018). Additionally, from today's view, the buildings have insufficient thermal insulation and outdated, inefficient heating equipment that has to be refurbished. But typically for social housing, the available budget for maintenance is limited and lies in the responsibility of the landlord, hence hindering the implementation of measures. Ultimately, the decreasing building quality lowers living conditions with all associated issues, detailed previously in subsection 2.1.2.

The lowered building appeal in combination with high competition with newly built residential housing can lead to a social transformation in the neighborhood: People with sufficient income move to more attractive housing and areas, leaving those with lower financial opportunities behind.

A derivative of this social transformation brings upon other phenomena such as the marginalization of ethnicities into the less demanded area. Hence, Black, Indigenous and

[1] According to Perelman (2015, p. 124), Le Corbusier's vision of housing was totalitarian, perceiving "society [...] as a body under the authority of an assemblage of different machines... welded to each other".

People of Color turn to the more unpopular but affordable housings in a city (Bolt 2018, p. 58).

In this context, *gentrification* is a common process which will be discussed in subsection 2.4.1. The concentration of underprivileged groups in settlements leads to a declining neighborhood reputation, city segregation as well as stigmatization of its residents by outsiders. Existing social problems exacerbate, while the housing estate depreciates enhancing the fluctuation even more. In case of the *Plattenbau* example, the large settlements started off as a popular modern housing option but nowadays are often stigmatized as social flashpoints, especially in Western perspectives.

Even if social housing buildings are viewed favorably, the task of keeping apartments affordable can be difficult depending on the respective state or city legislation. In the case of the *Unité d'habitation* building in Berlin, the construction was financially subsidized, but was bought later by a private investor in the 1960s. Due to the emerging need for renovation over time, the apartments were soon sold as condominiums for buyers who could afford them. The majority of apartments nowadays are therefore privately owned with rents mostly being above the local rent price index (Funke 2019). The process of privatization has induced the idea of affordable housing to move into the background.

In conclusion, the ideas of planners often have become more a utopia serving their own ideals than a universal and socially sustainable solution to housing shortage. Providing bare minimum existence standards does not suffice to truly deserve the title *social*, at least from today's perspective. Although the construction of social housing as large buildings can induce a variety of possible problems, that have to be tackled and prevented, the concept of dense housing has saved valuable urban space and enabled accommodation for many. But besides the issue concerning the social dimensions and the benefits of settlement densification, another aspect that currently raises concerns is the environment.

2.2 The environmental necessity for green buildings

Human development and eventually the advances of industrialization have lead to a high standard of technology, economic growth and the production of many life-changing products. During all the involved processes in the past centuries, the impact on the environment has been considered little to nothing as the main driver for most human activities were and often still are profit outcomes. Since industries are highly dependent on natural resources, they have caused a tremendous increase of greenhouse gas (GHG) emissions into the atmosphere with carbon dioxide holding the largest share (Paulo Gewehr et al. 2020). Anthropogenic activities are driven by fossil fuel combustion, transport and overall consumption patterns (Paulo Gewehr et al. 2020). The associated impacts on the environment are wide-ranging from air pollution, water contamination, depletion of natural resources, loss of biodiversity to species extinction. Additionally, the increase of GHG emissions has raised the mean surface temperature on Earth and causes melting polar ice, rise of sea levels and extreme weather events, such as floods and droughts (EC 2021). The persistent inability to link activities with their potential risks to the environment, flora and fauna and ultimately to human life backfired and has led us to the recent climate crisis. The renowned wildlife filmmaker Sir David Attenborough (2020) puts it as follows: “We often talk of saving the planet, but the truth is that we must do these things to save ourselves. With or without us, the wild will return.” Consequently, implementing measures to mitigate climate change and anthropogenic environmental impacts is vital for the mere human existence.

2.2.1 Upheavals in politics and society

Environmental issues have been existing long before the word *climate crisis* became a common term. But people most affected by the problems were also the most vulnerable group – the world’s low-income population, mostly in countries of the global south (Paulo Gewehr et al. 2020). Since this group holds only a small share of power in politics, the public attention and interest were very low, making it impossible to address the issues. At the same time, regarding to Hickel (2020), the more powerful and high-income countries of the global north are responsible for 92 % of the world’s excess carbon dioxide emissions, underlining the worldwide climate injustice. In the last years, there has been a change of mindset from powerful stakeholders, who have come to the revelation that climate change and environmental issues do not only effect vulnerable countries of the global south, but sooner or later also countries of the global north. Thanks in part to activist movements, such as the worldwide *Fridays for Future*-protests, the importance of consumption consciousness and addressing environmental issues has reached the center of our society and has finally put politics under pressure to act.

In 2015, the *Paris Agreement* displayed a landmark in climate politics and was signed by 195 countries. The agreement is a legally binding international treaty on climate change, which seeks to reduce GHG emissions. Countries agreed to put efforts into limiting global mean surface temperature increase to well below 2 °C and aiming for 1.5 °C, compared to pre-industrial times (Salawitch et al. 2017). The same year the *UN general assembly* also framed 17 SDGs in their historic *2030 Agenda for Sustainable Development*.

2.2.2 The impact of the building industry on the environment

To reach the climate goals, efforts for climate change mitigation have to be applied to the building sector as well. In 2019 direct and indirect activities in building construction caused the largest share of total global carbon dioxide emissions by 38 % and 35 % of total global energy use (UNEP 2020). Regarding the SDGs, sustainability in all building related emissions and impacts have to be achieved to reach a reduction in GHG emissions and other related environmental issues. Therefore the goal to make cities and human settlements more sustainable presented in Figure 2.1 also applies to the building sector.

In order to fully comprehend how the GHG emissions and energy use of the building sector are so high, all aspects and impacts in all life cycle stages of a building have to be considered. Considering all stages, is the foundation of life cycle assessment which is investigated in Chapter 3.

The first step in producing building material is the extraction of raw material by mining and harvesting. Currently, about 50 % of all extracted materials worldwide is used by the building industry (Hossain 2019). It is worth noting that 95 % of the materials come from non-renewable sources (Mahamadu et al. 2016). The extraction activities inevitably interfere with existing ecosystems and lead to the destruction of habitats for fauna and flora, causing loss of biodiversity and natural habitats. In addition, the extraction process generates waste and requires high amounts of energy in order to operate the appropriate machinery. As most energy is retrieved from fossil sources, the GHG emissions are high and air and water pollution are likely (Mahamadu et al. 2016).

Once the raw material is extracted further processing and manufacturing by heavy machinery with high energy demand are required to create usable building material. The transformation results in emissions, pollutants, further depletion of other resources such as water and generation of waste (Ding 2013).

Finally, the produced building material can be used for construction. Again, site activities require fossil fuel, water and create waste. For the construction of settlements, areas of natural habitats or agricultural land are cleared and built-on, sealing surfaces. By these activities, ecosystems for a variety of species are destroyed.

In all of the above stages the building materials have to be transported several times. Depending on the source of the material and the location of the construction site, long distances, even across continents, must be covered. Since again vehicles are mostly powered by fossil fuel, the transportation adds to the GHG emissions and air pollution on top of what is already being emitted. When taking a closer look at the ecology of building materials, it becomes clear that some of the impacts are not directly visible. This shows the complexity of capturing a building's entire embodied energy and all involved environmental impacts.

When the construction of the building is finished, the operation and maintenance stage of the building begins. This stage is the longest in the life cycle and can last 50 years or more. During this period of time, all sorts of energy in forms of heating, electricity and water is consumed. In 2019, around 70 % of the energy consumed by households in Germany was used only for space heating which is mainly fueled by fossil energy sources such as gas and mineral oil (Statistisches Bundesamt 2021). The amount of the consumed energy as well as requirements for maintenance and refurbishment are highly dependent on the choice of building material and its properties.

Finally, when refurbishment is not viable or economic, a building reaches the limit of its life span and is demolished. Even though this stage is associated with low energy consumption, the amount of waste is tremendous. In 2019, the building industry in Germany caused 230 million tons of waste, which accounts for about 55 % of the entire produced waste (UBA 2021). Hence, the building sector is the largest waste producer in Germany. The possibility to recycle construction and demolition waste depends on the choice of building material as well as in which country a building is demolished. Recycling is preferred but also requires new energy input. All material, that cannot be recycled, eventually ends up on a landfill and toxic components risk a release of pollutants in water and air. In Germany about 13 % of construction waste is not recyclable and is stored in landfills (BMU 2020a).[2]

When examining a building's life cycle it becomes evident that the building sector plays a major role in global climate change. The amounts of emissions, pollution and resource consumption are tremendous, causing a severe negative impact on the environment. If the goals of the 2030 Agenda are to be translated into action, it is crucial to consider the building sector and thus all the above-mentioned stages of a building's life cycle.

In addition to urbanization and population growth, that enhance the demand for buildings, the amount of residents living in the same household has decreased in the last decades. In 1965 the share of single-person households increased from 22,3% to 40,6% in 2020 (Statistisches Bundesamt 2000; Statista 2021a, p. 135). As multi-person households save floor area demand by sharing common areas such as kitchen, bathroom and hallway, the single household trend has drastically increased overall living space demand. In the same period of time the average living space per capita increased from 22,3m^2 to 47,4m^2 (Statistisches Bundesamt 2000; Statista 2021f, p. 69), more than doubling in size. Taking into account the consumed valuable urban space, building material and equipment, increased living space inevitably also means increased environmental impact. Additionally, larger living spaces are expensive to heat and to maintain (Viggers et al. 2017). Due to the high costs, it is likely to under-heat in cold seasons causing dampness and eventually mold (s. subsection 2.1.2). The size demands more maintenance and, if not executed, accelerates the degradation of the building structure. Considering the many negative impacts, adequate living space size has to be considered in design decisions.

This section has shown—although not visible at first glance—that living standards and residential buildings are connected to climate change and negative environmental impacts, eventually threatening our own human integrity. To get to the bottom of these complex issues, it is indispensable to question our own consumption patterns and dwelling standards. Therefore, the addressed environmental aspects have to be considered in the design stage in order to provide sustainable green building solutions.

2.3 Defining relevant building design requirements

Having elaborated the diverse issues that can occur in terms of construction and living in a building, the key insights from the previous sections can now be summarized to define crucial requirements and measures for designing a social and green building that promotes the SDGs within an urban environment. The following inferred measures are presented in Figure 2.4 and are the basis for the model design in Chapter 4.

[2]Name of the ministry was changed in 2021 to *Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz*

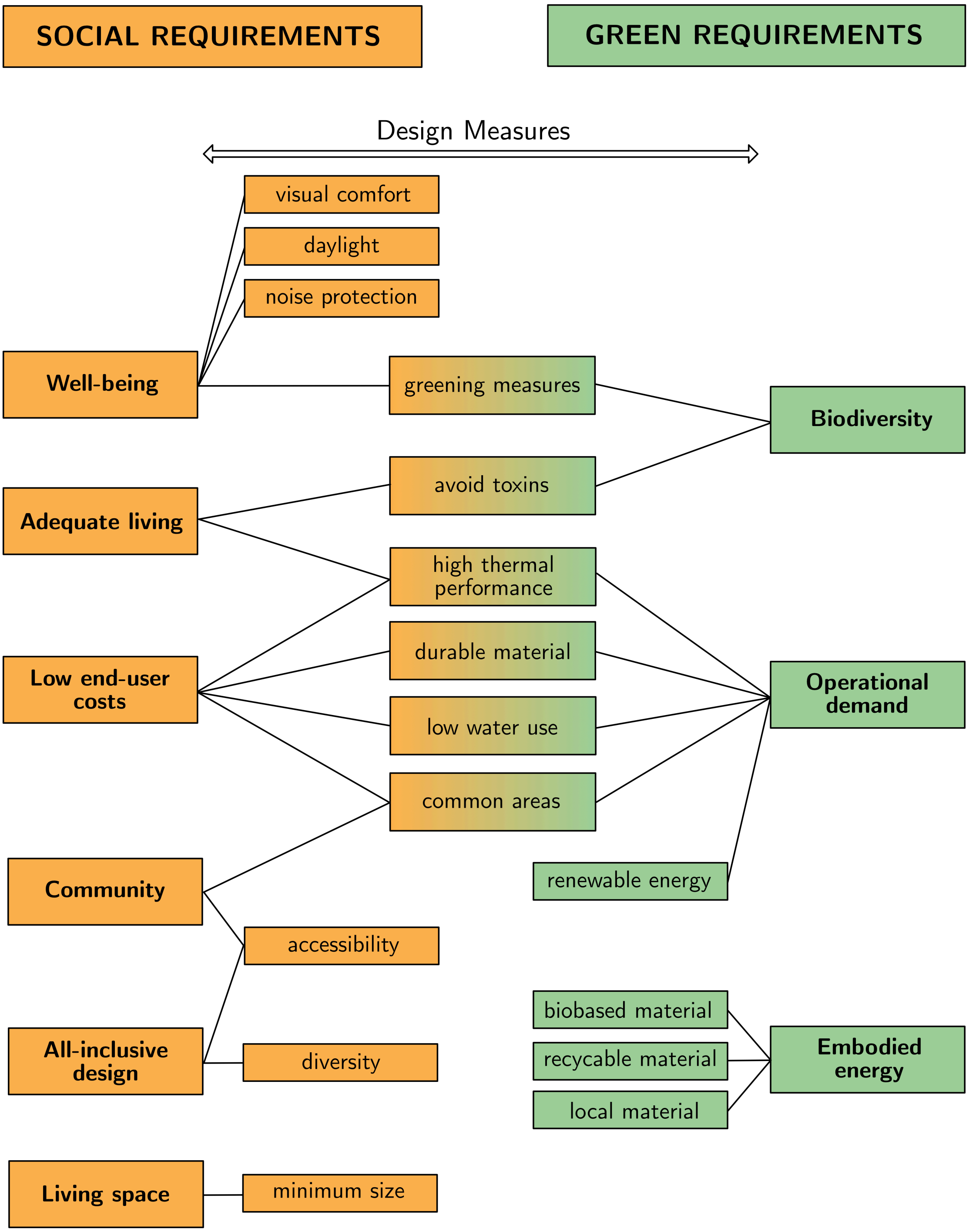

Figure 2.4: Building design requirements (left and right) and possible inferred measures (middle section) to implement social and green living requirements (own figure)

Social requirements

The first and most important aspect to make housing social is the provision of *adequate living conditions* as a part of human right. The residents should live in a healthy home with comfortable indoor temperatures that includes all basic facilities such as bathroom and kitchen. Further measures to promote *well-being* have to be carried out by taking into account beneficial impacts of visual comfort regarding building appearance, sufficient daylight, noise protection and greening measures. As *end-user costs* burden especially residents with low income, any costs regarding energy, electricity, maintenance or water have to be kept as low as possible by using proper insulation, energy efficient equipment, durable building material and so on.

Apart from individual needs, it is also important to strengthen the *community* needs of the occupants and create common areas where residents can connect, live out cultural practices or simply pursue a certain hobby. A special focus should be also be on *all-inclusive design* considering a spectrum of possible living concepts, building accessibility and adequacy for all people. The mentioned aspects represent prerequisites for residents to feel comfortable in their home and therefore support them to thrive and live a dignified life. Lastly, the overall *living space* needs to have an appropriate size, depending on the number of residents in one unit.

Green requirements

Green requirements have to be considered in order to mitigate the impact of the building industry on climate change and all its negative consequences that post a threat to all forms of life. The first concern relates to the properties of the selected building material, basic facilities and equipment to ensure a low environmental impact: Building materials should have a low level of *embodied energy*, which can be achieved by using local materials that require minimal processing, energy and water usage during extraction and manufacturing. At the same time, materials should be resource efficient. This is done by the reusability and recyclability of the materials, preferably from a biobased source. Additionally, any kind of toxins, pollutants or heavy metals, that are released in any life cycle stage, threaten *biodiversity* for flora and fauna as well as health of workers and residents. These should hence be avoided. Considering the length and impact of a building's use stage, reducing *operational demands* is a top priority. This applies to both the thermal properties of the building's envelope and all equipment regarding heating, electricity, water etc. To reduce any resource consumption even further, living space per person as well as the thermal envelope of the building should be designed as small as possible. A solution in urban areas that meets both requirements best are apartment buildings. In comparison to stand-alone buildings they provide densely neighboring units with multiple rooms, suitable for larger households that share common spaces and minimize the thermal envelope for lower heat-transfer (Viggers et al. 2017). The reduced land consumption also benefits the overall *biodiversity* in urban space by avoiding sealed areas and can be further enhanced through greening measures.

Examining Figure 2.4 it becomes evident, that most green building design measures also contribute directly to aspects of social living. For instance, avoiding toxins and pollutants helps to ensure adequate living as well as to enhance an overall healthy environment. These greening measures assure both well-being and biodiversity. The strongest commonality can be identified between energy and resource efficiency in correlation with low end-user costs as any savings benefit monetary relief for residents. However, the figure also shows a few measures that limit each other. While residents require an adequate amount of living space, from an environmental and cost-perspective floor area per capita should not exceed beyond what is really necessary or regarded as luxurious. The same applies to the size of windows for sufficient daylight without compromising the efficiency of the thermal envelope.

2.4 Recent developments in urban housing

In the last years, there have been various developments in urban housing that angle dwelling from different perspectives. This sections elaborates a few aspects that should be taken into account for future housing.

2.4.1 The housing market in Germany

Recently, the housing shortage in urban areas has gained broad public attention in Germany where studies have shown an existing deficit of around 700.000 missing housing units in the whole country (Holm 2018). The causes are complexly rooted in low building land availability, high population growth in urban areas, higher land consumption per capita (s. subsection 2.2.2) and political legislation. Since the 1980s, stakeholders in German politics have adopted laws that favored private investors in the housing market (Butterwegge 2021, p. 206). Real estates, as a popular capital investment, focus primarily on yields, pushing property prices up and inevitably increasing rental costs (Holm 2018). It is worth noting that most inhabitants in urban areas live for rent as apartments are usually owned by wealthy private individuals or real estate groups (Butterwegge 2021, p. 206). At the same time the number of low-income citizens are rapidly increasing in Europe (Kolokotsa et al. 2015). These households have more difficulties in finding affordable housing and eventually are forced to spend a higher percentage of their income in rent or move away from certain areas, to the advantage of more wealthy households. Such processes of displacement by rising rental prices is referred to as *gentrification* and can especially be observed in central inner-city locations (Kronauer 2018). The measurements to counteract these ongoing processes are as varied and complex as are the causes of the housing shortage. Eventually, the responsibility of enforcing appropriate actions lies in the hands of policymakers.

Since 2006, the responsibility for legislation on social housing promotion has been transferred from national to the federal level so that every state can set their own binding laws (BMI 2018a). In the case of the City of Hamburg, the senate determined in 2011 the so called *Drittelmix* (German for third mix) which sets the goal to obligate 35 % in relation to floor space of newly built dwellings to be subsidized publicly for low and middle income households (Hamburg Senate 2021). With this regulation, the city intended to strengthen affordable rents and provide a sustainable social mix in newly built areas. However, after termination of the funding period, social housing apartments in Germany lose their legal binding with regard to occupancy obligation after 15 up to 45 years (Zeit 2019; Horlitz 2018). If the apartments are owned by a housing association, the tenants are likely to rent under similar conditions as before. But in case of private owners, the apartments can be returned to the free market for larger profit margins and inevitably less affordable rents. Although there are efforts made by political stakeholders to provide social housing, the amount of new apartments is nearly not enough to compensate the loss through status expiration. As a consequence, the stock of social housing has decreased in the past years (Zeit 2019). It is becoming clear that the need for affordable housing is at an all-time high.

2.4.2 Home as a working place

For a long time employees, occupied in traditional office work, were tied to a company's physical location. Since the global pandemic started in 2020, a large number of people have been urged to work remotely in order to prevent further spread of COVID-19. In Germany, the government has passed legislation to obligate employers to offer a *home office* option to their employees provided that there are no operational reasons to the contrary (Corona Datenplattform 2021, p. 4). Many companies have managed to make the physical and mental shift by moving work flows to the digital sphere: meetings in person have been replaced by virtual communication platforms, local company networks are available via online database and so forth. As a result, the share of population working remotely exclusively or predominantly has increased from 4 % before the corona crisis to 24 % in January 2021 (Statista 2021b). Therefore employees spend a considerable amount of time in their own houses.

Just as the living circumstances inside people's homes are disparate, so can be the working conditions in *home office*. All possibly occurring housing problems, as elaborated in subsection 2.1.2, also affect inevitably the home working environment. What needs to be considered here, is that many households do not have excess space for a proper working place. Especially in urban areas, only people with sufficient earnings can afford to pay rent for an extra room merely for working. People, who live in a shared apartment for instance, have no other option than to work from their bedrooms. This brief example illustrates further the aforementioned large discrepancy between the wealthier and low-income populations.

Additionally, working from home has promoted less movement and spending less time outside with tremendous consequences for physical and mental health. According to a survey of a German health insurance, people spend even more time seated in front of a screen without moving, causing a significant increase of patients suffering from back pain (DAK 2021). Simultaneously, working from home can make it difficult to mentally separate leisure time from work, causing stress and less recuperation. Even though *social distancing* is crucial for the containment of COVID-19, less personal interaction with colleagues and people in general lead to feelings of social isolation and eventually loneliness (Berger et al. 2021, p. 1161). It does not come surprisingly that psychological illnesses have reached a high point in 2020 (DAK 2021).

Despite all these potential problems, it is important to raise awareness that, even after the end of the pandemic, *home offices* will continue to be an essential part of our work and social life due to advancing digitalization. So moving forward, the question to answer will not be how to move back to working on site, but how to implement *home office* in a way that benefits human life. In this context, it must be emphasized that working remotely also offers many advantages. Employees have the option to organize their working hours and thus their day more flexible, customized to their needs. As there it is not necessary to commute, a lot of time can be saved and spent instead with pursuing hobbies, doing sports or simply with loved ones. In view of multigenerational living and inclusion of people with disabilities, it is easier for everyone to access their working place and in case of any emergency, house members are still closeby.

When thinking about possible solutions for adequate *home office*, setting up an extra office room in every apartment is not viable as this demands floor area in an inefficient way. Furthermore, only wealthy residents can afford to pay for this extra expense. Instead, a promising solution could be the provision of a common area in a residential building that is reserved explicitly for *coworking*, not only for those from creative industries and freelancers, but also those in need of an office working place outside of their apartments. In this way, people have access to a near and adequate working place, provided that building measures are implemented for a healthy indoor environment, sound insulation and sufficient space. Necessary office appliances, such as printers or a coffee kitchen, could be shared and offer human interaction even outside the respective employment sector. Together with other common spaces for recreation, such as green roofs or a sports facilities, the daily working life can be eased and hence well-being increased.

Although the idea of *coworking* in the context of *home office* is beneficial and dedicated to office employees with lower income, it has to be considered that the ability to work from home is still a privilege mostly reserved again to those with higher education and earnings. These professional groups are more likely to engage in cognitive activities that can be easily shifted to home (A. Müller 2021, p. 91). Therefore, in the interest of including the part of the population that does not have this privilege, extra effort should be made to provide other amenities, such as a public library or café, open and barrier-free to everyone (A. Müller 2021, p. 90).

2.4.3 Modern housing concepts and future outlook

In recent years, planners have understood the importance of including the needs of future tenants and tried to implement the combination of social and environmental aspects in their housing designs. In the following, two examples from Europe are further elaborated. Aspects of the designs will be taken into consideration for the model example in Chapter 4.

Prinz-Eugen-Park in Munich

The *Prinz-Eugen-Park* is an urban settlement constructed in 2016 with 1800 apartments in Munich (Hafner et al. 2020, p. 10). A part of the district is an ecological model settlement with 8 multi-story buildings including 566 mostly subsidized and privately rented apartments (s. Figure 2.5) (Hafner et al. 2020, p. 15).

Figure 2.5: The ecological model settlement in the *Prinz-Eugen-Park* in Munich (Sjahanschah et al. 2020)

All buildings in this district are executed in wood construction with elements of solid timber, wooden frame construction and reinforced concrete (Hafner et al. 2020, p. 22). By an increased use of wood, it was possible to reduce material from nonrenewable sources such as metals and minerals (Sjahanschah et al. 2020). This benefits the embodied energy as wood components serve as temporary biogen storage and therefore lowers environmental impact. Additionally, care was taken to ensure that all wood components had certification of sustainable forest management (Sjahanschah et al. 2020). Although all buildings are unique, differing in shape, size and component use, planners intended to focus on compact design to minimize the respective thermal envelopes. In combination with proper insulation and efficient heating appliances the compulsory energy efficiency standard is reached by demanding only a low amount of primary energy. For the interior design densification, mixing social classes and providing units for various living concepts are guiding principles. Besides smaller apartments for few people, there are also units adequate for larger households. In combination with a variety of common areas such as a workshop, a music room and many more (Hafner et al. 2020, p. 92), the consumed living space per capita in the settlement is reduced. Additionally, the buildings are embedded in a park landscape with spacious green areas, playgrounds, communal gardens, vegetable patches and many green roofs to add more value to living comfort and local biodiversity.

Due to all these measures, the *Prinz-Eugen-Park* is a unique pilot project for sustainable housing construction in Europe, considering environmental as well as social aspects.

Kalkbreite in Zurich

The *Kalkbreite* is a modern seven-story building complex that offers living space for about 250 people combined with commercial areas in the heart of Zurich and was inaugurated in 2014. The intention behind the design was to plan a settlement that combines social and ecological aspects. The construction is a column slab building made of concrete with a lightweight wood facade and contains polygonal shapes that form an elongated ring (Maier 2013). The building height on the south side is reduced in favor of providing sunlight to an inner yard and playground, which are accessible to the public. Together with the greening measures on the rooftops with community gardens, the *Kalkbreite* offers visual variations (s. Figure 2.6).

Figure 2.6: The inner courtyard of the *Kalkbreite* in Zurich (Volker Schopp 2014)

Moving forward to the building's interior, the principle of diversity carries on. The number of rooms within a unit varies by apartment, so many different household sizes can coexist in the building. One-room apartments, that are grouped into clusters with a larger common room, are available as well as shared multi-room apartments. Thinking beyond traditional living structures, planners have even implemented one housing unit where up to 50 people can live, sharing a communal kitchen (Energie Schweiz 2021). These different living forms help to enhance social mix including a wide spectrum of ethnic background, age, gender, ability and income. Generally, the concept is dedicated to minimize the living space consumed per person, which is why the amount of rooms in one apartment can only exceed the number of residents by one. Another way to reach this goal, was to provide a generous supply of common spaces for the residents, where they can share goods, work and interact with each other. There are areas of office work places, workshop, cafeteria, sauna, music room and many more (Energie Schweiz 2021). By implementing these measure, an average living space per capita in the building of 32,6 m^2 is achieved, which is considerably lower than the city's average of 45 m^2 (R. Müller et al. 2020) and contributes to lower embodied energy and carbon, enhancing environmental sustainability. Regarding the operational stage, insulation with high thermal properties were used allowing very low energy demands for space and water heating (Maier 2013). For general electricity consumption a solar system is attached to the roof.

The *Kalkbreite* is a showcase for residential architecture that considered many of the relevant living aspects discussed in this chapter and disrupts the traditional way of building large housing estates.

Turning living spaces into *smart homes*

A component to be considered in the future of living is the ongoing digitalization. Digital devices, such as smartphones, computers, tablets etc., take up a large part of our human lives. Whether it is participating in an online meeting in *home office*, using a the smart watch to track fitness or letting a vacuum robot clean our homes. A lot of daily processes in our society are now geared to functioning via a digital device. Of course it has to be said that all these technologies are not bare necessities of human life, but to imagine life without these devices, which have the potential to ease daily life and tasks, is nowadays unthinkable and also cumbersome for a lot of people (Anderson et al. 2018). The motivation behind using technical advances is to resolve any sort of task quickly and efficiently.

In the context of dwelling, home automation systems, described by the generic term *smart home*, have gained popularity in the last years (Frondel 2021, p. 411). In 2017 around 7 % of all households worldwide used such systems inside their homes and the number is expected to rise to 21 % by 2025 (Statista 2021d). The principle of a *smart home* is to monitor and to intelligently operate a house by using smart links between technical devices and sensor technology. By this, appliances for lighting, temperature, housekeeping, security and more can be controlled automatically. This is made possible by communication between different devices through internet connection and is referred to as the *Internet of Things* (IoT) (Chebudie, Abiy Biru et al. 2014).

The aims and possible advantages of a *smart home* are wide-ranging. First and foremost is the potential attributed to reducing energy consumption, including electricity and heating, and associated environmental impacts through efficient management and automatic optimization (Estermann et al. 2020). Generally, the smart system can detect abnormalities during an operation process and counteract these or notify facility management (FM) and the end-users. For instance, if sensors for temperature and humidity measure values outside an optimal range, residents could be warned and adjust ventilation behavior in order to prevent mold growth. If a resident opens a window, the heating devices in that room are automatically turned off by the system. Similar principles apply to water use. Examples like these show the potential not only for consumption management but also for improving indoor air quality and living comfort. Additionally, smart home devices that take over typical household chores such as a cleaning robot can safe time that instead can be spent more meaningful with loved ones or hobbies. It comes as no surprise that *smart home services* enhance well-being (Sequeiros et al. 2021).

Furthermore, the integration of smart systems into *home health care* for patients and the elderly is a potential alternative to certain health care services such as assisted living or nursing homes. Considering that the share of older population in Europe is expected to increase significantly in the next decades, while the young population decreases (EC 2019), solutions for future independent home living are of interest. In recent years, home care robotics have been developed technologies such as fall and motion detection or air quality sensors (Piekarz 2021). The data can be used for behavioral monitoring to help medical practitioners to obtain accurate health data beyond self-reporting and examination in a medical facility. With all these measures, the burden on the health care system could potentially be reduced, diagnoses and thus treatments for chronic diseases improved and more accessible and low-cost health assistance provided (Helal et al. 2009). By this, people could receive appropriate health care services tailored to their needs for more independent living. Another aspect of *smart home* include communication and entertainment such as a multiroom system with smart links between TV, speakers distributed in different rooms and streaming platforms controlled via smartphone app. As shown in Figure 2.7 *smart home services* can generally be grouped into the three categories *energy consumption and management*, *lifestyle support* and *safety*.

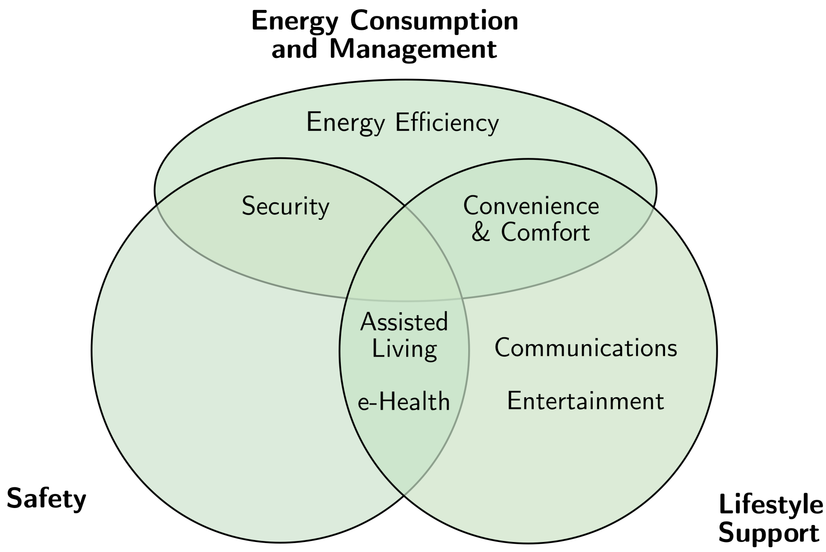

Figure 2.7: Types of smart home services according to Balta-Ozkan et al. (2013) (own figure)

Although *smart home devices* are getting more popular, voices of criticism are also present. One major concern is the invasion of privacy by technologies that can compromise the resident's personal security. The large amount of information about daily routines, energy bills and so forth raise the question of how the data can be securely protected against misuse by third parties. This potential threat of intrusiveness is of particular importance, keeping in mind that article 12 of the *Universal Declaration of Human rights* states that "[n]o one shall be subjected to arbitrary interference with his privacy, family [...] [or] home [...]" (UN 1948).

Beside privacy issues, in the study conducted by Balta-Ozkan et al. (2014) in the UK, Germany and Italy, participants expressed concerns regarding installation and maintenance cost of the services. *Smart homes* were perceived as a luxury, more reserved for a wealthy white middle class. Another point that concerned participants was the reliability of services on computer systems. If, for instance, a remote control unit for operating several devices malfunctions, none of these could be used. Additionally, in order to operate *smart home services* a certain amount of technical knowledge is required, which can be challenging, especially for older generations.

Regarding environmental aspects, a study by Frondel (2021) has shown that the energy savings through *smart home technologies* can be inhibited by a rebound effect caused by improper handling by the end-user. For instance, remote controlling via app allow residents to turn on the heating before they arrive home, increasing the total consumption.

As described in this section, there are many advantages and disadvantages to be considered before deciding on which devices should be added to a *smart home*. Nevertheless the utility as well as the necessity of smart devices have to be evaluated individually based on the needs of the residents. Due to the use of IoT for energy management and occupant comfort, smart technologies have the potential to enhance the determined building design requirements. All mentioned aspects will be further taken into account for the determination of digital assets for the practice oriented example in Chapter 4.

2.4.4 Efforts to implement green buildings

As seen in the examples in subsection 2.4.3, there has been a shift of priorities regarding newly built housing in the last decades: Stakeholders in politics have recognized the environmental impact of the building industry and the importance to take action in order to mitigate climate change and to meet the objectives of the *Paris Agreement* by 2050. As mentioned before, the operational stage of a building demands large amounts of energy to provide heat, cooling, warm water, ventilation and electricity. These services have been mostly dependent on fossil fuels causing tremendous GHG emissions (UNEP 2020). Therefore, state regulations towards green buildings are most and foremost directed towards reducing the primary energy demand and increasing the use of renewable sources. The German government, for instance, has passed various laws since the 1970s to define certain standards in new buildings for minimum insulation values, the efficiency of heating systems and the integration of renewable energy (Beckmann 2020, p. 18). The most recent legislation was the *Gebäudeenergiegesetz* (GEG) (2020), in which requirements for energy-efficient buildings are defined. The main rating parameter is the annual primary energy demand for heating and warm water supply considering upstream process chains and transmission heat loss (BMI 2018b, p. 6). Eventually, the industry adapted to political frameworks and developed a variety of terms and definitions for energy efficient buildings with different respective requirements that are even higher than the compulsory standard. The most recent revision in German building legislation of the year 2020 set a minimum standard for new constructions as *nearly zero-energy buildings* (BMI 2018b, p. 5), which means that these houses require a low amount of energy and additionally compensate a part of their demand by incorporating the use of on-site renewable energy such as solar panels (Beckmann 2020, p. 18). Furthermore, the government has financially promoted the building standard *KfW 40*, which requires new-built to only consume 40 % of primary energy and 55 % of transmission heat loss compared to the reference building defined in German energy legislation *GEG*.

So far, the regulations only require energy certification for the operational stage to be mandatory. Life cycle stages before and after, are not included in any of the building definitions. Although the efforts to incorporate energy efficiency into building practice have to be acknowledged, critiques argue that the ecological efficiency of a building can not be made only focusing on one life cycle stage (Beckmann 2020, p. 93). Furthermore, Asdrubali et al. (2020) have shown in their study, improving the thermal envelope can reduce the operational non-renewable energy demand significantly. However, this reduction goes hand in hand with increased embodied energy due to the necessary material to obtain better building performance. In Figure 2.8 the share of embodied energy in comparison to operational energy depending on the type of building based on the data of Azari (2019, p. 127) is presented. In conventional buildings the embodied energy takes up to 6-20 % of the entire life cycle energy use whereas in low energy buildings the share increases to 26-57 % can even make up to 100 % for *net zero buildings*.

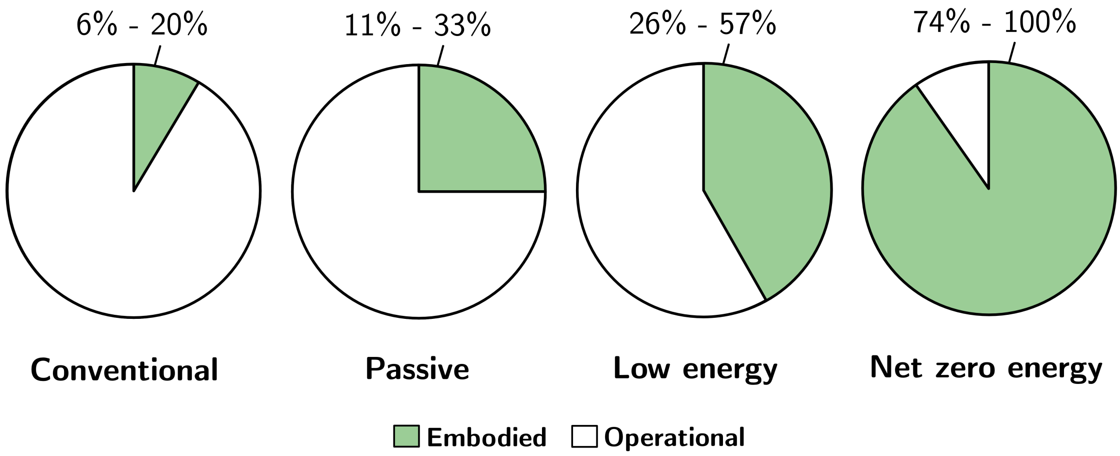

Figure 2.8: Share of embodied energy in life cycle energy use of residential buildings with various levels of operational energy efficiency according to Azari (2019, p. 127) (own figure)

The data shows that the more energy efficient buildings are in the operational stage, the larger is the significance of embodied energy. It becomes evident, that in the optimal case addressing the entire life cycle is necessary to gain a fully comprehensive conclusion on environmental impacts of a building.

3 Building sustainability assessment methods and design requirements

The aim of this chapter is to elaborate ways to implement environmental and social aspects of living into building practice. First, the methodology *life cycle assessment* is explained (section 3.1) as well as the integration of *building information modeling* (section 3.2). Appropriate methods for evaluating buildings are introduced (section 3.3) to eventually select adequate programs and determine a workflow (section 3.4). For the selection a German project location is taken into account.

3.1 Life cycle assessments for buildings

As society, politics and industries have gained larger awareness about the importance of environmental sustainability of consumption goods, various efforts have been made to develop a tool to evaluate products. The outcome is the *life cycle assessment* (LCA), a methodology that analyzes environmental impacts throughout the life cycle phases of a product (s. subsection 2.2.2) and can help to identify potential design weaknesses. With this knowledge, planners of a construction can justify and improve design decisions scientifically in favor of creating green buildings. LCA is defined by the international ISO 14040:2006-07 (2006) and is presented in Figure 3.1.

As seen in Figure 3.1, a common LCA study consists of 4 phases: The first step is the determination of the *goal and scope* to answer the question which life cycle stages are to be considered in the analysis. By this, system boundaries can be identified. For instance, it is possible to take into account only the inputs raw material extraction, processing and manufacturing (*cradle to gate*), to consider additionally the product disposal (*cradle to grave*) or even the recycling of waste material (*cradle to cradle*) (Gorse et al. 2016, p. 201). In Figure 3.2 the life cycle phases of a building according to life cycle phases of a building according to EN 15978:2011 (2011) and EN 15804:2013 (2013) are shown. The different modules include the production of material by extraction and manufacturing (A1-3), the building construction process (A4-5), the use stage during occupation (B1-7), the demolition and waste at the end-of-life stage (C1-4) and additionally, benefits and loads beyond the system boundary such as recycling (D).

Once the system boundaries are determined, the *inventory analysis* follows. In this step, all inputs in form of materials and activities as well as their output within the system are quantified. This includes precise information about building material, embodied energy and

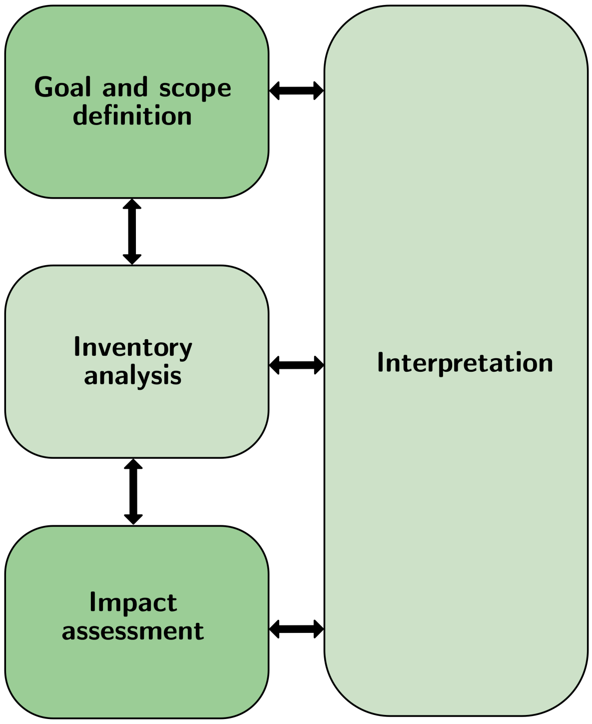

Figure 3.1: Phases of a LCA according to ISO 14040:2006 (2006) (own figure)

so forth. Next, the *impact assessment* can be performed by translating the gathered data into environmental impacts. This can be achieved by using conversion factors, that are usually retrieved from LCA databases (Gorse et al. 2016, pp. 202-203). Assessed impacts can include global warming potential, acidification potential, eutrophication potential, fossil fuel depletion, smog formation potential, ozone depletion potential, ecological toxicity and water use. The final step is the *interpretation* of the results. All calculated impacts have to be evaluated with reference to the predetermined *goal and scope* of the LCA.

Typically, LCA is an iterative process. Based on the outcome of the interpretation the product design has to be changed and afterwards reevaluated through all four steps again. With this approach, weak points can be identified and improved creating a product with less environmental impact.

The described methodology is very flexible and leaves room for users to adapt LCA to their own products and needs, making it even applicable for complex structures like buildings. To perform LCA in practice, there is a large variety of dedicated software, specialized in buildings, on the market with distinct approaches, system boundaries and so forth.

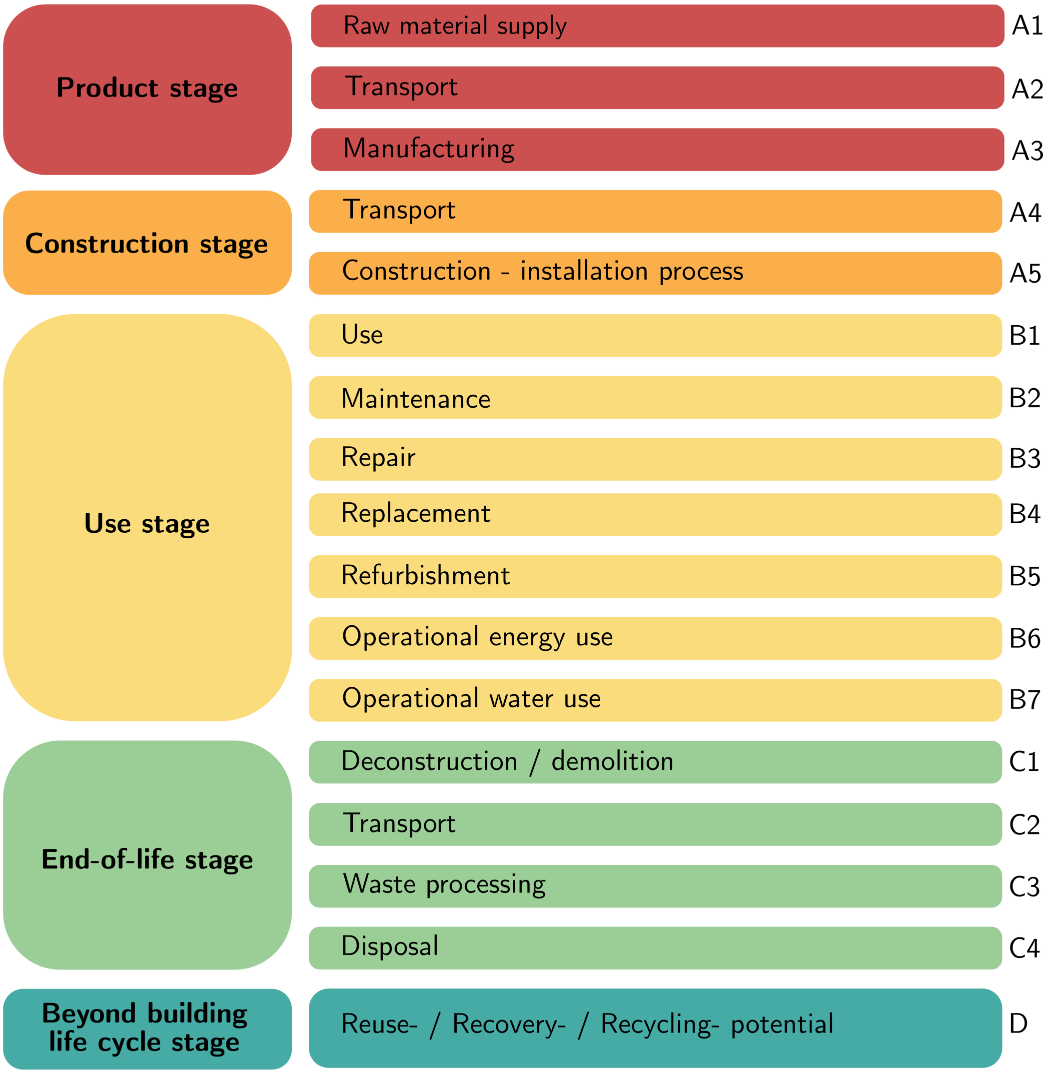

Figure 3.2: Life cycle stages of a building according to EN 15978:2011 (2011) and EN 15804:2013 (2013) (own figure)

3.2 Integration of BIM in LCA

In order to receive the most comprehensive results, LCA would have to be performed after the final design of a building, when detailed data about used products, quantities and so forth are available. Simultaneously, LCA should be implemented as early as possible in a project as the resulting impacts are highly dependent on the design. It becomes evident that there is a paradox in performing LCA making it more difficult to include this methodology in practice (Di Bari et al. 2019, p. 2). The amount of required data might not be available in early project stages, especially for larger and more complex buildings.

A solution to this challenge is the implementation of building information modeling (BIM). BIM is a methodology for networked planning and managing essential building design data. Information relevant to design, construction or facility management are exchangeable and interoperable for various stakeholders by using a digital format such as industry foundation classes (IFC) (Ilhan et al. 2013). The BIM method involves creating a digital model with all the project data and enables multi-disciplinary planning with more collaborative working avoiding errors and incompatibilities (Carvalho et al. 2020). Recently, the adoption of BIM in the building industry has been increasing due to the many benefits such as cost and time saving, improved quality etc. (Ismail et al. 2019).

Moreover, BIM has great potential in creating more environmentally sustainable buildings, referred to as *Green BIM*, and can be beneficial for performing LCA (Ismail et al. 2019). The reason for this is the high amount of data availability and accuracy that is needed for a comprehensive LCA. Besides data about environmental impact of a certain material, precise information about building systems and components are crucial (Hopkins 2020). BIM allows an integrated design even at an early stage and accurately produces material quantities take-offs for the inventory database. Furthermore, applications for building sustainability can be performed such as energy or lighting analysis (Carvalho et al. 2020). With all this gathered information, an input of higher data quality into LCA could be accomplished reducing model uncertainty. Eventually, the results are more representative and help to optimize greener design decisions.

To integrate BIM data into LCA, Wastiels et al. (2019) distinguish five different strategies. The first approach requires the extraction of geometrical and material information from the BIM model. This can be achieved in form of exporting a bill of quantities (BOQ) (1), using an open exchange format like the IFC (2) or transferring the BIM information into a BIM viewer tool (3). In all these analog approaches the data is afterwards fed into an external dedicated LCA software. A more automated strategy can be accomplished through the use of a plug-in to perform LCA directly in the native BIM environment (4). The advantage of this approach lies in the immediate visualization of LCA results into the geometrical model giving the user an instant feedback about the most severe impacts and which building components cause them. In another strategy specific LCA information is already embedded into BIM objects of the model, instead of adding the data later in a LCA tool (5). Until now, this approach has not been implemented widely as there is still a lack of BIM objects that include LCA information (Wastiels et al. 2019). The selection of an appropriate integration strategy is dependent on the available software and the applicability to a project.

3.3 Building sustainability assessment methods (BSAMs)

3.3.1 Development of building certification systems (BCSs)

As LCAs are complex, performing them demands high level of expertise and time. The market outside academic research, however, requires simplifications and speed in order to integrate LCA into feasible practice. For this reason, BCSs, a type of BSAM, have been developed since the 1990s by various institutions in different countries of the world as a tool to rate the sustainability of buildings (Kubba 2012, pp. 14-15). These certifications use simplified LCA to determine negative environmental impact (s. subsection 2.2.2) and define various categories for which partial scores can be gained. The final added up score gives an insight about the extent of building sustainability and shows the level of reached certification depending on the benchmarking system. This approach allows more transparency to the design process and awareness about environmental impacts. As any methodology, BCSs and LCAs are limited and have uncertainties. The purpose behind these schemes is not to fully illustrate all environmental impacts of a building's life cycle one on one but rather to mitigate these as much as possible (Hopkins 2020, p. 15).

Additionally to environmental aspects, many BCSs extend their view on sustainability by adding a social and an economic dimension which together embody the so called triple bottom line (s. Figure 3.3) that is also reflected in the before mentioned 17 SDGs by the UN (s. Figure 2.1). With these added aspects, BCS can not only serve as a tool for designing green but also sustainable buildings. Over the years, many BCSs have addressed social, economic, and urban factors in addition to environmental indicators (Ebert et al. 2010, p. 28).

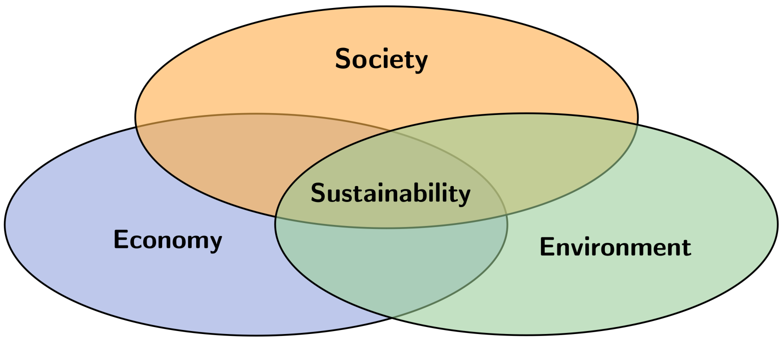

Figure 3.3: Triple bottom line of sustainability according to Elkington (1997) (own figure)

Although BCSs are currently not mandatory by legislation and used for commercial purpose only, many investors demand performing these to demonstrate building performance in new constructions (Obrecht et al. 2019, p. 2). The ratings give operators and users of a building a comprehensive overview of its sustainability. By now, numerous BCSs have established on the market that consider significantly different scopes, goals and ratings in their system (Sánchez Cordero et al. 2020). So far, there is no one-size-fits-all solution. The decision on which system to choose depends primarily on the location of a project. While some BCSs are applicable internationally, others are specialized on certain countries and their application is only appropriate there. Furthermore it has to be kept in mind that each project has a unique composition of environmental, social and economic factors so that one BCS might perform in one environment better than in another (Krajangsri et al. 2018, p. 3). Before deciding which scheme to select, it is therefore critical to be aware of which aspects or categories are relevant and should be reviewed.

In the following, three BCSs are further presented and later to be compared. Their selection was based on their applicability for residential buildings, their relevance due to widespread adoption and their compatibility with a German location. The respective user guides serve as the basis for the analysis of the BCSs.

Leadership in Energy and Environmental Design (LEED)

LEED was launched in 1998 by the non-government organization *U.S. Green Building Council* (USGBC 2022b). Firstly designed for application in the USA, the rating system has since adapted to other national customs, becoming one of the most prominent scheme on the international market (Sartori et al. 2021, p. 7). The latest version was released in 2020, including a specific package for apartment buildings and uses a cradle-to-grave approach for LCA with a study period of 60 years. The scoreboard consists of the categories integrative process, location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation and regional priority (USGBC 2022a).

Building Research Establishment Environmental Assessment Method (BREEAM)

BREEAM was the very first certification system launched by the *Building Research Establishment* from the UK in 1990. The scheme presented is designed for evaluating office buildings and served as the basis for following certification systems such as LEED (Ebert et al. 2010, p. 30). Since then, BREEAM has found wide international application offering evaluation of many different building types, including apartment buildings. The latest international version was released in 2021 and includes the categories management, health and well-being, energy, transport, water, materials, waste, land use and ecology, pollution and innovation. In terms of LCA, a cradle-to-grave approach is aimed for and the study period is set at 60 years.

Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB)

DGNB is the most recent certification system of the ones introduced in this section. Since launching in 2009 in Germany, DGNB has dominated the German certification market and gained international success (DGNB 2022). This evaluation is based on an equal distribution of scores based on the three pillars of sustainability including environmental, economic and socio-cultural and functional quality at 22.5 % each. The remaining scores are calculated according to technical, process and location quality. In terms of LCA, DGNB thrive for a circular economy and apply a cradle-to-cradle approach, investigating a use period of 50 years.

3.3.2 Common issue with BCSs and development of *Level(s)*

As mentioned before, BCSs are not mandatory by legislation and are applied voluntarily in the building industry. Therefore, the so far introduced schemes are all by non-governmental organizations. A major issue in the industry for implementing sustainable buildings in practice more easily has been the heterogeneity of the many different BCSs on the market. As Sánchez Cordero et al. (2020) have shown in their study, there are discrepancies between all the assessments of BCSs, lacking a broader standardization. To fill this gap, the EU has developed the framework *Level(s)* which was first tested in 2017 (EU 2019) and finally launched in 2020 with open access (LIFE Level 2020). The efforts by the EU to create such a tool align with their aim to reach the SDGs for the building sector. *Level(s)* is a free and open-source tool that provides clear sustainability points and aims to provide a common language for all stakeholders involved. Therefore, it can be used by a variety of groups in planning, design, financing and execution. Depending on the user's need and stage of a project, there are three different *Level(s)* of evaluation (EU 2021):

Level 1: *Conceptual design*: involving early-stage qualitative assessments of the basic conceptual design;

Level 2: *Detailed design and construction*: involving quantitative assessment of designed performance and monitoring of construction;

Level 3: *As-built and in-use performance*: involving monitoring and surveying the activity of the completed building and its occupants.

With this categorization, *Level(s)* can be implemented flexibly and adjusted on the basis of the available information. This is specifically advantageous in early design stages. In the framework macro-objectives are defined, including greenhouse gas and air pollutant emissions along a buildings life-cycle, resource efficient and circular material life cycles, efficient use of water resources, healthy and comfortable spaces, adaption and resilience to climate change and optimized life cycle cost and value (Dodd et al. 2021, p. 10). The study period considers 50 years of use. Although *Level(s)* is not a certification system and does not provide any benchmarking, it can help to identify *hotspots* of environmental impact, improve design decisions towards better indoor quality or estimate costs along building life cycle.

Operators of existing certification schemes are encouraged to use the framework as a guideline for improving and adjusting future updates in order to provide impetus for further development. DGNB, for instance, investigated their conformity with *Level(s)* indicators and found that their rating system for existing and renovated buildings was mostly consistent with the criteria proposed (DGNB 2021). With this development the EU intends to mainstream the European BCS market using a framework that is adjustable to specific local regulations while establishing prioritized objectives for creating sustainable buildings.

3.3.3 General comparison of BSAMs

The four presented BSAMs are summarized in Table 3.1, which shows that the basic approach of all systems is quite similar at first glance. The largest difference can be seen in *Level(s)* being a framework that unlike the others doesn't set benchmarks or certifications but serves as a guiding tool for sustainability. Although benchmarking systems are advantageous and give the user a direct quantitative feedback about building sustainability, *Level(s)* dispenses with rating to focus more on the general application of sustainable building practice (Simoes Silva 2021, p. 23).

Table 3.1: Overview of BSAMs (own table)

	LEED	**BREEAM**	**DGNB**	**Level(s)**
Type	BCS	BCS	BCS	Framework
Applicability	international	international	international	EU
Version	v4.1 Residential BD+C Multifamily homes (2020)	International New Construction Version 6.0 (2021)	Version 2018	Version 2021
System boundary	cradle-to-grave	cradle-to-grave	cradle-to-grave	cradle-to-grave
Study period	60 years	60 years	50 years	50 years
Benchmarking	yes	yes	yes	no

Investigating the respective sustainability protocols, many differences can be detected. One scheme might address a certain topic which is not included in another and vice versa. Additionally, the BCSs with rating weigh their categories differently, making a comparison between one of them rather difficult. Nevertheless, a few common overarching categories can be determined and are presented in Table 3.2. The topics covered in all BSAMs are energy, materials and resources, water efficiency, pollution and waste and indoor environmental quality are included in all schemes. This is consistent with previous studies, which indicate that these topics are the most analyzed (Bernardi et al. 2017; Sartori et al. 2021, p. 16).

Regarding environmental building aspects, almost all BSAMs address the green design requirements described in section 2.3. The only exception is *Level(s)* which does not include biodiversity in their scope. A point relevant to residential buildings, that is not included in any BSAM, is the consideration of living space per person. Although DGNB, for instance, has determined a criteria regarding efficient land use, the number of people living in a dwelling is not taken into account.

3.3.4 Comparison of social design requirements

Examining the categories listed in Table 3.2, it becomes evident, that the environmental pillar of sustainability remains the main focus in building assessment. Most BSAMs therefore have low emphasis on social and economic dimensions (Sartori et al. 2021, p. 3). Realistically, the size distribution of the three circles of the *triple bottom line* in Figure 3.3 would have

Table 3.2: Comparison of categories included in BSAMs (own table)

Common categories	**LEED**	**BREEAM**	**DGNB**	**Level(s)**
Energy	●	●	●	●
Materials and Resources	●	●	●	●
Water efficiency	●	●	●	●
Pollution and Waste	●	●	●	●
Site selection	●	●	●	
Natural desaster resilience		●	●	●
Life cycle costs		●	●	●
Indoor environmental quality	●	●	●	●
Innovation	●	●		
Management	●	●		

Table 3.3: Comparison of environmental building requirements included in BSAMs

Green requirements	**LEED**	**BREEAM**	**DGNB**	**Level(s)**
Biodiversity	●	●	●	●
Low embodied energy	●	●	●	●
Operational demand	●	●	●	●

to be more uneven. Nevertheless, all schemes address the social pillar to some extent and have each a category mainly dedicated to human health and well-being. With regard to the BCSs, their focus on these categories is resembled by the share of total score. The scheme with the largest share is held by *DGNB* with 22.5 %, followed by *BREEAM* with 21.58 % and finally LEED with 12.5 %. For *Level(s)* the share of relevance is not quantified, making the user emphasize on the topics due to their needs. The respective category denominations are presented in Table 3.4 including a comparison with social design requirements for dwellings determined in section 2.3.

Table 3.4: Comparison of social aspects included in BSAMs (own table)

		LEED	**BREEAM**	**DGNB**	**Level(s)**
Main category	Subcategory	Indoor environmental quality (12,5 %)	Health & well-being (21,58 %)	Sociocultural & functional quality (22,5 %)	Healthy and comfortable spaces (-)
Adequate living	avoid toxins	●	●	●	●
	thermal comfort	●	●	●	●
Well-being	noise protection	●	●	●	●
	daylight visual comfort	●	●	●	●
Low end-user costs	-		●[1]	●[1]	●[1]
Community	-			●	
All-inclusive design	accessibility		●	●	●
	diversity			(●)	(●)
Living space	-				
Other	-	Enhanced Compartmentalization	Water quality, Private space	User control, Safety and security	

[1] covered in another category

First of all, design criteria regarding indoor environmental quality are covered by all BSAMs, including healthy indoor environment, thermal comfort, noise protection and daylight. For these aspects of health and well-being, there seems to be an overall consensus showing the acknowledged importance as part of obligatory design. Visual comfort regarding building appearance, however, is not generally addressed. All-inclusive design in buildings by providing accessibility has been covered by all schemes. On the other side, diversity of living concepts is partially addressed only by two. While *DGNB* advocates a design that allows diverse functioning and retrofitting according to user's needs, *Level(s)* aims for adaptability and hence higher space utilization. Although the topic of diverse living is not addressed directly, these definitions enable flexible design. Another underrepresented requirement is the strengthening of community by providing common areas which is only covered by *DGNB*. Topics that are not mentioned in any BSAMs are living space size as well as visual comfort regarding building appearance. Finally, low end-user costs are considered in all BSAMs but LEED within another category that addresses life cycle costs.

3.3.5 Summary and suggestions for improvement

As seen in the previous sections, many methods to assess the sustainability of buildings are available on the market. Each one includes different scopes, topics and benchmarks. The main goal of most schemes is the design of green buildings, focusing on the environmental dimension of sustainability. Therefore the predetermined green design requirements were covered by all BSAMs with the exception of *Level(s)*, lacking specific consideration of biodiversity.

Social design requirements are covered to some extent in all BSAMs, mainly by ensuring adequate room temperature, sufficient light, noise protection and healthy indoor environment. But with regard to BCSs, it should be kept in mind that in some schemes the mentioned requirements are not as weighted as in others, making one more applicable for implementing social features than another. In the investigated BCSs DGNB had the most balanced distribution of scores.

Comparing the BSAMs with all predetermined social design requirements, it becomes evident that DGNB and *Level(s)* cover most points, followed by BREEAM and lastly LEED. The deficits can be predominantly attributed to requirements that are specifically related to residential buildings. Neglected topics concern the provision of common areas and alternations in building appearance for less monotony. Furthermore, basic facilities such as toilets are nst mentioned, but are expected to be regarded as self-explanatory unspoken standard for common dwellings. The most relevant neglected point is the consideration of how many people will live in the planned buildings and how much floor area will one resident inhabit. From a social perspective, sufficient living space per person has to be ensured. Furthermore, this aspect is also missing with regard to green design requirements. A large building could pass as green, while only a few people live in it, ignoring the drastic land use as well as resource consumption in all upstream and downstream process chains calculated for one person. At the same time, wasteful occupation of valuable urban land leads to less housing space for the rest of the community. As the determination of living space size has such a broad impact, it should be integrated in future considerations.

In summary, BSAMs need to improve in favor of considering all pillars of sustainability more equally, following a holistic approach. In this sense, DGNB seems to be already well positioned, since the triple bottom line determines the basic structure of the system while the other two BCSs should have a more balanced distribution of scores. As *Level(s)* does not use benchmarking or a scoring system, the focus is more flexible and not specifically forced into one area of sustainability. Each category can be emphasized within their own scope, depending on the user's needs. With regard to the detected missing design requirements, all BSAMs should integrate more considerations that in particular address needs in residential buildings. The suggestions in this section can serve as a stimulus for further improvements.

3.4 Tools selection and workflow for building assessments

For designing and assessing the practice-oriented apartment building, tools and workflows are applied in Chapter 4 have to be determined based on their suitability and feasibility.

First of all, a building design will be elaborated by means of the determined measures and requirements and will include a structural analysis based on rules according to Neufert et al. (2016). Due to the benefits of BIM, a virtual model of the planned building is to be created. For this, the program *Revit* Version 2022 from *Autodesk* (2022) is selected, as it has been the most widely used BIM software (Unifi 2019). The level of detail (LOD) of 300 is targeted for the BIM model. According to Obrecht et al. (2020), this level is optimal for performing LCA.

Then, to further detailing and optimizing the concept, a BSAM is used. After weighing the introduced systems in this chapter, *Level(s)* is considered the most suitable. Although the other methods have been more applied due to their years of availability, BCSs in the EU are expected to have synergies with *Level(s)* in the future, in order to use a common language and to make evaluations more comparable (Simoes Silva 2021, pp. 25-26). The intended lack of benchmarking is considered beneficial for the building assessment in this research, as it allows focus on every objective individually. A comprehensive analysis of various sustainability parameters can be performed without having to take into account the weighting of scoring. This is in particular meaningful for the assessment of social design requirements. Regardless of the level of information available, *Level(s)* can be applied even at early project stages, using Level 1 or 2. Another advantage is that *Level(s)* unlike other BCSs has open access providing a detailed user manuals for every macro-objective[1]. In Table 3.5 the macro-objectives, indicators and the level of assessment to be investigated are presented. As the example will be in the stage of *Conceptual Design*, all selected indicators are to be assessed on *Level 1*, which includes qualitative reporting. In *Level(s)* the fourth macro-objective explicitly addresses design measures regarding direct impacts of climate change on buildings. Although this point has not been mentioned in this work so far, considering these potential future issues will add value to the building assessment and thus to the design. Additionally to the *Level(s)* indicators, measures to fulfill requirements regarding *living space* and *community* are further investigated. Aspects of visual comfort regarding the building appearance will be covered in *indicator* 4.3. By this approach, all previously determined building requirements are addressed.

The first three indicators from *Level(s)* are further investigated quantitatively in accordance with *Level 2* assessment. The BIM model, which is created in the process, can be used to retrieve a precise material take-off from all building components, as required for indicator 2.1. Next, the derived building information from the model is used for performing LCA to take into account the operational energy (1.1) as well as global warming potential (GWP) (1.2) throughout the building life cycle. By now there are many software tools available,

[1] *Level(s)* user manuals are retrieved from https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/412/documents.

Table 3.5: Level(s) and additionally determined macro-objectives, indicators and selected level of assessment (own table)

	Macro-objective		Indicator	Level
1	Greenhouse gas and air pollutant emissions along a buildings life cycle	1.1	Use stage energy performance	1 , 2
		1.2	Life cycle Global Warming Potential	1 , 2
2	Resource efficient and circular material life cycles	2.1	Bill of quantities, materials and lifespans	1 , 2
		2.3	Design for adaptability and renovation	1
3	Efficient use of water resources	3.1	Use stage water consumption	1
4	Healthy and comfortable spaces	4.1	Indoor air quality	1
		4.2	Time outside of thermal comfort range	1
		4.3	Lighting and visual comfort	1
		4.4	Acoustics and protection against noise	1
5	Adaptation and resilience to climate change	5.1	Protection of occupier health and thermal comfort	1
		5.2	Increased risk of extreme weather events	1
		5.3	Increased risk of flood events	1
6	Optimized life cycle cost and value	6.1	Life cycle costs	1
-	Other		Living space Community	

some of which have the ability to process information from a BIM model. The most favorable BIM integration option is using a tool that provides automated processing within BIM software and therefore simplifies analysis. However, it should be taken into account, that the data exchange between BIM and LCA is mostly done manually, as plug-ins are still at an early stage (Obrecht et al. 2020). For an appropriate selection, *Level(s)* requires a tool that is able to conduct LCA in accordance with EN 15978:2011 (2011), which sets norms for the environmental building assessment calculation. Furthermore the tool, as well as the used LCA database, needs to be applicable for a German location. For guidance, *Level(s)* provided a list with software and databases suitable to the framework (Wolf et al. 2020). Another tool requirement within the scope of this thesis is the availability of the software via student license or open access. With the mentioned criteria many tools were filtered out and finally, the most suitable LCA-tool was the *One Click LCA* (2022) tool. It offers a student license to perform LCA after EN 15978:2011 (2011), includes the established German databases such as *Ökobau.dat*, as well as a large amount of *Environmental Product Declarations* (EPD) suitable for German locations. For the connection with BIM technology the tool also provides a software plug-in for *Revit*. The life cycle stages, as shown in Figure 3.2, production (A1-3), maintenance and material replacement (B1-5), end of life (C1-4) as well as benefits and loads beyond system boundary (D) can be directly calculated by *One Click LCA*. However, a deficit of this software is that operational energy (B6) cannot be calculated directly, but has to be obtained from another source. Therefore the German LCA-tool *CAALA* (2022) is used additionally. The calculation of the operational energy is based on DIN V 18599-2:2018-09 (n.d.[a]) regarding energy efficiency calculation of buildings using primary energy factors from DIN 4701:2003-01 (n.d.[b]), which norms calculations for heating, ventilation and air conditioning (HVAC) systems. The program allows an import of gbXML-files which can be retrieved from the created BIM-model. Afterwards the obtained data about operational energy is imported to *One Click LCA*. The reason why *CAALA*, although it is a LCA tool, is not used for the calculation of impacts in the other life cycle stages is the inaccuracy of material take-off due to limits of the gbXML file. The direct connection of *One Click LCA* with the BIM model is considered beneficial and is therefore preferred.

Using both tools, quantitative optimizations are to be carried out. The use of *CAALA* supports design decisions regarding the thermal envelope, especially in terms of insulation thickness, and developing a suitable energy concept. Then, by performing *One Click LCA hot spots* of environmental impacts can be determined and if necessary materials with lower life cycle emissions exchanged. Additionally to GWP, which is the main focus of the *Level(s)* assessment, potentials for acidification (AP), eutrophication (EP), ozone depletion (ODP), photochemical ozone creation (POCP) are calculated. As *Level(s)* does not demand any benchmarking, LCA data for embodied energy will additionally be calculated for a building with the same shape but with conventional non-bio based materials. To ensure comparability, insulation of conventional design will be adjusted to match operational energy of the optimized design. The indicator 2.1 regarding bill of quantities (BOQ) and bill of materials (BOM) will be included in the LCA investigation.

All other indicators of *Level(s)* are not investigated by program-based calculations. It is worth mentioning in this context that for most green building requirements a large set of tools are available as certain parameters are measurable and calculable. On the other hand, social building requirements concerning health and well-being can hardly be quantified, which is why in the mentioned BCSs possible measures are enumerated in a checklist and depending on their implementation, rating scores are awarded. In this context, a gap in standardization can be identified. While the importance of the social pillar of sustainability increases, further research and development of tools with aligning indicators and parameters are desirable. The attempt by *Level(s)* to standardize building evaluation therefore is a step in the right direction.

The Figure 3.4 summarizes the workflow of the entire described process. After all data from the BIM model, *CAALA* and *One Click LCA* are obtained, the actual process of building evaluation can start. The *Level(s)* and self determined indicators are roughly grouped into green, climate change related and social requirements. Each indicator is evaluated and leads to adjustments in the created BIM model, initiating the iterative process. When all requirements are sufficiently met, the building optimization is finished.

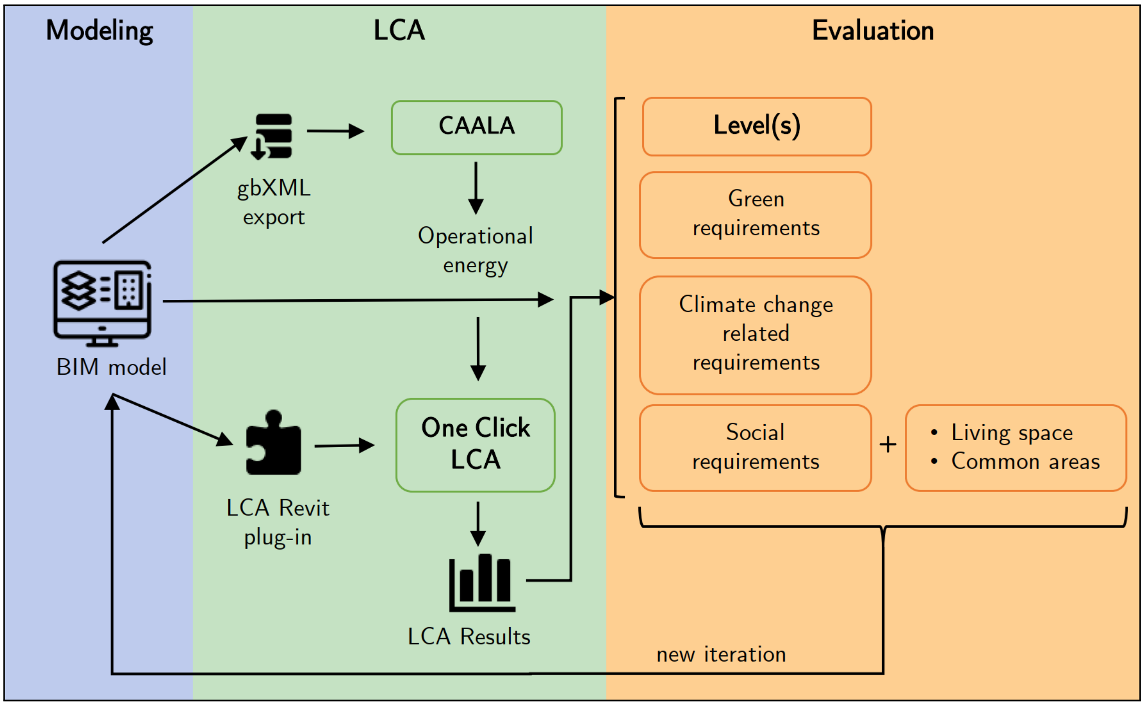

Figure 3.4: Workflow for BIM connected LCA and building assessment (own figure)[2]

[2]Icons retrieved from http://icons8.com/.

4 Practice-oriented example of a smart apartment building

In this chapter, a practice-oriented example for a green, social and smart apartment building is presented. First, general information and the structural design concept are presented (section 4.1). Then, all previously determined indicators are investigated and the process of optimization is described. Starting with green measures (section 4.2), operational energy with *CAALA* is calculated in order to determine a suitable energy system and necessary thermal properties of the building. Afterwards, environmental impacts over the life of the building are determined with *One Click LCA* to locate *hot spots* and to set the structure of components. To assess environmental sustainability, the results are compared with a building design that uses predominantly conventional non-biobased materials. Then, the residual measures for green, climate change related (section 4.3) and social requirements (section 4.4) are elaborated qualitatively.

Finally, when all optimizations are completed, a smart building concept is developed. The aim is to utilize certain digital assets to further enhance the building requirements and investigate an appropriate architecture for data security and privacy (section 4.5). The chapter finishes with a comparison to modern concepts and a guideline on how to assess a social, green and smart building (section 4.6).

4.1 Basic building design concept

4.1.1 General building description

The planned apartment building is located in the City of Hamburg. Here, the plan area *Barmbek-Nord 11* for a new residential district was identified. It is assumed that the building will be located in the extension of *Wittenkampstraße* as marked orange in Figure 4.1. The infrastructure is ideal for new dwellings as the area is surrounded by other apartment buildings and is in proximity to public transit. The subway station *Habichtstraße* as well as a bus stop are within walking distance. Furthermore, several supermarkets as well as different schools nearby are identified on the map. These conditions are considered optimal for a residential building.

When modeling the building, it is assumed that the terrain is at ground level. The building shape will be generally rectangular with the longitudinal orientation in the north-south direction. The external dimensions of the building are about 30 m x 15 m with a height of

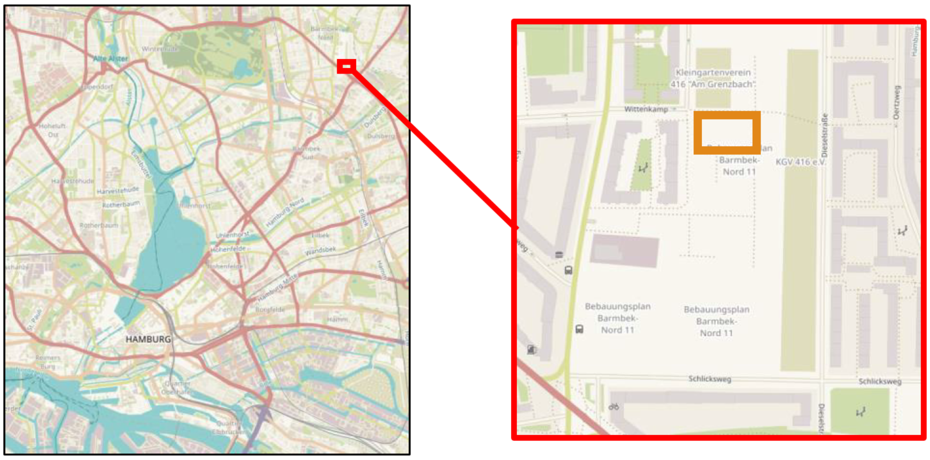

Figure 4.1: Location of the building in Barmbek-Nord, Hamburg (OpenStreetMap 2022)

16 m as shown in Figure 4.2 and Figure 4.3. The total gross internal area is 1743 m^2 and the net floor space 1457 m^2. Above ground level there are four floors with the same gross floor area and below that a basement of smaller size. The upper three floors each contain four apartments of different sizes, for a total of 12 units. All of them have a spacious open living room and kitchen with separate rooms that range from two to four. Assuming that each room is inhabited by one person, the estimated number of occupants for the whole building is 33. The ground floor is reserved for communal mixed use including a coworking space, library, sports and community rooms. On top of the building there is a green roof, partly accessible for recreation and partly reserved for a photovoltaic system. Another green area is a backyard garden. Finally, the accessibility to all floors is ensured by stairs and elevator.

Figure 4.2: 3D-view of the practice-oriented building example (screenshot in *Revit*)

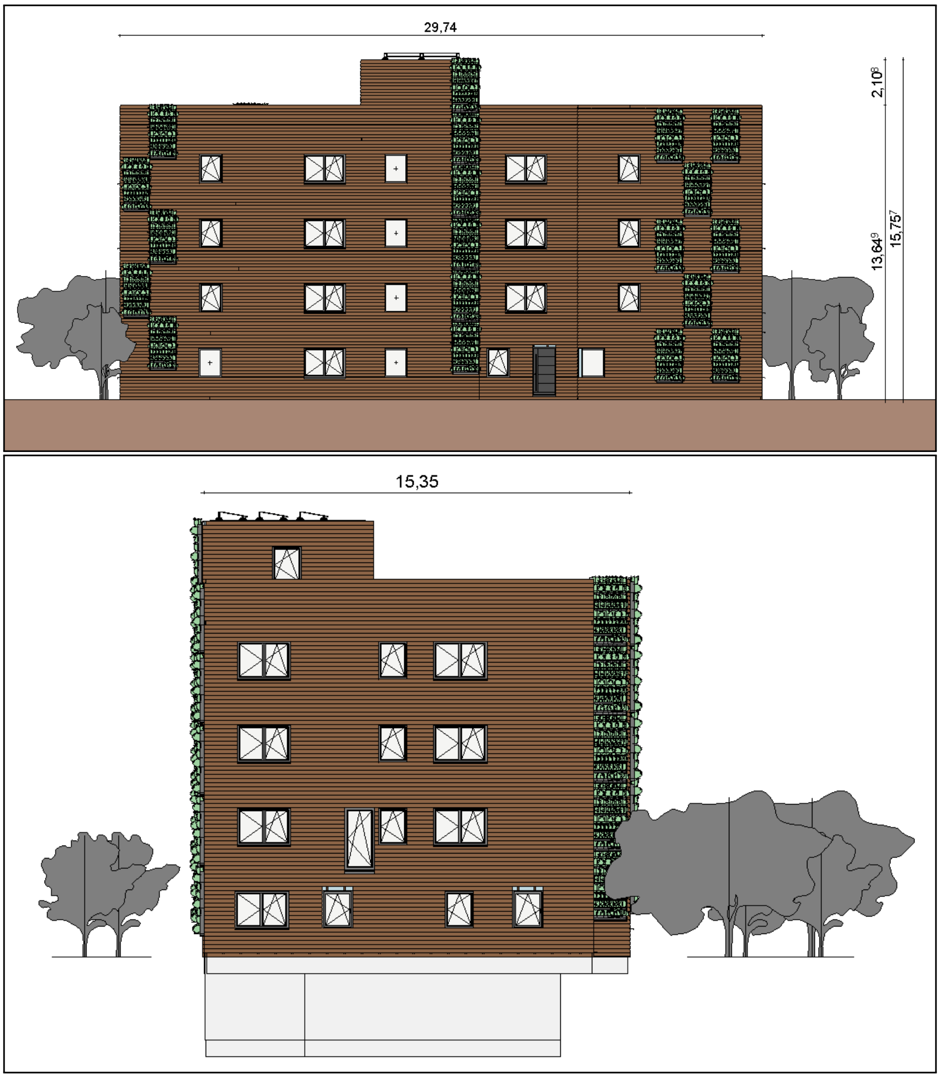

Figure 4.3: Side views of the practice-oriented building example (screenshot in *Revit*)

4.1.2 Structural design of the building

In order to meet sustainability requirements, the building should use as much material with a low environmental impact as possible. Therefore, wood as a biobased material is considered for the structural design. By now, there are numerous examples of tall buildings using wooden components for safe load transfer, such as the *Prinz-Eugen Park* (s. subsection 2.4.3). This development was made possible through the use of engineered wood products which are stronger than solid sawn material, enabling more application possibilities (Green et al. 2017, p. 27). For this building design, cross-laminated timber (CLT) is selected as the main building material for all components, except the foundation and basement walls. Here, reinforced concrete slabs are provided to ensure reliable load transfer into the ground and longtime protection against soil moisture. According to Schneider et al. (2016), the thickness of the floor slab is estimated roughly via the rule of thumb

$$d\,[\text{cm}] = \frac{H_{\text{building}}\,[\text{cm}]}{30} = \frac{1200\,\text{cm}}{30} = 40\,\text{cm}. \tag{4.1}$$

In accordance with the German guideline for water-impermeable concrete components, a thickness of 20 cm is assumed for the basement walls (DAfStb 2016, p. 11).

For the bracing and load transfer of the building, an adaptable and flexible floor plan is favorable. This can be accomplished by a combination of load-bearing components made from CLT including exterior walls, interior walls, columns and beams as presented in Figure 4.4. Along the longitudinal direction approximately in the middle of the building runs a load-bearing interior wall. Parallel to this wall two beams are placed in north and south direction with support of evenly distributed columns, so that a maximum ceiling span of 4 m is reached. These elements ensure longitudinal bracing. For cross bracing, three load-bearing walls are placed in transverse direction.

Since a detailed structural design of the system is not feasible within the scope of this thesis, the pre-dimensioning of the load-bearing components is carried out on the basis of available data from manufacturers. Examples for common components can be found, for instance, in a brochure by Derix (2022) or in a large database from Binderholz (2022b). On the basis of these information, a thickness of 100 mm five-layer CLT for the exterior and interior load-bearing walls is assumed.

For the ceilings a pre-dimensioning table by the manufacturer Binderholz (2022a). According to this, a maximum span of 4 m in a multi-storey building requires 140 mm of five-layer CLT. In order to take into account a higher stress on the roof, 160 mm five-layer CLT is assumes here.

Lastly, a U-shaped elevator shaft made from reinforced concrete is placed next to the staircase. Here, a wall thickness is of 20 cm is taken into account.

The final building component constructions are determined and presented after the assessment in subsection 4.2.2.

With the determined assumptions about dimensions and components the building is

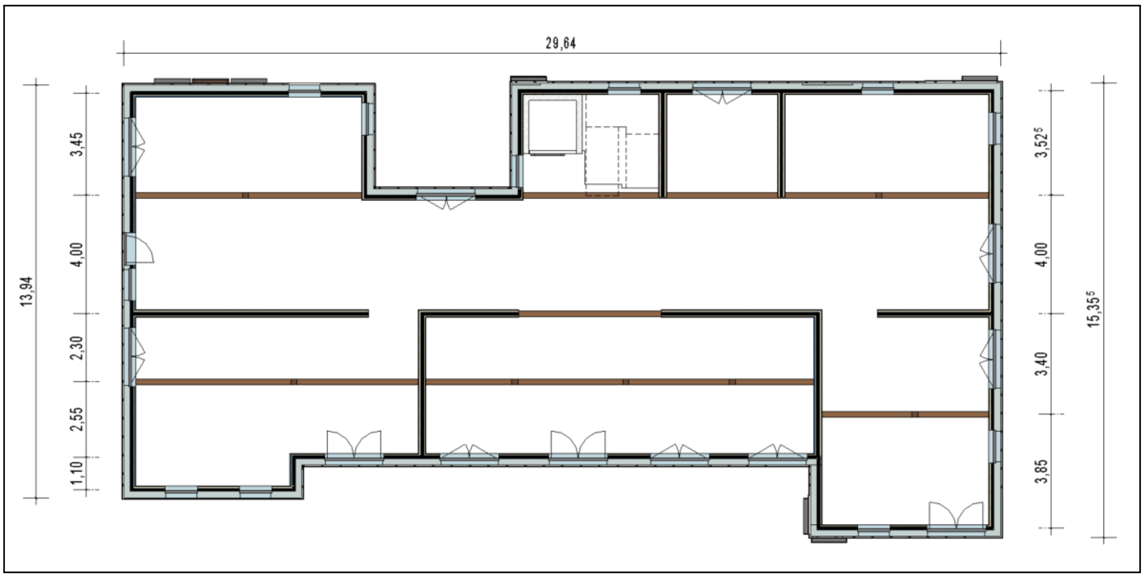

Figure 4.4: Plan view of load-bearing components for vertical and horizontal bracing on the first floor (screenshot in *Revit*)

modeled in *Revit* including all aforementioned load-bearing components and additionally non load-bearing elements such as interior walls, windows and doors.

4.2 Implementation of green building requirements

4.2.1 Operational energy

The first step in optimizing the building is the investigation of the use stage energy performance. This will give insight about how the building envelope can be optimized in terms of shape as well as structure and material choice of the components. The most important parameter is the operational primary energy derived from non-renewable sources. For the assessment, *CAALA* requires a gbXML export from the BIM model in *Revit* by calculating analytical surfaces via energy analysis. To retrieve this information, rooms are defined on each floor with different building components that have boundary properties. Depending on the property assigned to the room bounding component the software creates an analytical surface, e.g. exterior wall or window. Afterwards the gbXML file is exported and checked by an online tool viewer to detect any major issues in the export. In this case the tool *Ladybug* (2022) is used. Issues occurred mainly due to incorrect mapping of component connections, especially in the area of the staircase and the flat roof. Instead of one analytical surface for the ceiling on the fourth floor, top and bottom were falsely modeled, creating a large air gap. As this issue was due to different height definitions for ceilings and roof in *Revit*, the roof height was adjusted in a separate BIM model. Although this does not correspond to reality, a more correct energy model can be reproduced. A few other surfaces were misidentified, but were considered negligible compared to the size of the model. The final visualization of the gbXML file is presented in Figure 4.5.

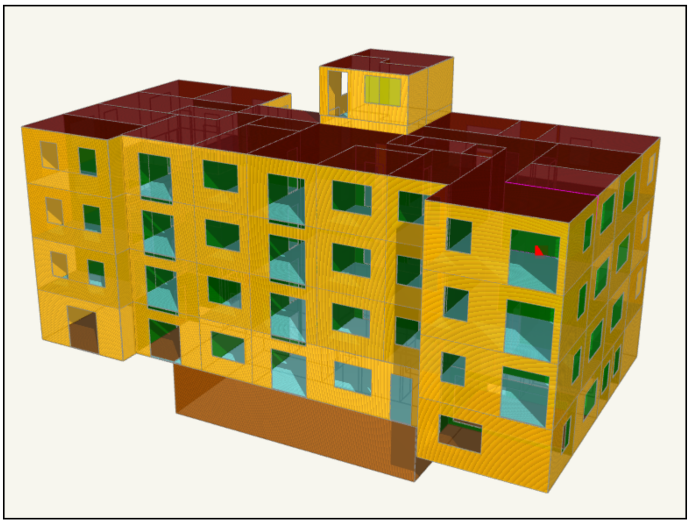

Figure 4.5: Visualization of the gbXML file (screenshot in *Ladybug*)

When major issues are resolved and the energy model is plausible, the gbXML file is imported to *CAALA* via their online platform accessible through web browser. Analytical surfaces are assigned to *CAALA* naming of building components. Every component category is listed and materials can then be selected respectively. This manual assignment proves to be a hindrance to the automation process. Any adjustments regarding material choice or thickness in the BIM model have to be reselected in *CAALA*. After the thicknesses of the load-bearing elements made from CLT and reinforced concrete are fed into the software, appropriate insulation materials are determined. To meet the preference for biobased products, wood fibre insulation is used for the exterior walls. Due to higher stress by soil moisture, extruded polystyrene (XPS) insulation is installed in the foundation and basement walls. As the flat roof is accessible and a material with high compressive strength is required, expanded polystyrene (EPS) is selected. The choice of these materials are also adapted to the available component structure of manufacturer Binderholz (2022a). Now, the thicknesses of insulation can be adjusted to improve the energy performance of the building. With each alteration, *CAALA* gives immediate feedback about total operational primary energy use as well as the final and useful energy for heating and hot water. The insulation thicknesses are increased until there is no significant value improvement, keeping in mind to minimize material use in favor of embodied energy. For the windows a heat-efficient design with triple glazing and wood framing is selected. It is assumed that the exterior doors have the same thermal properties as the windows. While optimizing the exterior components the upper limit for the thermal conductivity related to thickness (U-value) as defined in the German building energy legislation (GEG) (2020) is taken into account. The final component structures are presented in subsection 4.2.2. New material layers for exterior components, which were not considered so far, such as interior installation layers, are reuploaded to *CAALA*. As shown in Table 4.1, all U-values fall significantly below the upper limit.

Table 4.1: Thermal conductivity related to thickness of exterior components compared with GEG reference values (own table)

Exterior Component	**U-value** W/(m^2 K)	**U-value,ref GEG** W/(m^2 K)	**Evaluation**
Foundation	0,188	$\leq 0,35$	✓
Basement walls	0,190	$\leq 0,35$	✓
Exterior walls	0,110	$\leq 0,28$	✓
Roof	0,108	$\leq 0,2$	✓
Windows and doors	0,9	$\leq 1,3$	✓

After all exterior components are determined, the surface-area-to-volume ratio is lowered to optimize energy efficiency. This is achieved by adjusting the building shape to a more rectangular form.

In the next step, *CAALA* is used to determine a suitable energy system. A heat pump using groundwater is found to give best results in primary energy use for space heating and hot water. Heat distribution is carried out in all rooms by underfloor heating. Additionally a mechanical ventilation with heat recovery is installed. Taking into account these demands and the prior optimizations, an operational primary energy use of 19 kW h/(m^2 yr) is calculated in *CAALA*. As shown in Figure 4.6, this value is significantly lower than the energy efficiency requirement of the German *KfW 40* building standard (s. subsection 2.4.4). The optimization of operational energy demand for heating and hot water is therefore complete.

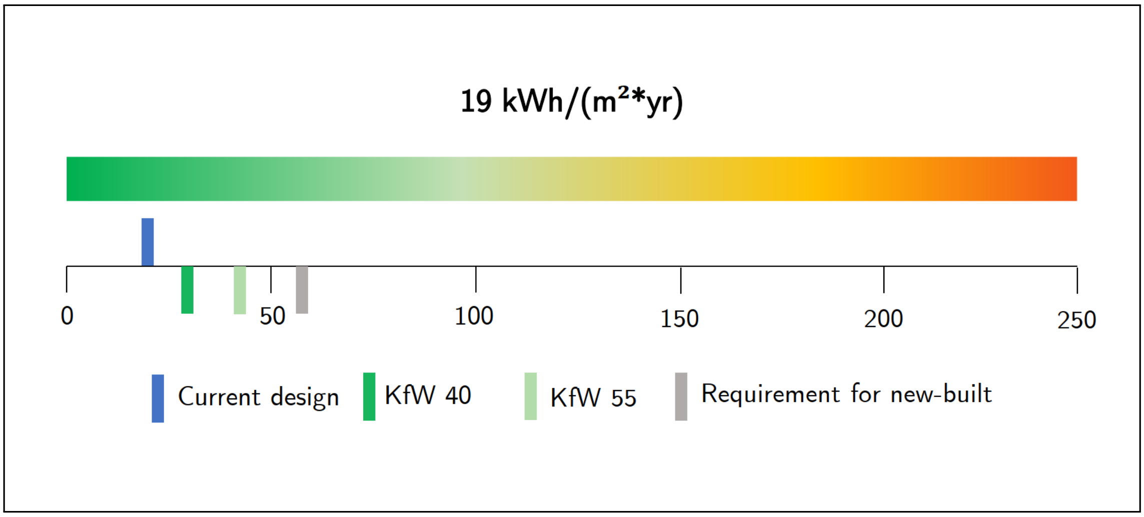

Figure 4.6: Non-renewable operational primary energy result from *CAALA* (own figure)

Apart from investigating the building performance, attention is also given to designing the building appropriate to the number of occupants by limiting the floor area per person (s. subsubsection 4.4). As larger buildings require more energy to heat (Viggers et al. 2017,

p. 256), avoiding excess space is beneficial for saving energy. It is worth noting that the operational primary energy value—in accordance with the *GEG* calculation—is expressed per square meter, entirely leaving out the dependency of consumption rates due to building size and consumers. The interpretation of *Level(s)*, however, takes this into account by calculating all yearly energy demands based on the consumption rates.

Although the design can already be regarded as energy efficient, user electricity should also be taken into account in addition to the *GEG* requirements. According to Fisch et al. (2018, p. 83) buildings, that have a high thermal energy performance, user electricity can make up to 50 % of the total energy demand. Considering that electric devices play an important role in human personal and work life nowadays, a more holistic assessment approach is favorable for this example.

In the residential part of the building user electricity includes household and communication equipment as well as lighting. Assuming that all devices have the highest efficiency class, a consumption of 20 kW h/m^2 in relation to the living space can be estimated in the planning phase (Fisch et al. 2018, p. 84). Since the ground floor is mixed-used, a consumption estimate of 30 kW h/m^2 for offices is assumed and implies using energy efficient equipment (ASEW 2013).

For producing renewable energy on site, a photovoltaic (PV) system is installed on the flat roof with a total area of 140 m^2 and an output of 19,354 kWh/yr. By means of an electricity storage system, a use rate of 80 % is targeted. The remaining electricity produced is fed into the local power grid.

Table 4.2: Building services and their respective energy calculations based on Level(s) (own table)

Building service	**Energy need** kWh/yr	**Energy carrier** -	**Delivered energy** kWh/yr	**Non-renewable primary energy** decimal factor	kWh/yr
Heating	50,691	Electricity	12,237	1.8	22,024
Hot water	15,732	Electricity	8,740	1.8	9,437
User electricity (total)	15,483	PV panels	15,483	0	0
User electricity (total)	14,107	Electricity	14,107	1.8	25,392
Exported renewable energy	n/a	PV panels	-3,8718	0	0
Total	96,012	-	46,695	-	**56,855**

In Table 4.2 the energy need, the delivered energy as well as the non renewable primary energy of building services depending on the energy carrier are presented. Values for heating and hot water are retrieved from *CAALA*. For the calculation it is assumed that the power generated from the PV system is used to cover user electricity. As the demand exceeds the amount of PV electricity, the remaining difference is compensated from the local power grid. Finally, the total primary energy of all building services is calculated by considering primary energy factors to 56,855 kWH/yr.

In Figure 4.7 the distribution of primary energy depending on the building service is presented. Although the generated electricity from the PV panels is already deducted, user electricity holds with 45 % the largest share. This is even higher than the primary energy required for heating, which is at 39 %. Hot water has the smallest share with 16 %. Despite not being part of the *GEG* regulation, this calculation shows that it is important to take into account user electricity. By doing so, more realistic and representative results can be obtained for operational energy and eventually for LCA.

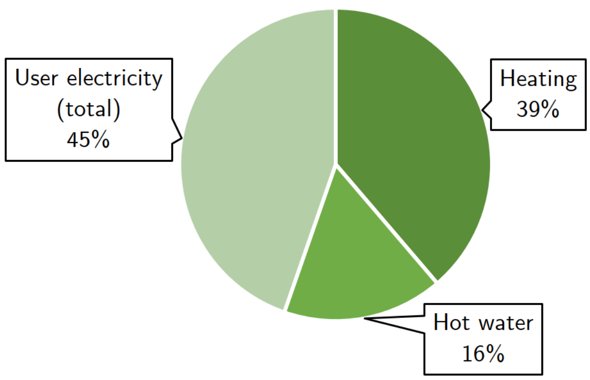

Figure 4.7: Non-renewable primary energy results of building services from *CAALA* (own figure)

4.2.2 LCA of the building

Investigating the global warming potential of a building, specific focus lies on the embodied energy and carbon resembled by used materials. To minimize the environmental impact of greenhouse gases emitted throughout the building life cycle, the first step is to implement measures to achieve optimum material efficiency. The previously determined compact rectangular building shape for thermal energy savings as well as designing space size appropriate to the number of occupants lead to efficient space utilization and thus material efficiency. In this context, the use of CLT also shows further benefits. The components are prefabricated with precise measures adjusted to the building allowing more efficient material use through waste reduction especially on the construction site.

In the next step, material data and quantities need to be gathered to calculate global warming potential. Therefore all building elements and details are modeled in *Revit*. Environmentally friendly materials with a focus on low carbon print are chosen whenever possible. The following description refers to the final structures of each component after all optimization steps.

First of all, the structure of load-bearing components is determined and added to the BIM model. Regarding the foundation and basement walls made from reinforced concrete, sealing sheet and XPS insulation are added to the exterior side. As the basement will only be used for storage and technical equipment, there are no further requirements for wall or floor finishes.

As previously mentioned, the thicknesses and structure of the other CLT elements are selected from the database by manufacturer Binderholz (2022a) to comply with standards on the market, so that the quantities are in a plausible scale, saving material. The exterior walls have a wood fiber insulation layer and as a facade timber cladding with counter battening. On the interior side, there is an installation layer made from mineral wool and a gypsum board finish. This layer allows the placement of all necessary ducts for electricity, heating, ventilation and water supply. The interior load-bearing walls are enclosed by the aforementioned installation layer which also serve as sound insulation (s. subsubsection 4.4).

On top of the upper floors trickle protection, expanded clay fill, impact insulation and screed with underfloor heating are added. As a finish ceramic tiles are selected for the bathrooms and parquet for all other rooms are selected. On the bottom side of the floor an installation layer with gypsum board is attached.

The basic structure of the flat roof consists of a sealing sheet, EPS insulation and a plastic roofing membrane additionally to the CLT slab. On top of that an intensive green roof based on the design from the manufacturer Paul Bauder (2022) with a separation layer, root protection sheet, drainage and water storage element, a filter layer, soil substrate and plants. Analogue to the upper floors, on the bottom side an installation layer is attached.

Next, the non load-bearing interior partition walls are designed. For this, 90 mm CLT is used. Installation layers are added from both sides to walls with higher requirements of sound insulation (e.g. separation between housing units) or where ducts will be necessary in use (e.g. bathroom). All other non load-bearing walls are finished with just a gypsum board layer. The placement of these partition walls including doors is based on the outcomes of the sections regarding living space and common areas (s. section 4.4). The structure of the main building components is presented in Figure 4.8.

Other structures that are added for a more detailed and accurate design are the U-shaped wooden stairs, wood framed windows, wooden doors and a parapet wall. The latter ensures height protection on the accessible green roof and is modeled by extending the wood fibre insulation and timber cladding of the exterior wall.

After all materials are determined and the structures added to the BIM-model, the LCA for calculating GWP based on the CO_2 emissions can be performed. The life cycle stages that are automatically computed by *One Click LCA* include production (A1-3) and transportation to site (A4), maintenance and replacement of material (B1-5), end of life (C1-4) and additionally benefits beyond the system boundary (D). For maintenance and material replacement (B1-5) lifespan defaults depending component function set by *Level(s)* are considered. Furthermore, operational energy (B6) regarding electricity demand from local

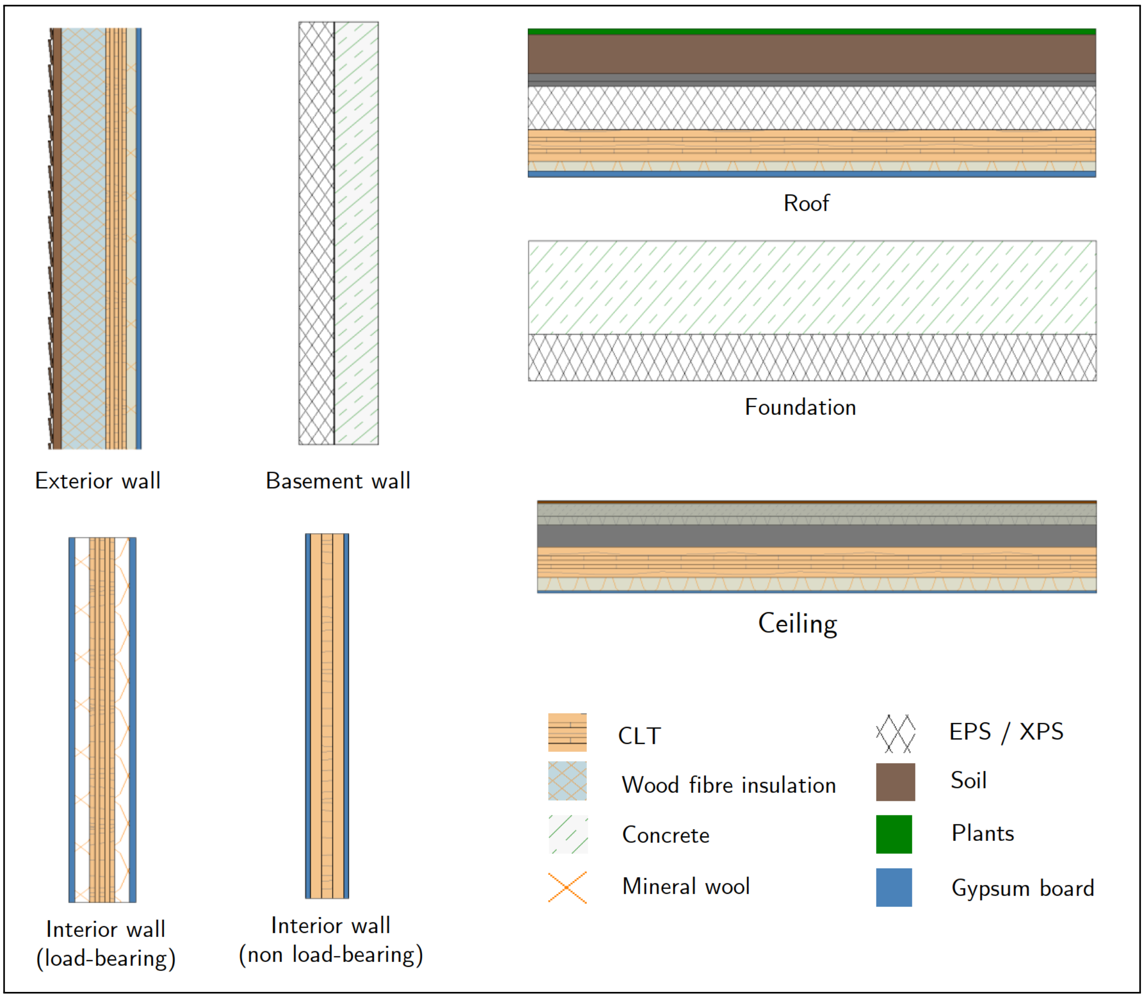

Figure 4.8: Structure of exterior and interior building components (own figure)

power grid is added on the basis of the calculations in the previous section. The calculation period is set to 50 years.

Using the *Revit* plug-in, all relevant LCA data of materials and their quantities are directly imported to the *One Click LCA* cloud. Unlike the *CAALA* tool, which requires a separate gbXML export and import, this procedure allows more automation and accurate material take offs as they exactly resemble the amount that are modeled. Adjusting mistakes or adding elements to the BIM model can be mirrored more effortlessly into the LCA tool. After the data is imported to the cloud, all materials with BIM nomenclature have to be assigned to materials from available LCA databases. As the building is located in Hamburg, only materials suitable for German location are being considered. EPDs used are retrieved from databases such as *Ökobau.dat*, *IBU*, manufacturers or *One Click LCA*. In this assessment, the elements from the shell structure, the above described finishes as well as doors and windows are included in the LCA scope. The life cycle impact of utilities such as sanitary systems, kitchen equipment, ducts, lights, furniture etc are not investigated. Regarding concrete elements, the reinforcement steel is not in the BIM model. Therefore the volume of these elements are retrieved from BOM in *Revit* and manually inserted to the LCA tool considering a 2 % share of reinforcement steel.

During the process of connecting BIM data to the LCA tool, several issues were identified. When mapping out all materials, some are automatically assigned based on the internal BIM naming. Nonetheless, all materials have to be reevaluated and if necessary reselected, which makes this part of the procedure very manual and therefore prone to potential user errors. In this step, clear and uniform naming of materials and components is important for correct and precise allocation, speeding up the evaluation process. However, even under these conditions, depending on the size and the LOD of the model, mapping is a time-consuming process. On top of that, BIM objects which are downloaded from an open source or manufacturer databases, do not always contain required LCA relevant information. Issues appear when the name of an element and its material cannot be determined with certainty, especially if the BIM object contains data in a language foreign to the user. This shows the requirement for more LCA specific standardization. Another issue was the inability of the plug-in to import the timber cladding of the exterior wall to the cloud which was inserted manually.

After the mapping of all materials is complete and operational energy values are inserted, results can be calculated.

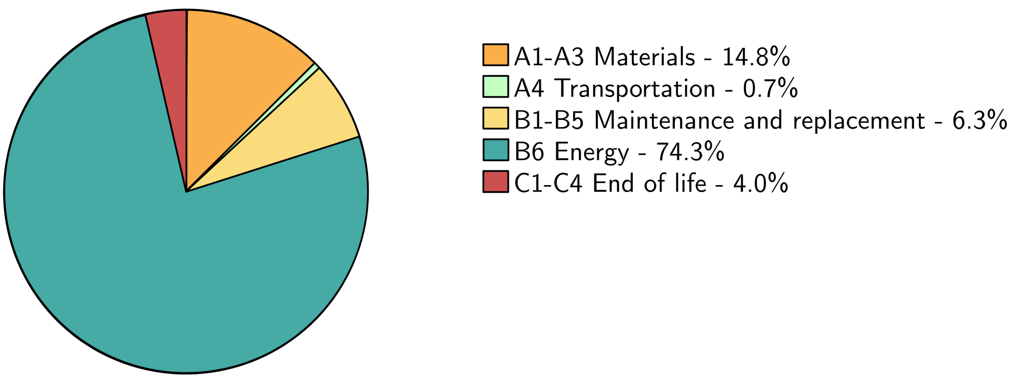

Figure 4.9: Global warming CO_2 of life cycle stages from *One Click LCA* (own figure)

Regarding global warming potential, the most CO_2 equivalent emitted by far is through operational energy, which is about 77 %, as shown in Figure 4.9. This result could lead to the assumption that the thermal performance of the building is not sufficient, although it already has been optimized in the previous section. The explanation for this outcome lies in the fact that from early design considerations materials with known low greenhouse gas emissions were used such as wood, lowering the embodied carbon. This is also reflected in the tool's own *Carbon hero benchmark* result, which sets the CO_2 calculation in a cradle-to-grave scope without operational energy in relation with a benchmarking system based on Western Europe apartment designs. According to this rating, the design reaches the highest classification and even falls far below the limit value (s. Figure 4.10). In contrast

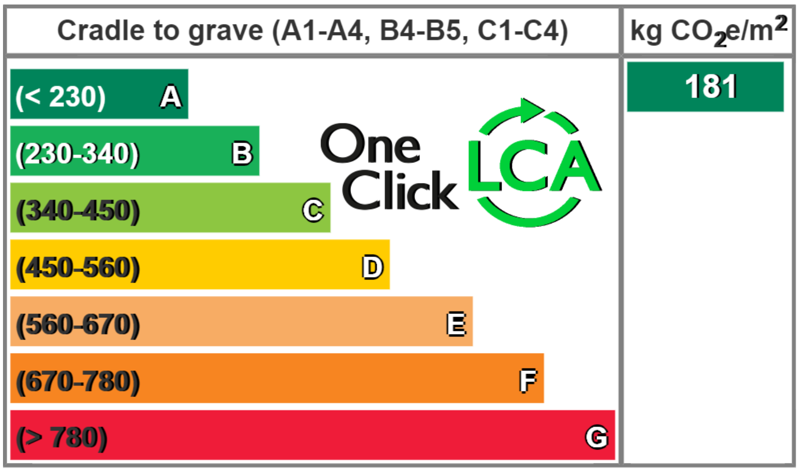

Figure 4.10: Global warming CO_2 of life cycle stages (screenshot in *One Click LCA*)

to the criticism in subsection 2.4.4 of modern energy-efficient buildings with large share of embodied carbon, both indicators were simultaneously taken into account in this design and respectively optimized. In this case the large share of operational energy can therefore be interpreted as environmentally beneficial.

Investigating the choice of material, concrete contributes most to global warming potential in the production stage, even though CLT is most dominant in the design. It is worth mentioning, that CLT additionally serves as biogenic carbon storage, which is calculated in a separate category. All of this indicates the lower impact of CLT and confirms its suitability for creating green buildings.

In Table 4.3 the quantitative results of all impact categories depending on the life cycle stage are presented.

Table 4.3: LCA results of investigated environmental indicators depending on life cycle stage (own table)

Life cycle stage	**GWP** kg CO2eq	**AP** kg SO2eq	**EP** kg PO4eq	**ODP** kg CFC11eq	**POCP** kg Etheneeq
A1-A3	1.81E+05	6.59E+02	1.22E+02	5.51E-03	9.05E+01
A4	8.25E+03	2.66E+01	5.73E+00	1.52E-03	8.10E-01
B1-B5	7.63E+04	2.69E+02	4.71E+01	9.09E-04	5.42E+01
B6	9.1E+05	6.9E+03	1.6E+03	2.7E-02	2.4E+02
C1-C4	4.87E+04	5.82E+01	1.26E+01	4.19E-05	4.90E+00
D	-3.09E+05	-1.05E+03	-2.33E+02	-3.45E-03	-4.92E+01
Total (D excluded)	**1.22E+06**	**7.86E+03**	**1.80E+03**	**3.53E-01**	**3.92E+02**

Comparison with conventional building components

As *Level(s)* does not provide any benchmarks, the design is compared to a version that uses predominantly conventional non-biobased materials. The previously created BIM model is used and adjusted, replacing CLT, wood and wood fiber insulation elements. The exterior and interior walls are made from sand lime stone while using mineral wool for insulation. The roof and the ceilings are replaced with reinforced concrete. The columns are exchanged to reinforced concrete and HEB profile beams are placed on top. Furthermore, aluminum framed windows with triple glazing are used. Foundation, basement walls, facade as well as the dimensions of all elements and layers remain unchanged.

First of all, the new components are inserted in *CAALA*. As the building surface area remains the same, the previous gbXML export file can be used. To ensure comparability the insulation thicknesses of the exterior walls and the roof have to be adjusted until the building components reach the same U-value as the prior design. By this, the same operational primary energy use is achieved so that the environmental impact of all other life cycle stages are comparable. Exterior wall insulation remains the same whereas roof insulation is raised from 22 cm to 26 cm. All altered components are then adjusted in the BIM model and imported to the *One Click LCA cloud*.

After mapping out all materials the same values for operational energy (B6) are added to the LCA to finally obtain the results presented in Table 4.4 and Figure 4.11. GWP, as the most relevant indicator in this assessment, is increased by 19 %. This result is mostly caused by emissions during the production stage (A1-A3), which are 123 % higher than the building with predominantly biobased materials, showing clearly the benefit of designing with a large share of wood components. The same trend is observed for the indicators AP, EP, ODP and POCP with values increased between 1 % and 5 %. Furthermore, it should be noted that in the comparison the dimensions of building components were not altered, even though their correct structural would require larger thicknesses. For instance, according to the manufacturer KS (2022), the minimum thickness for load-bearing sand limestone is 11,5 cm which is larger than the dimension used in this design. Therefore, it is probable that material quantities in a more realistic structural analysis are larger than the assumptions in this example, resulting in even higher indicator values. Nevertheless, the comparison clearly indicates that, although both building design options presented have the exact same operational energy performance, the structure with focus on wood material has a much lower environmental impact than the conventional one. This once more, shows the importance of considering LCA for a more insightful assessment of green buildings.

Table 4.4: LCA results of conventional design compared to optimized design with biobased materials (own table)

Life cycle stage	**GWP** kg CO2eq	%	**AP** kg SO2eq	%	**EP** kg PO4eq	%	**ODP** kg CFC11eq	%	**POCP** kg Etheneeq	%
A1-A3	4.0E+05	+123	1.0E+03	+56	2.2E+02	+80	6.4E-03	+15	1.2E+02	+30
A4	9.4E+03	+13	3.2E+01	+19	6.8E+00	+19	1.7E-03	+14	8.8E-01	+8
B1-B5	1.1E+05	+45	2.7E+02	+1	4.4E+01	-8	5.5E-05	-94	5.1E+01	-6
B6	9.1E+05	0	6.9E+03	0	1.6E+03	0	2.7E-02	0	2.4E+02	0
C1-C4	2.1E+04	-57	2.2E+01	-62	4.6E+00	-64	1.0E-04	+151	1.8E+00	-63
D	-1.6E+05	-47	-1.1E+03	+1	-2.5E+02	+6	-5.9E-03	+70	-5.6E+01	+13
Total (D excluded)	**1.5E+06**	**+19**	**8.2E+03**	**+4**	**1.9E+03**	**+5**	**3.6E-02**	**+1**	**4.1E+02**	**+5**

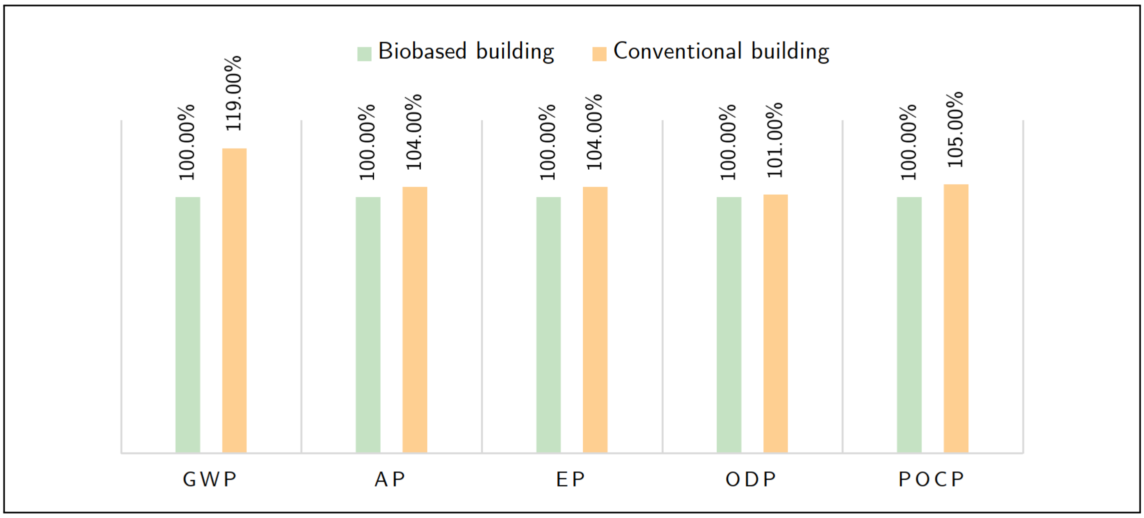

Figure 4.11: Total LCA results of conventional design compared to optimized design with biobased materials (own figure)

4.2.3 Other green building requirements

In the following other requirements and measures in order to design a green building are presented.

Design for adaptability and renovation

The structural design of the building incorporates the use of columns and beams for a more adaptability and flexibility in renovation. With only a few load-bearing internal walls (s. Figure 4.4) partition walls can be placed suitable for user requirements, allowing more internal space configurations. If throughout the building life the wall layout is to be altered, the non load-bearing walls can be removed. As for the necessary ducts, the height between floors of 3 m is sufficient to ensure an installation layer for more flexibility in routing of services. The main service equipment cannot be relocated as easily and can therefore be placed in the basement.

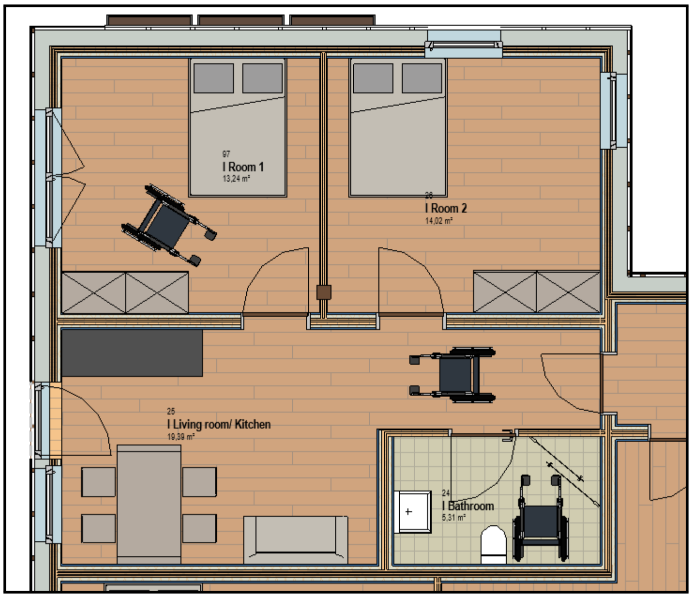

Figure 4.12: Wheelchair accessibility in apartments (screenshot in *Revit*)

Another important aspect is the adaptability of access requirements for any person with mobility restrictions. Firstly, the building is equipped with an elevator to easily reach all floors of the building. Doors and corridors have a width of 90 cm or at least 1.50 m respectively, to ensure easy wheelchair mobility. Same applies to the bathroom sizes in all apartments, which provide sufficient and effective space utilization thanks to movable shower doors. In Figure 4.12 one of the apartments is presented with exemplary placements of wheelchairs. The other units are built analogously. Regarding the ground floor, one accessible restroom is integrated into the floor plan.

Operational water consumption

In order to incorporate a suitable water system, it is important to investigate possible water scarcity of the location. The building is in the river basin Elbe with a summer water exploitation index (WEI+) of 1.99 % (<20 %) (EEA 2018). According to the *Level(s) Excel* tool, this region is ranked place 66 out of 105 European river basins regarding water scarcity. Therefore, the availability of water is not a dominant issue for this region. As water consumption plays a significant role for both the environment and occupant costs, measures for reduction still have to be implemented.

First of all, equipment with water saving properties is used. The toilets have dual buttons (6 l and 3 l flush) to adjust consumption according to needs. The taps in the bathroom and kitchen have low flow rates of 3.5 l/min and 10 l/min respectively, while the shower heads are assumed to have 6 l/min.

Then, the grey water from bathroom wash basins and showers is reused by integrating a treatment system which can be placed in the basement. The filtered water is collected in a tank and eventually distributed to the toilets and washing machines. By these measures, the demand as well as the amount of water supplied to public wastewater treatment plants can be reduced. In Figure 4.13 the principle of the system is presented.

As for vegetated areas, the green roof with an area of about 350 m^2 and a backyard area are covered with lawn, which demand irrigation, especially during hot and dry seasons. Furthermore, a communal garden area for vegetables and fruits is optional. Drip irrigation will be installed for the lawns, while the communal garden can be watered manually.

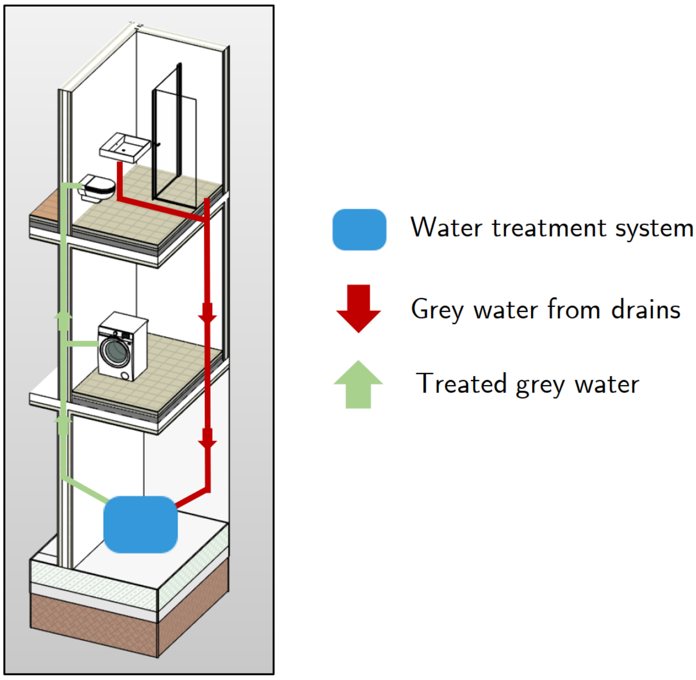

Figure 4.13: Grey water treatment system with water from wash basins and showers for toilets and washing machines (own figure)

4.3 Implementation of climate change related requirements

Protection of occupier health and thermal comfort

To face future menace of climate change threatening occupier integrity and well-being, measures to make the building more adaptable and resilient to potential environmental changes are to be taken.

According to Schlünzen et al. (2018), Hamburg—as a metropolitan city—has an increased risk of overheating in summer additionally to the global temperature rise due to the heat island effect. To ensure thermal comfort, the building envelope has high insulation levels and shading by roll-down shutters are installed for all windows. A way to buffer high temperatures in the surrounding area is the implementation of green spaces to reduce sealed surfaces. In this design a green roof, a backyard as well as vertical greening elements in the facade are incorporated as shown in Figure 4.14. Not only are these measures beneficial for mitigating heat island effect, but also serve as spaces for recreation to boost mental health and favor visual comfort (Douglas et al. 2021).

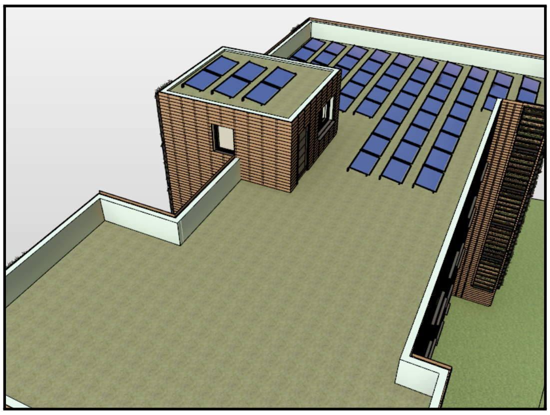
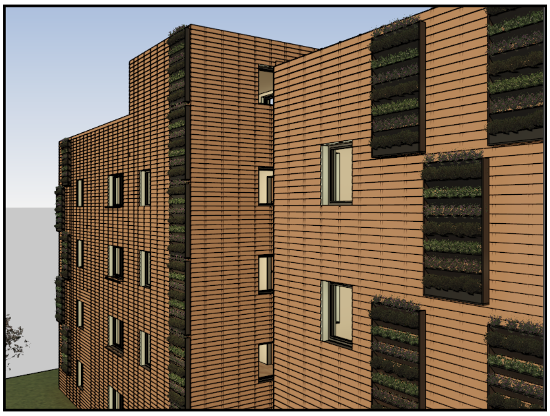

Figure 4.14: Accessible green roof with PV panels and green wall elements on the north side of the building (screenshots in *Revit*)

Extreme weather events

The German government has prompted the *Deutschen Anpassungsstrategie an den Klimawandel (DAS)*, an adaptation strategy plan in which potential vulnerabilities to climate change and mitigation measures to be aimed for are presented.

The released document by BMU (2020b) states the observation in recent years of temperatures above average, droughts and extreme weather events such as storms and heavy rains causing significant damage to buildings. Due to the expected increased occurrence of heat waves, measures to keep indoor temperature at comfort level are a top priority for dwellings. This has been discussed in the previous section.

Regarding urban areas with mostly sealed surfaces, damages by high precipitation and storm have increased significantly (BMU 2020b, p. 13). Here measures of creating permeable surfaces and retention areas are discussed in the following section.

As a countermeasure to the increasing occurrence of storms, soft adaptability actions are also considered. This mainly concerns measures that allow residents staying indoors within the protection of the house. For instance, those with the ability to work from home can use the coworking space while students can follow online lessons from the library.

Increased risk of flood events

Studying the floor risk maps of Hamburg (LGV 2019), the location of the building is not in a warning area for high exposure. However, it should be taken into account that the nearest water body is the Osterbekkanal within 1 km distance, then the tributary Alster (3,5 km) and the river Elbe (6 km). To counteract potential future flood events and high precipitation, natural drainage is achieved by avoiding impervious surfaces. The soil layer of the green roof and backyard garden serve as a water catchment while the vegetation absorbs water. The surroundings of the building will include porous pavement to allow water infiltrating the ground effortlessly. To further enhance the ability to adapt to high amounts of water, a storm water retention pond is placed in a part of the backyard (s. Figure 4.15). With these measures the risk of damage is mitigated.

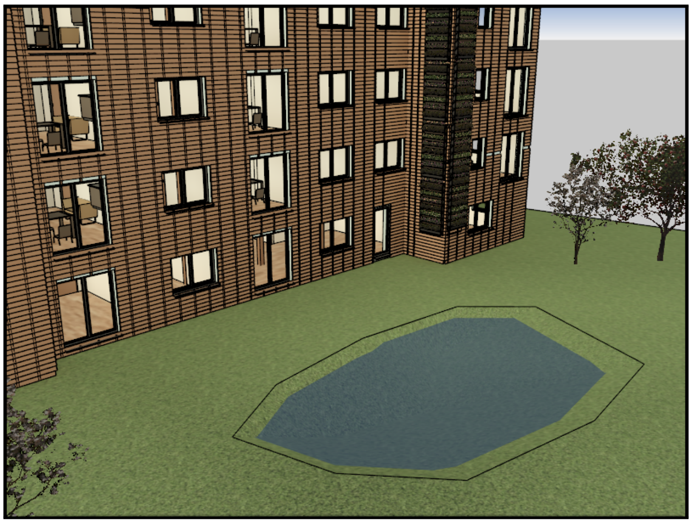

Figure 4.15: Storm water retention pond in the backyard of the building (screenshot in *Revit*)

4.4 Implementation of social building requirements

Indoor air quality

The requirements for indoor air quality is depending on the vulnerability of the residing group of people and the amount of time that is expected to be spent in certain areas. Regarding the apartments, occupants will spend a considerable share of their day here. Although, the mixed-use floor will not be occupied at all times of the day, it has to be kept in mind that the concept of the building is based on a design for all people, regardless of special needs, age, disability etc. Therefore a high expectation of good air quality is assumed for the entire building. For the finishes as well as fit-outs only materials are considered, which have low emissions of indoor pollutants (e.g. VOCs) and provide certification accordingly.

Due to the local oceanic climate, inadequate room temperatures and humidity during winter season increase the risk of indoor mold growth, harming occupants' health. The thermal performance of the building envelope in combination with the heating and ventilation system prevent the formation of such.

Another possible contamination source is the proximity of a busy main street, entering the building by inflow of outside air through manual window ventilation. As the exposure in the residential parts is expected to be higher, none of the apartments are located on the ground floor. Additionally, the mechanical ventilation system allows controlled fresh air supply by filtering outdoor pollutants before they enter the building.

Time outside of thermal comfort range

The measures elaborated in subsection 4.2.1 regarding thermal envelope, heating and ventilation systems with heat recovery ensure adequate room temperatures during winter. Additionally, a high percentage of windows are placed on the southern side, benefiting internal heat gains and reducing energy consumption. During the night, when outdoor temperature drops, closed roll-down shutters can be used to further improve the thermal performance.

On the other side, during summer, high insulation levels ensure less heat up. Here, in turn, the large window area on the south side is disadvantageous. To prevent overheating, roll-down shutters can be used as shade.

Lighting and visual comfort

The design takes into account the integration of sufficient light in the rooms to ensure the human health and well-being. Particular attention is focused on ensuring inflow of natural sunlight through large window areas. Due to the location in an urban area, the adjacent multi-level buildings are in close proximity, possibly compromising direct sunlight. To counteract this, windows are placed preferably in southern direction, while only few are oriented towards north. As the ground floor naturally receives less light, placing apartments here is unfavorable. Instead they are on the upper floors. Additional benefits relate to occupants' security feeling. Windows on the upper floor are not easily accessible from the outside and are not at the eye level of pedestrians creating more privacy. Inside the apartments, most open living rooms and kitchens are oriented towards the south to have sufficient sunlight in the common areas.

Then, for energy efficient electric lighting LED modules are used in all rooms. To adjust electric lighting to personal needs, dimmers are installed.

Regarding visual comfort of the building appearance, the wooden facade and the green wall elements contribute to a more natural environment. By this, stress of occupants can be reduced and health and well-being improved (Ling et al. 2018).

Acoustics and protection against noise

Proper sound protection for dwellings is of great importance to ensure mental health of occupants and their ability to feel comfortable within their own homes. Especially in apartment buildings with many adjacent units, but also in busy urban areas, this indicator can become critical. For the assessment of this design, the national German guideline DIN DIN 4109-1:2018-01 (2018) is taken into account for verifying minimum sound and impact insulation properties compliant with the norm. The specific values for critical components are retrieved by manufacturer's data of the selected components.

First of all, the building is in close proximity of the busy *Steilshooperstraße* and *Habichtstraße*, both causing a potentially high airborne sound exposure. The value for external noise level L_a is estimated at 65 dB. The correction factor K_A for living spaces and offices are 30 dB and 35 dB respectively. As the exterior walls are the same for all floors, the more critical value of 30 dB is applied. Finally the required sound reduction index $R'_{w,req}$ is calculated by

$$R'_{\mathrm{w,req}}\,[\mathrm{dB}] = L_{\mathrm{a}}\,[\mathrm{dB}] - K_{\mathrm{A}}\,[\mathrm{dB}] = 65\,\mathrm{dB} - 30\,\mathrm{dB} = 35\,\mathrm{dB} > 30\,\mathrm{dB}. \tag{4.2}$$

As shown in Table 4.5 the requirements against external noise are met.

Table 4.5: Protection verification against exterior noise (own table)

Building component	**R'$_w$** dB	**R'$_{w,req}$** dB	**Evaluation**
Roof (without substrate)	43	≥ 35	✓
Exterior walls	59	≥ 35	✓
Windows and doors (triple glazing)	35	≥ 35	✓

Inside the building protection against interior sound and impact must also be ensured. This mainly affects walls and upper floors between apartments or work units on the ground floor. Interior walls separating apartments contain mineral insulation and gypsum board on both sides, while ceilings have an impact insulation layer of 40 mm. Table 4.6 shows the existing and required values for sound reduction index R'_w and impact sound level $L'_{n,w}$. The values for upper floors do not include the flooring layer. In all cases the requirements are clearly met.

Table 4.6: Protection verification against interior sound and impact (own table)

Building component	**R'$_w$** dB	**R'$_{w,req}$** dB	**Evaluation**	**L'$_{n,w}$** dB	**L'$_{n,w,req}$** dB	**Evaluation**
Interior walls between apartments and working units	69	≥ 53	✓	-	-	-
Ceilings between apartments and working units	77	≥ 54	✓	40	≤ 50	✓
Ceilings above basements	77	≥ 52	✓	40	≤ 50	✓

It is worth mentioning that especially in solid wood structures, soundproofing can be a challenge if not done properly (Teibinger et al. 2018, pp. 35-36). Particular care and attention is required especially in the design of connections between different components to reduce flanking sound transmission. Therefore, the interior walls are supported on elastic intermediate layers to decouple them from the ceiling.

In addition to the structural measures for interior noise protection, rooms on the ground floor, that are expected to have opposing sound levels, are placed as distant as possible. As the coworking space and the library on the ground floor require more quietness, these rooms are adjacent and oriented towards the backyard. Noise is also expected from HVAC building equipment, which is placed in a technical room as far as possible from the apartments in the basement. Washing machines are on the ground floor and are surrounded by well insulated interior walls.

Finally, it should be added, that construction site activities can also make an enormous contribution to noise pollution due to the use of heavy equipment and the time it takes to erect a building. Although not related to occupants of the future residence, these activities effect the neighborhood and their well-being. In this context, using prefabricated CLT enables high speed construction and ultimately leads to less disturbance and noise exposure for the entire vicinity.

Life cycle costs

The life cycle costs in this assessment are strongly connected to costs related to operational energy and water consumption as well as the amount of materials used for construction and maintenance. Regarding the latter, optimizations were carried out for a lean design. At this point, it should be mentioned that a more detailed structural analysis could be performed to further reduce material use, but is not feasible within the scope of this thesis. However, it is ensured that all components have realistic dimensions by using available information from common manufacturers. During construction the use for CLT also leads to cost reduction due to its prefabrication and high speed assembly.

Most relevant for occupants is operational consumption. The rectangular shape of the building allows an optimal volume-envelope ratio for saving construction material and achieving a high thermal performance in combination with appropriately selected insulation thicknesses. Furthermore, the building's long side is oriented in north and south direction for natural heat gains in winter. Through these measures, costs for heating can be significantly reduced, preventing *energy poverty* (s. subsection 2.1.2). During summer the high thermal insulation helps to keep the building at comfortable temperature level, so that cooling system is not intended, saving these potential costs. Regarding water consumption, the demand is lowered by the separation and reuse of grey water for toilets and the use of devices with lower flow rates.

Mitigation measures for potential building damage associated with climate change will also allow for reduced costs. The design of the surroundings with permeable surfaces and the installation of a storm water retention pond protect the building from high water load and therefore lower maintenance demand.

Living space

As described in subsection 2.1.2, sufficient space is crucial for living in dignity and therefore indirectly a human right. Meanwhile finite land availability in urban areas and environmental impact of increasing living space consumption in Germany pose the need for an upper limit. The challenge in design is then to consider and balance both conflicting requirements.

Looking into legislation, in 2000, the City of Hamburg released the act for *minimum requirements for adequate housing* (2000), which determined a minimum floor area and number of rooms depending on the amount of household members in order to secure adequate housing . These requirements are to be executed in this design. Regarding the upper limit for living space per person, the modern housing concept *Kalkbreite* in subsection 2.4.3 is taken into account with 33 m^2.

To use the available space as efficient as possible, larger household sizes are considered. Per residential floor there are four different apartments containing separate room numbers between two and four. The smallest separate room size is 12 m^2. In each unit an open kitchen and living room is placed which counts as one room. To ensure that no space is wasted, the degree of occupancy has to be sufficient. Therefore the rule prevails that the number of residents per unit must at least be consistent with the number of separate rooms. In practice, this would have to be contractually agreed with the respective tenants. With three identical floors of residential use the total number of occupants for the building is 33. As the apartments are designed towards small and efficient space consumption, storage compartments are provided in the basement. Lastly, all units have at least one bathroom. In Figure 4.16 the floor plan of a residential floor with four different units marked in color are presented.

Figure 4.16: Floor plan of residential floors (screenshot in *Revit*)

In Table 4.7 the respective floor area of each apartment and number of separate rooms are compared with the legislation requirements. It becomes evident that the minimum values are respected. If only counting in the apartment areas, the total floor area is 1060 m^2 with living space per person at 32 m^2. This result corresponds to the value of the *Kalkbreite*. As the common areas are designed for daily occupancy, it is reasonable to take these into account for living space as well. Therefore, the average floor area per person for the entire building is to be calculated in accordance with the German *living space ordinance* (2003). All areas on the ground floor with the exception of corridor, staircase, technical and laundry room are added as well as 50 % of the accessible rooftop area, which is the part without PV panels. Finally, the living space for the entire building is calculated to 1219 m^2 with a floor area per person of 37 m^2. This is beneath the average of 40.2 m^2 in Hamburg 2020 (Statista 2021e). Therefore, the design can be evaluated as a proper compromise between space sufficiency and efficiency. Furthermore, it it is worth mentioning that companies that allow working remotely will save tremendous office space, benefiting environmental sustainability even more.

Table 4.7: Floor area in designed apartments compared with legislation requirements (own table)

Unit no.	**No. of occupants**	**Total floor area [m^2]**		**No. of rooms**	
		existing	required	existing	required
I (red)	2	52	≥ 20	3	≥ 1
II (blue)	2	57	≥ 20	3	≥ 1
III (green)	3	74	≥ 30	4	≥ 2
IV (yellow)	4	107	≥ 40	5	≥ 3

Community

Although the apartments are smaller, advantages of having spacious living space and thus general quality of living should not be compromised. Therefore a large focus in this design are several common areas to enhance sense of community for a diverse group of people, regardless of their profession, ability, age and so forth.

First of all, the ground floor is intended only for community purposes and is presented in Figure 4.17. The largest area is reserved for an open coworking space. Here, the occupants have the opportunity to work from home under conditions that are similar to a regular office. Additionally, there are two meeting rooms, two single booths and a kitchen that also serves as a break room. As not all people are involved in work that can easily be shifted to home, a library with a separate quiet working division, e.g. for doing homework, is also included. Other large areas are two multi-purpose community rooms which can be used for all sorts of activities. They can serve e.g. as meeting place for gatherings of associations, religious groups, as venues for art, music or dance practices or generally as a community center. To further give occupants the opportunity to be physically active, a sports room is also planned. Besides sharing spaces, a laundry room with communal washing machines is provided. As not each housing unit requires an own device, occupants benefit financially while enjoying the amenity of not having to leave the house for a laundromat. Furthermore, space and noise can be saved and avoided in the apartments. To take into account the diversity of people, restrooms are available for women, men, all genders as well as one with wheelchair access. Lastly, the large corridor can also be used as a gallery for exhibitions, embellishing the entrance and endorsing local professional or hobby artists. With regard to the shared premises, it should be added that in the implementation it is possible to open the space to the public. This could, for instance, take place as renting coworking desk spaces, organize sport courses, neighborhood meeting and so forth. Although this building is specifically designed for the needs of its occupants, neighborhood involvement in reality plays an important role so that social entitlement is extended beyond mere property lines.

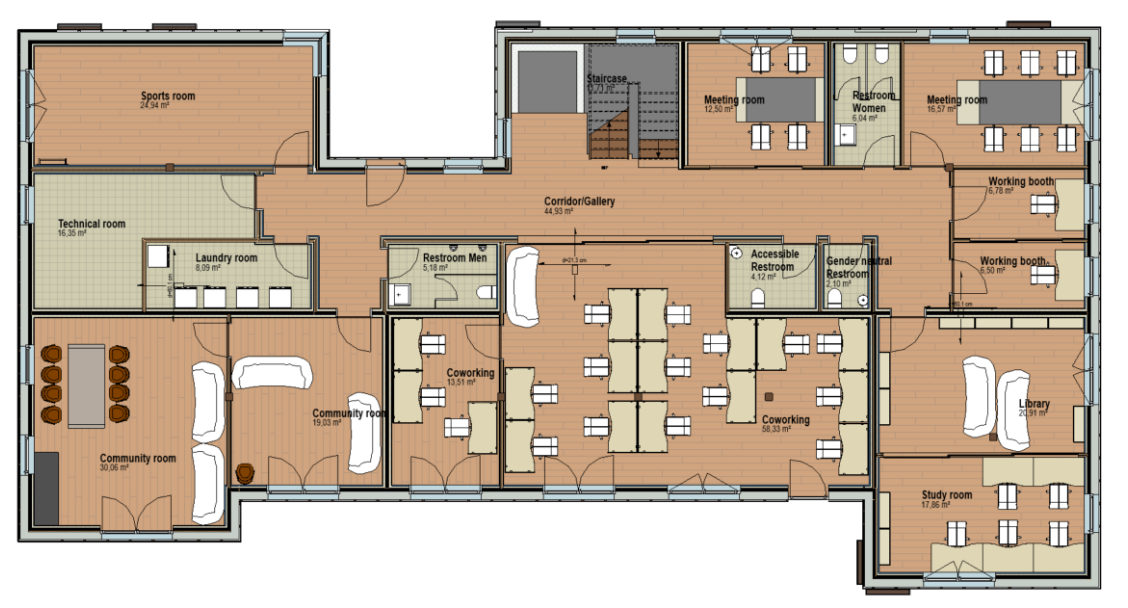

Figure 4.17: Floor plan of the ground floor with common areas (screenshot in *Revit*)

The idea of community is continued in the apartments. All units are suitable for a variety of household sizes and can be inhabited by any kind of living structure from roommates to families. The open kitchen and living room provides optimal conditions for household members to meet and spend time with their loved ones.

Regarding the exterior of the building, a green roof and backyard garden with large lawn areas are integrated. In both areas a communal garden for growing crops or other plants is optional. The intention is to create spaces for recreation and releasing stress by spending more time in a natural environment.

4.5 General design of a smart building

The performed assessment in the previous sections allows for elaborating certain measures to achieve green, climate change related and social requirements for buildings. In this section these achievements are further improved by using smart technology. The aim is to determine which digital assets are helpful in fulfilling the defined building requirements. As Sponselee (2020) argues in regard of home care, there is large effort of implementing smart technology in various projects, but their acceptance and effectiveness were not as high as expected. The author stresses the importance of adapting devices based on specific user needs. This approach, in combination with the requirements elaborated so far, is applied in the following to all smart technology implementations.

4.5.1 Basic architecture for data maintenance and security provision

As mentioned in section 2.4, smart building technologies gather a large amount of information regarding occupants' personal data like daily patterns etc. Among users, this has raised concerns of intrusiveness relating to sensing technologies (e.g. touch-based input), monitoring methods which interfere user privacy (e.g. video camera) and security of personal data collection and storage (Asaithambi et al. 2021, p. 2). The possible misuse by third parties grows even more important when a smart home is extended to a work environment, such as the proposed coworking space, considering potential violation of employee rights, e.g. through unlawful surveillance. Gathering of data within a smart building therefore needs to be balanced between using the least intrusive and at the same time most effective methods for enabling automated processes. It must be decided from case to case whether the intrusiveness accepted is worth potential risks associated with sensing technologies and monitoring methods. Considering the human right to privacy and the deep concerns many people still have (s. section 2.4), the aim in this smart building design is to gather as much data for personalisation and automation from least intrusive data sources, where the identity cannot be recognized. Sensing technology and monitoring methods like cameras, are only deployed when the value of their use is regarded extremely high.

On the other hand, it is worth mentioning, that the sense of privacy is also highly dependent on the secure handling and storage of personal data. If this factor can be ensured, there is more leeway in using more intrusive data sources as the correct further processing and managing can be trusted by users. Due to the large number of different occupants in apartment buildings, safe management is especially important to make sure, users only receive and have access to information that concerns them. Also, some data might be confidential to users and should not be available to building operators or landlords. The task is therefore, to create a smart building system with IoT devices that ensure highest amount of security and privacy.

In a generic IoT architecture, devices such as sensors at the edge of the network, generate data which is collected and then stored in a cloud. Here, the actual computing takes place where the data is processed using computational models of analytic for automation and stored. Then, a command is finally sent to an actuator (Asaithambi et al. 2021, pp. 5-6). For instance, a temperature sensor can detect that a room is not warm enough to ensure thermal comfort. This information is forwarded to the cloud which then gives the command to the HVAC system that heating in the specific room should be elevated.

To process the amount of data, large cloud data centers are located remotely, most of the time far away from the actual IoT devices. Characteristically, cloud centers are geographically centralized, provide services for a vast amount of users and store data permanently (Habibi et al. 2020, p. 69111). These factors increase their overall vulnerability for malicious intruders and the severity of cyber attacks (Modi et al. 2013, p. 8). Furthermore, the distance of the computing location to end-user devices cause latency and limited real-time interaction, potentially triggering actions against an anomaly (e.g. pipe burst) too slowly and thus compromising automation performance.

A possible solution to these issues is relocating a part of the cloud computing to an intermediate layer, referred to as *fog layer* (Rahmani et al. 2018, p. 7). Fog nodes are distributed in the proximity of the edge layer, each managing a set of IoT devices locally with decentralized data storage. The communication between edge layer and cloud is extremely reduced, as only relevant data for long-term storage and analysis is forwarded. By this, data volume, latency and energy consumption for computing are significantly reduced (Risteska Stojkoska et al. 2017, p. 1460).

In this design the proposed architecture of Qureshi et al. (2021), using IoT integrated in fog and cloud computing (IoTFC), is implemented and presented in Figure 4.18. Qureshi et al. (2021) also make assumptions regarding specific technical equipment that can be used for the smart building architecture. In this investigation only the generic structure is elaborated.

The first layer is the edge of the network which includes all IoT devices such as sensors, actuators, smart equipment (e.g. smart washing machine) and user interfaces (e.g. smartphone). The connectivity between IoT devices and fog nodes is ensured by using *bluetooth low energy* (BLE) for sensors and actuators as a wireless network protocol. At the same time it is assumed that WiFi is used for smart devices and user interfaces. Then, the fog nodes are deployed in each apartment and mixed-use area (coworking, sports room etc). This type of communication technology is designed for small amounts of data transmission and provides security through encryption (Qureshi et al. 2021, p. 108). The single distributed fog nodes form a network, connected with a common Ethernet switch. Then, a building fog node will process data for slower actions such as maintenance schedules. Finally all data that require immense storage volume and long-term analysis are transmitted to the cloud, as the last layer.

Furthermore, Qureshi et al. (2021) propose security measures specifically for multi-user purpose. This is relevant in an apartment building considering the different stakeholders

[1]Icons retrieved from http://icons8.com/.

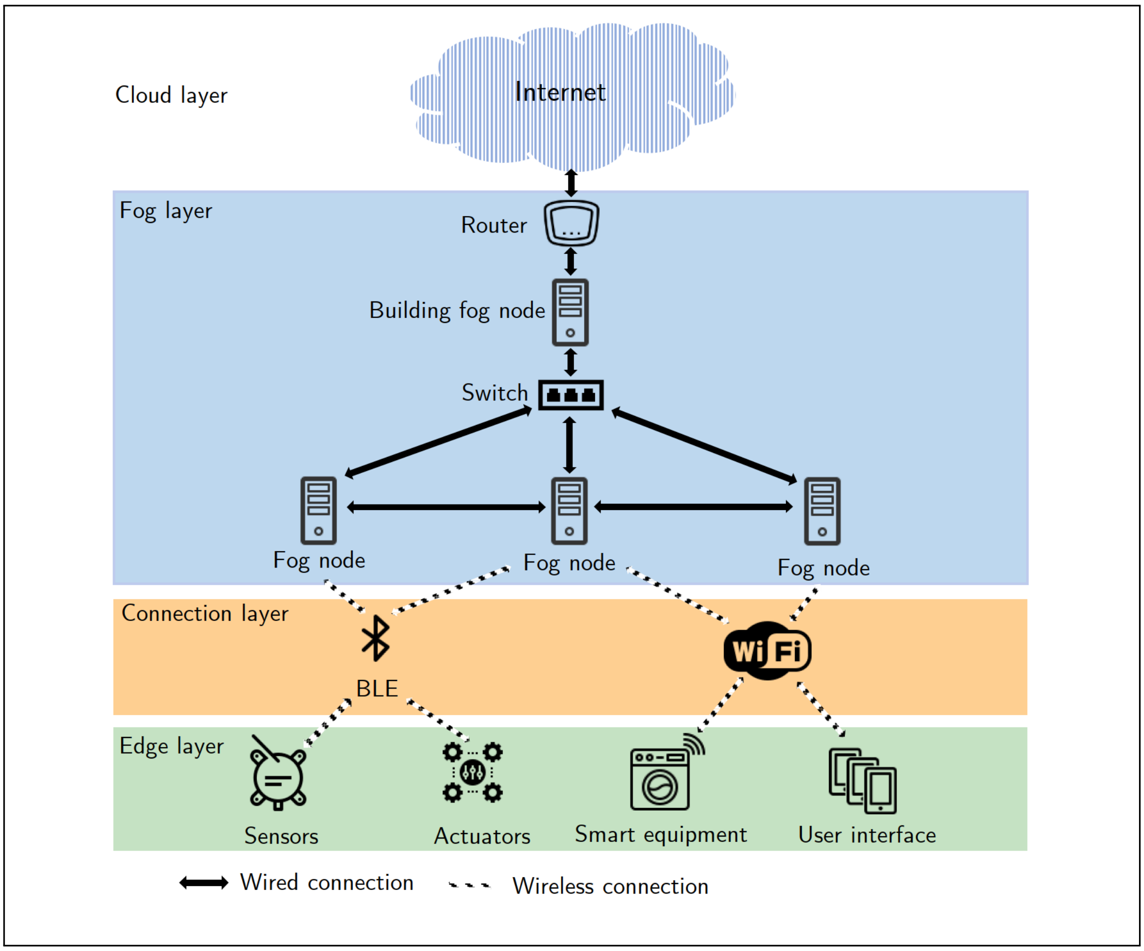

Figure 4.18: IoTFC smart building architecture according to Qureshi et al. (2021) (own figure)[1]

such as occupants, management staff or visitors. First of all, *dynamic role-based access control* (dRBAC) model is suggested for managing access of network or data only to those who have a certain permission. In comparison to the conventional model, which grants access to users according to an assigned role (e.g. occupant), an apartment building requires more parameters such as location etc. Another important topic to address is the correct authentication due to the many IoT services provided. While some IoT devices are mobile (e.g. smart phone), others are stationary (e.g. sensor). To avoid increasing system latency for identity authentication, dividing the control mechanism at edge, fog and cloud level is suggested.

Living in a smart building where essential equipment such as heating is regulated through automation system, it is vital that any kind of anomaly threatening a seamless process are detected and resolved. Therefore, at intermediate fog node level an *anomaly based intrusion detective system* (AIDS) is implemented. For monitoring the entire network and detect malicious attacks centrally, *network based intrusion detective system* (NIDS) is used at the building fog node.

Lastly, privacy of generated data must be ensured in a way that certain information cannot be traced back to the identity of a user. If, for instance, cameras are used, people must be pixelated in any kind of surveillance footage. Regarding the identification of people through location, the concept of *Mix Zones* is used which enables change of pseudonyms for devices (Beresford et al. 2003, p. 46). Additionally, Qureshi et al. (2021) suggest adapting a modified version of a component called *SwapMop* developed by Salas et al. (2018) that allows performing device services without the need to know its location.

As seen in this investigation, IoT architecture within smart buildings needs to have a proper safety and privacy standard in order to ensure seamless system functioning and protection of personal data. With the growing demand for smart building technology (s. section 2.4), it becomes evident that providers have a great responsibility on thoroughly informing users about how cybersecurity is implemented in the offered system and how data is further processed when it leaves the premise to the external cloud. Considering the complexity of IoT, there is a need for regulations to obligate providers to follow certain security and data protection standards. An important milestone in the EU has been reached with the *General Data Protection Regulation* (GDPR 2022), in which organizations that target or collect personal data must comply with security obligations and face monetary penalties in the event of a breach.

4.5.2 IoT services and deployed sensors

In the following, all implemented IoT services and sensors in the building design are described. This includes the areas of energy and water management, facility management, health and well-being, management of common areas and future pandemics and climate change scenarios.

Energy and water management

The first major implemented category for smart home applications concerns energy and water management requirements in the operational phase of buildings. Intelligent automation should help occupants to optimize demands according to needs.

As one of the largest factor for operational energy, the heating system is programmed to adjust depending on occupancy, weather and time of the day to ensure comfortable room temperatures and energy saving. Temperature and humidity sensors, being the most important indicators, are therefore deployed in every room. During the night or absence, the heating system is lowered whereas on cold winter days increased. In addition, roll-down shutters can close automatically for extra thermal insulation. In summer, overheating can be prevented by closing roll-down shutters partly during the day, depending on temperature and sunlight exposure. Furthermore, smart windows and doors are equipped with contact sensors. If windows in a room are opened manually, heating and ventilation are turned off. At the same time, windows and doors can be closed automatically e.g. in case of absence. In order to avoid wasting energy in all these scenarios, information about human presence plays an important role. In this design, non-intrusive detection with low-resolution thermal sensors is utilized. A possible implementation strategy, introduced by Singh et al. (2019), achieves high accuracy when placing sensors on ceilings, avoiding the use of multimedia or wearable devices for more user privacy and comfort.

Next, user electricity for light can be optimized. Smart bulbs are triggered if human presence is detected by thermal sensors and automatically turn off in case of absence. To save even more energy, dimmers are installed. With the help of light sensors, the lighting is adjusted to a predetermined illumination value, depending on daylight and occupancy.

To cover the electricity consumption partially self-sufficiently, it was assumed, for a simplified calculation in subsection 4.2.1, that a PV system on the roof generates electricity for own use. In practice, the distribution will depend on the demand of the users and should be managed automatically by the smart system. In other words, electricity consuming equipment will receive power from the PV system whenever available. When more electricity is generated than is needed, it will be stored in a battery. In case the consumption level is lower than the energy generated on site, electricity from storage or local power grid is supplied to compensate the difference. In order for equipment to communicate, smart user devices, such as washing machines, dish washers etc., are utilized.

For appropriate watering of the green roof, the backyard garden and the green walls, a smart irrigation system is considered. Moisture sensors measure the humidity of the soil and in case of dry periods without sufficient precipitation watering is initiated by the system.

Finally, to measure and track demand values for all user energy within this building and on the premise, meters are installed. This includes energy for heating, ventilation, water and user electricity. Users are able to view their demand on a user interface, e.g. smart phones or tablets in every apartment or common space, receiving direct feedback about consumption patterns and building awareness. If certain predetermined target values are exceeded, the user is notified so that they can improve their consumption behavior. This will help to reduce energy and water need while minimizing operational costs for occupants.

Facility management and safety

As gathering information about a building is a critical factor to FM, all the previously mentioned devices used for the IoT system contribute to smoother operations. The interconnection and metering of all building equipment regarding HVAC, water and electricity supply allow monitoring and detection of deviations such as leaks. Anomalies or system failures can be identified and located more easily, so that FM staff can react faster to rectify errors. This prevents supply loss, damage of building structure and injury of FM staff as well as occupants. Additionally, the implementation of BIM technology from design to as-built stage helps FM to gain exact information of which components were used while constructing and what needs to be replaced.

Another aspect of FM is the cleaning of buildings which is considered in this design for the common areas on the ground floor and the corridors. Sensors for waste garbage cans, soap dispensers and paper towel containers are installed to detect the fill level while in the restrooms sensors for doors allow capturing person frequency. With these information, the smart system can develop schedules for cleaning, automatically appropriate to demand and notifications can be sent directly to responsible staff members. In this context, there is the possibility of integrating a cleaning robot into the system. A contemporary example developed by the company *Mira Robotics* is presented in Figure 4.19. It shows a robot that can take over household chores such as dusting, mopping, refilling dispensers and containers, cleaning restrooms or managing waste disposal intelligently. However, these kind of robots are still in development for autonomous functioning. This elaboration resembles a proposal of how they could be integrated into a smart building in the future.

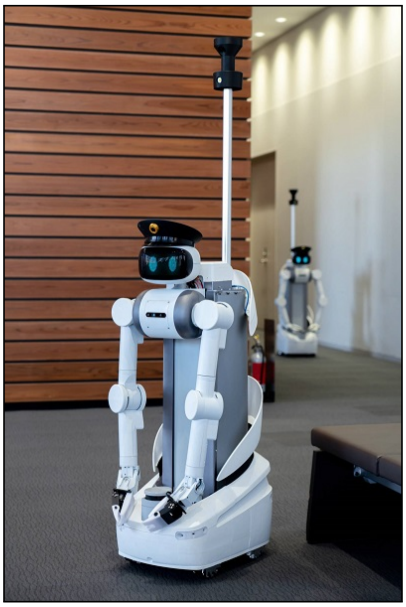

Figure 4.19: Robot *ugo* for household chores (Robotics 2020)

In this design, a technical room on the ground floor is reserved for deployment of robotic technology and charging stations. The cleaning robot communicates with smart doors, windows and elevators, which open on demand in order to allow access to certain spaces. Depending on the aforementioned deployed sensors, the system creates a cleaning schedule which is implemented by the robot. In addition, a drone for cleaning exterior windows, doors and PV panels is utilized. Using the same principle as the cleaning robot, the drone can leave the technical room through the smart window and is activated whenever it receives a command by the system. Another robot is integrated for cutting the lawn in the backyard garden and on the green roof.

As the robots can access certain rooms and possibly need more intrusive sensors such as cameras to function correctly, the vulnerability and risk of intruding hackers is high. At this point it should be mentioned once again that the implementation of such robotic assistance has to be compliant with safety standards for privacy.

Another point to ensure is the provision of safety in the building. This regards only allowing people access to the building with certain permission. Conventionally this is ensured by using a mechanical door lock. As mentioned previously utilization of intrusive technology, such as face or fingerprint scan, should be avoided in this design. Therefore smart locks are installed, which can be controlled via smart phone app. Using this technology is also convenient for the management of the common areas on the ground floor. Granting entry for external users can be done easily by issuing a digital access authorization. To ensure that the lock system still operates in failure situations such as data disconnection, it is recommended to integrate failover design so that the lock can still be used with a conventional key (Atlam et al. 2020).

Health and well-being of occupants

To promote health and well-being of occupants, a high level of indoor air quality is crucial. As mentioned previously, comfortable room temperatures are ensured appropriately to weather, occupancy and time. The additional humidity sensors help to prevent mold growth as well as spread of bacteria and germs. This can be particularly important in terms of reducing the probability of infection of airborne diseases such as COVID-19. In cases of higher occupancy (e.g. in the coworking space) or high humidity (e.g. in bathrooms), ventilation is triggered and users can be additionally notified to adjust their behavior regarding manual window opening in case measured values exceed limits. Sufficient air exchange is also crucial to prevent built-up of pollutants and toxic compounds e.g. from cleaning products. Therefore sensors for air quality are installed measuring pollutants like carbon monoxide, formaldehyde, nitrogen dioxide, volatile organic compounds, particulate matter and more (Zhang et al. 2020). There are various multi-sensors on the market, but a specific device is not recommended in this building design. To improve air quality, the smart system can again trigger ventilation and sent notifications or even an alert on mobile devices, if limits are exceeded, e.g. in case of fire.

Another point to improve the health of occupants is to support *ambient assisted living* (AAL) with the help of suitable features in the smart building. For the elderly, people with disabilities or chronic illnesses, AAL can be particularly helpful, as digital support can promote independent living for greater patient autonomy and help ease the burden on the healthcare system (s. section 2.4). In this concept, fall detection is implemented by incorporating thermal sensors. In case of emergency, the system can send an alert or call for help. The suitability of this design for inter-generational and diverse cohabitation with integrated coworking space amplifies the benefit of fall detection. As family members or neighbors are in the immediate vicinity, they are able to check on the potentially injured person. It is worth mentioning that fall detection also benefits non-disabled people. In addition stationary technologies, wearable sensors such as wristbands to monitor health data (e.g., sleep pattern, heart rate, etc.) can further improve monitoring and help detect and prevent diseases.

Finally, the supply of sufficient light to promote mood and well-being is ensured by the intelligent building system. Automatic dimming with light sensors ensures that the lighting meets the needs of the occupants at all times.

Management of common areas on the ground floor

The IoT architecture of the proposed smart building is also used for the management of the common areas on the ground floor. Through a *House app*, which can be installed on any smart device such as smart phone or tablet, occupants can gain access to a booking platform. Desks in the coworking space, meeting rooms, sports room, community rooms or the washing machines in the laundry room can be reserved prior to usage or occupation. The app shows schedules and ensures seamless daily routines so that users can fully focus on their work tasks or free time. Additionally, information about energy and water demand or notifications about fall detection or other emergencies can be retrieved.

For the coworking area a paperless office is considered as the employees work remotely using their own computer devices. An indispensable prerequisite for this is a stable and fast internet connection e.g. using fiber optic internet coverage. At this point it should be mentioned that the largest share of energy consumption in offices is accounted for by lighting (ASEW 2013). To save electricity and costs, the automatic lighting system with thermal and light sensors enhance efficient utilization. This also helps to maintain a healthy and adequate work environment for employees.

Lastly, the library is also managed automatically by including smart shelves for a permanent real-time inventory of books. If users want to borrow a book, they can scan it in the app, so that the whole process is registered in the system.

Future pandemics and climate change scenarios

Integrating sensors to detect human presence can be beneficial in future pandemic scenarios. If the level of occupancy is high, e.g. in a full coworking space, the ventilation system can be triggered and thus the probability of infection reduced. If a person is infected, others that were present in the same room for a significant amount of time could be warned, using information from schedules. In this case privacy must be ensured by anonymizing the identity of the infected person. Furthermore, the cleaning robot can be utilized to disinfect surfaces such as desks after each use for more security.

Another scenario to be expected in the future are extreme weather events due to climate change. Here, a smart system is also useful to enhance the resilience of the building and the safety of the occupants. For heat waves, the aforementioned digital services help to maintain comfortable indoor temperatures. In the event of a severe storm, a warning from the weather forecast could cause the system to perform a predefined safety check protocol. For instance, windows and doors can be closed automatically, preventing injury and damage. Furthermore, a weather sensor can be installed on the exterior of the building, measuring parameters such as temperature, humidity and wind speed in real-time (Djordjevic et al. 2019, pp. 196-197).

In more extreme scenarios, it is also possible that occupants cannot leave the building for a period of time due to extreme weather, lockdown or quarantine. This raises the question of how providing basic needs such as food can be obtained if occupants are restricted to stay inside. A possible solution for such events is the implementation of delivery services. In the context of food, the number of people using such services has steadily increased in recent years and is expected to continue to rise (Statista 2021c). While traditional delivery of food from restaurants, supermarket shopping or mail is done in person using cars or bicycles, there are companies that have developed robots to take over these tasks autonomously, such as *Starship Technologies* or *Nuro* (Banker 2022). This can also benefit AAL for elderly and people with disabilities or chronic diseases.

4.5.3 Overview of IoT devices and link to building design requirements

The described IoT devices are deployed in every common area, apartment or room, depending on its function. In Figure 4.20, smart devices located on the ground floor such as washing machines, cleaning robots, bookshelves, elevator and the entrance door with a digital lock are presented. The fog nodes are indicated in red and are deployed within each common area unit. The building fog is located in the basement.

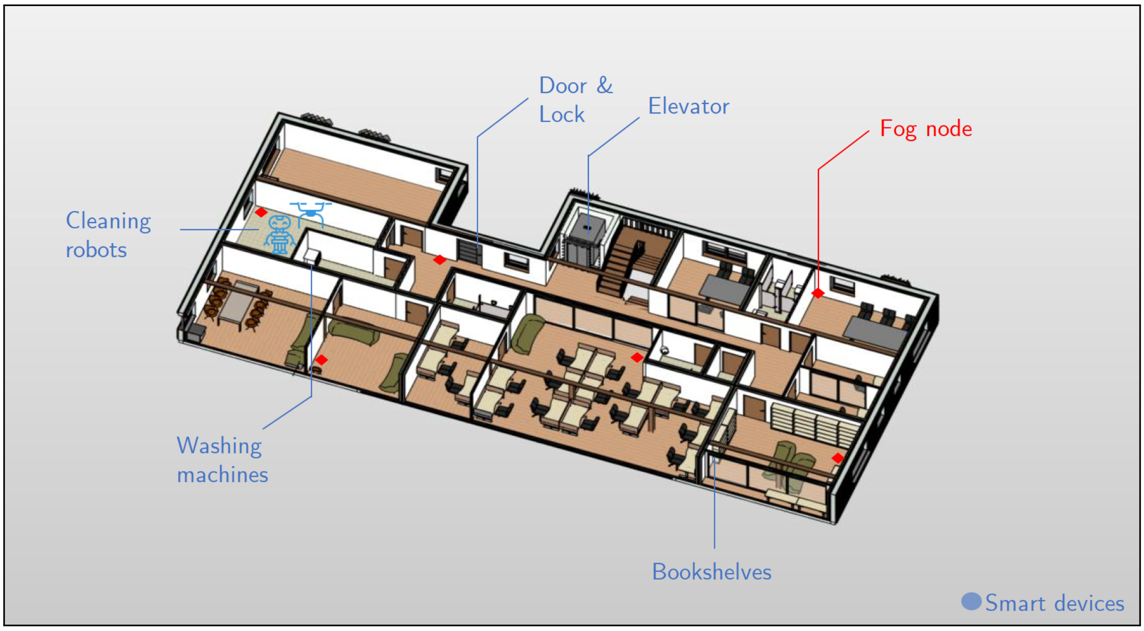

Figure 4.20: Deployed smart devices and fog nodes on the ground floor (own figure)[1]

To summarize the deployed sensors, smart devices and actuators, Figure 4.21 shows the selected IoT devices exemplary for apartment III (s. Figure 4.16). The sensors must be deployed in every room in order for the system to function at its full automation potential. Outside the building a weather sensor is installed to generate real-time information, especially in case of extreme weather events. As Figure 4.22 shows, data from sensors

[1]Icons retrieved from http://icons8.com/.

and smart devices is collected and forwarded to the either a fog node or, if relevant for long-term storage and analysis, to a cloud. Here, the data is processed and machine learning takes place. Depending on the data, the smart system sends a command to actuators for heating and ventilation or smart devices, providing optimal living conditions automatically. Therefore, direct inputs by users or manually programmed routines are optional but not necessary.

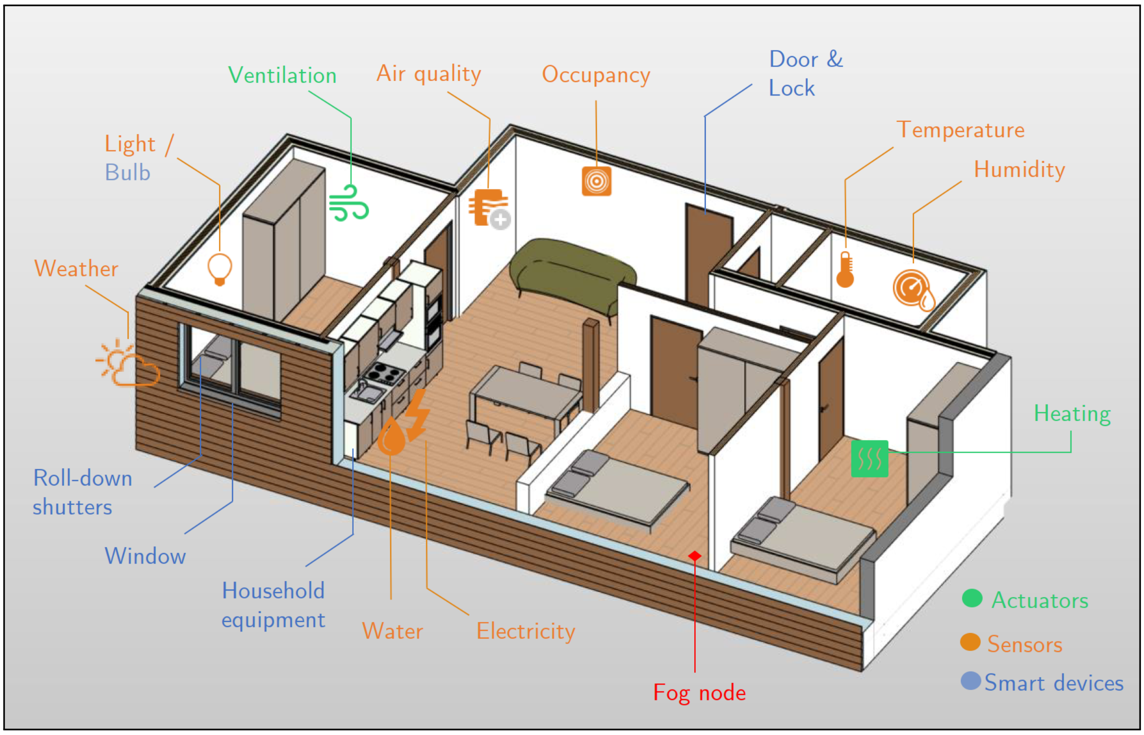

Figure 4.21: Deployed sensors, smart devices and fog node in apartment III (own figure)[1]

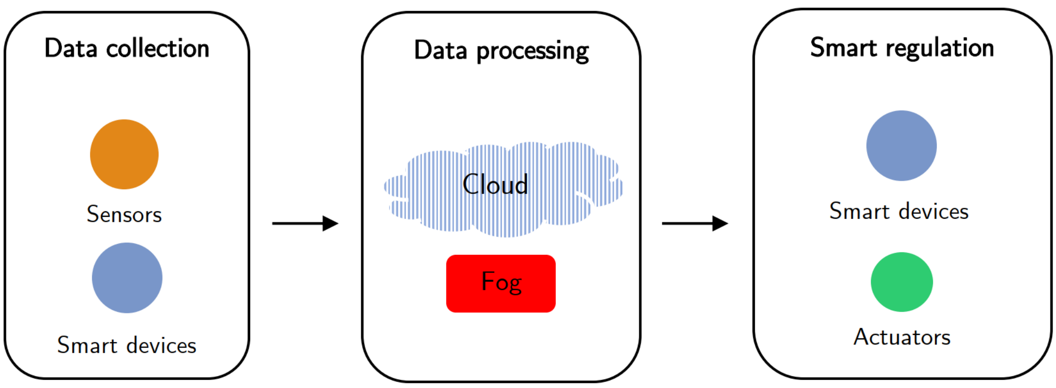

Figure 4.22: Data flow in the proposed smart building (own figure)[1]

[1]Icons retrieved from http://icons8.com/.

The selection and implementation of the presented IoT devices is based on their benefit to the building design requirements regarding green, climate change related and social measures. Table 4.8 shows an overview on how the proposed smart building benefits the respective indicators. For green building requirements, the most contributing implementation is the automation of the HVAC system which ensures energy efficiency, saving the demand of operational energy and thus reducing the building's environmental life cycle impact. Furthermore, the smart building allows immediate detection of anomalies for quick rectification of errors and gives users a feedback about their consumption. By all these measures, the costs for end-users are also reduced. Then, the integration of AAL allows the building to be even more adaptable to users' needs and health.

Table 4.8: Overview of links between implementation of smart building and building design requirements (own table)

Building design requirements	**Indicator**	**Benefit of smart building**
Green	Operational Energy	HVAC automation detection of anomalies consumption feedback
	LCA	HVAC automation
	Design for adaptability and renovation	AAL
	Operational water consumption	detection of anomalies consumption feedback
Climate change	Protection of occupier health & thermal comfort	HVAC automation air quality monitoring
	Increased risk of extreme weather events	HVAC automation building safety check
	Increased risk of flood events	building safety check
Social	Indoor air quality	air quality monitoring
	Time outside of thermal comfort range	HVAC automation
	Lighting and visual comfort	lighting automation
	Acoustics and protection against noise	-
	Life cycle costs	HVAC automation consumption feedback
	Living space	-
	Community	management of common areas

Regarding future climate change scenarios, the HVAC system is adjusted automatically due to occupants' needs and environmental conditions, ensuring thermal comfort, during both cold and hot weather. To further enhance health, air quality monitoring and lighting automation are implemented, creating an adequate indoor environment. In the event of extreme weather or floods, the smart building can perform safety checks which help to warn occupants, lowering damage and injury. Finally, the integration of a *House App* allows easy management of the common areas on the ground floor for social interaction.

All these points show that, if selected and implemented correctly, IoT services of a smart building can significantly contribute to enhancing design requirements, thus improving living conditions and environmental performance. In addition, the proposed system makes the building more adaptable and resilient for future issues to come.

4.6 Evaluation of building design

4.6.1 Comparison of the design with other modern buildings concepts

Looking into the building concepts *Prinz-Eugen-Park* and *Kalkbreite* (s.section 2.4), the focus of their designs are mostly on aspects of environmental impact regarding operational energy efficiency and life cycle emissions. In addition, they also have an explicit social emphasis relating to community, diverse living concepts and occupants well-being with aspiration of enhancing all pillars of sustainability.

The design of the proposed apartment building incorporates all these requirements of the modern housing concepts by conducting a *Level(s)* assessment including a thorough analysis of operational energy, LCA, indoor environment etc. Additionally to the framework, aspects of living space and community are taken into account. By using this assessment approach, this practice-oriented example covers all relevant ideas of the modern housing concepts.

However, two new design aspects are introduced that have not been a focus nor implemented in *Prinz-Eugen-Park* and *Kalkbreite*. The first aspect is the consideration of creating a building adaptable and resilient to climate change. Taking into account the likeliness of extreme weather events, floods etc., which occupants will have to face, is a large advantage and might be indispensable in the future. Secondly, the most outstanding difference between this building example and the two modern concepts is the integration of IoT technology. The utilization of the proposed digital assets enhances the determined requirements beyond what can be expected for a traditional building. Furthermore, the smart devices increase service performance by adapting flexibly to users' needs. Due to this dynamic feature, the smart building can be used and adjusted for other potential scenarios such as pandemic events, creating a new level of building services. In this examination, the use of IoT technology is therefore found to be exceptionally beneficial for creating a building not only appropriate from a present perspective but also for future scenarios to come.

4.6.2 Summary and guideline for designing a green, social and smart building

In Chapter 4 the design example of a dwelling with 12 apartments for a total of 33 occupants located in Hamburg was elaborated, in which green, climate change related and social aspects were implemented. Additionally, an architecture for a smart building was proposed to further enhance the aforementioned requirements and to equip the building for future scenarios. In the following, the strategy for designing such an apartment building is presented.

First of all, it is recommended that a BIM model is developed and continuously adjusted in the process of building design. The basis for optimizations is the utilization of the *Level(s)* framework with the macro-objectives and indicators as selected in this example and referred to as building design requirements. Although the other aspects of the framework have not been regarded relevant to the scope of this work, it is optional to include these. While performing the BSAM, special focus should be put on conducting a LCA with a dedicated tool and including a thorough calculation and analysis of operational energy. Additionally to the requirements set by *Level(s)*, measures to enhance sense of community by integrating common areas as well as adequate living space size should also be investigated. This procedure is described in section 3.4.

To further enhance building requirements, a smart building system should be developed. The integrated IoT devices concern energy and water management, facility management and safety, health and well-being of occupants, management of common areas and the consideration of future scenarios such as climate change and pandemics. The sensors, actuators and smart devices in this example are specifically selected accordingly to the climate of the location and general needs of occupants. Such an approach is essential in order to create a building with appropriate user services. In practice, it could be optional to conduct surveys with future occupants to adjust the system to their needs and to give a proper introduction for the elderly or people with less technology experience. These measures will increase the likelihood that occupants will accept the digital enhancements, by which the effectiveness and success of smart technology adoption would be achieved. As user concerns regarding data security and privacy must be addressed, the most essential prerequisite for a smart building is the design of an appropriate and safe IoT architecture. In this example an IoTFC system is proposed. Lastly, it should be kept in mind that the utilization of IoT devices with sensing and privacy interfering methods, like fingerprint scan or multimedia recording, are still perceived intrusive to users. Whether or not to implement these technologies must be decided on a case-by-case basis, weighing potential benefits against risks. However, providing an architecture for data management with high safety level, can enable more leeway in IoT device choice.

In Figure 4.23 a simplified workflow is proposed for the implementation of a smart residential building and consists of two main considerations. The first one is the selection of IoT devices. It should be evaluated if the device is contributing to the determined social, climate change related and green building requirements. Also benefits regarding future scenarios should be taken into account. If the function of the device is rated valuable, it is implemented ensuring appropriate utilization. Furthermore, the intrusiveness should be analyzed and, if necessary, the selection reconsidered. The other part of the design relates to proper data management. Here, it is necessary to integrate an architecture that provides a high level of data security and privacy. If all these requirements are met, a human-centered and environmental friendly design of a smart building can be achieved.

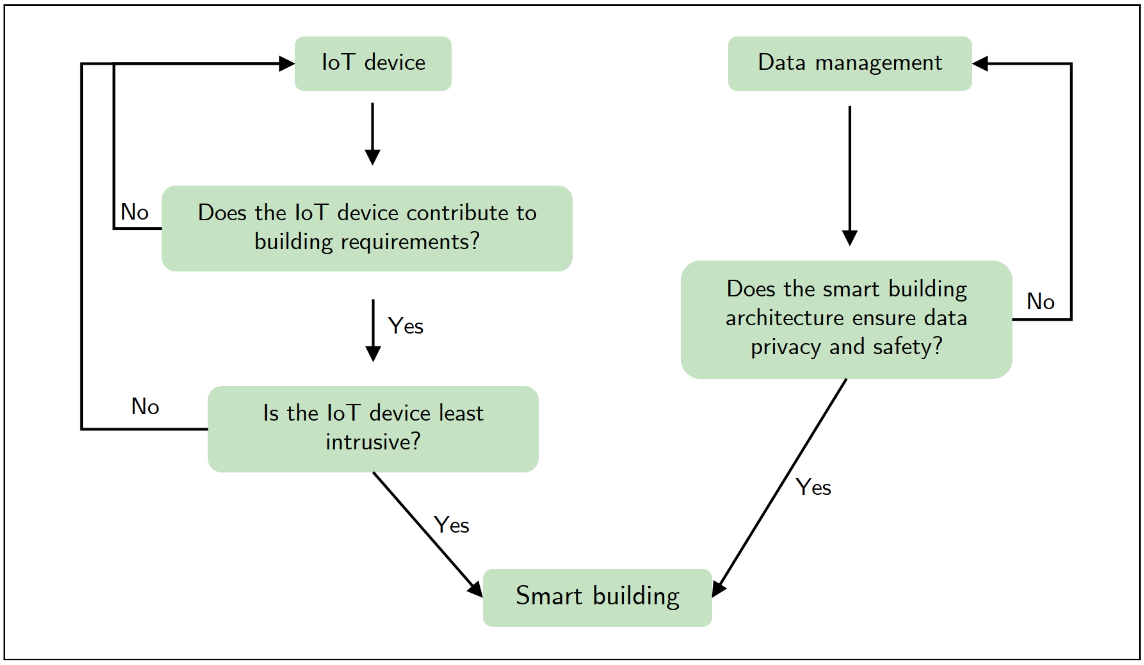

Figure 4.23: Workflow for designing a smart building (own figure)

5 Conclusion and Outlook

Summary

This thesis investigated the design of a smart apartment building with social and environmental objectives.

First of all, the challenges of providing adequate housing in urban areas were identified and set in perspective with human rights. It became evident that low-income households are particularly more vulnerable to issues of inadequate dwelling conditions, showing the importance of providing social housing. As examples in Europe of the past century, the design of *Unité d'habitaction* and *Plattenbau* were analyzed and common issues as well as criticism from today's perspective were identified. The investigation showed that providing the mere living minimum, defined by a top-down approach of planners, does not suffice to consider a building truly socially acceptable. Next, the connection of dwellings to the environmental impact of the building industry was drawn. Considering the 17 SGDs, set by the *UN general assembly*, the enormous GHG and other emissions caused throughout the life cycle of a building, a drastic change in construction practice is required. Based on the identified issues, essential social and green building design requirements were determined. The research showed that many measures such as high thermal performance overlap.

Afterward, recent developments in urban housing were elaborated upon. It was shown that a severe housing shortage prevails in German urban areas, particularly to the disadvantage of low-income households. Furthermore, the global COVID-19 pandemic combined with the ongoing digitalization has spawned opportunities for *home office* and intertwined dwelling with work, calling for a change in how residential buildings are designed. Two modern housing concept examples, *Prinz-Eugen-Park* and *Kalkbreite*, were then introduced to show how planners have tackled social and environmental issues in practice recently. However, a new component that should be considered in the future of dwellings is the transformation of living spaces into *smart homes* using IoT technologies. While smart devices have great potential for enhancing building design requirements, data security and privacy are major concerns among users. Moreover, in recent years German politics have put effort into implementing green buildings in practice by adopting binding regulations for new-builts. The focus, however, lies on operational energy efficiency.

As by this, impacts in all other life cycle stages of a building are excluded, LCA as a more holistic approach is introduced. After identifying LCA, the integration of BIM due to its high data availability and accuracy for a comprehensive assessment was advocated. Then, four common BSAMs in Europe were introduced and compared based on the determined building design requirements. A general gap was identified in the aspects of living space and community. On the basis of these findings, a workflow using BIM, LCA and the *Level(s)* framework for assessing buildings was proposed. Using this workflow, a practice-oriented example was modeled by means of *Revit* and green, climate change related and social design requirements assessed. While all aspects were analyzed qualitatively, operational energy as well as LCA of the building were additionally investigated quantitatively by using the tools *CAALA* and *One Click LCA*. The designed structure is an apartment building made predominantly from biobased materials. It includes twelve apartments distributed on three floors, a ground floor with common areas, a basement, a green roof, a backyard garden and exterior green wall elements. This assessment achieved to create a social and green residential building.

Finally, the design of a smart building was determined. An IoTFC system, using fog nodes to shift a part of computing from an external cloud to a local layer closer to IoT devices, was proposed as a suitable architecture. By this, automation processes and data security can be significantly improved. Deployed sensors, actuators and smart devices were selected for energy and water management, facility management and safety, health and well-being of occupants, management of common areas and potential future scenarios. All the used IoT devices were strongly connected to the building design requirements and helped to enhance these. In addition, the smart technologies allowed for more adaptability and resilience for future scenarios. The integration of such devices was also the main distinction between the design example and other modern building concepts. Based on all these investigations, a guideline was created for designing a green, social and smart building.

Conclusion

The investigation in this thesis showed that adequate housing is a fundamental human right which must be provided by society. As households with low income are particularly threatened by the housing shortage in urban areas and are at higher risk of living in poor building conditions, political stakeholders need to minimize the gap between rich and poor by adopting appropriate regulations. It is important to note that power inequalities do not occur merely along one axis, in this case class, but also intersect with other forms of discrimination that have to be addressed by society likewise. At the same time, the task for planners of new residential buildings is to take into account the objective of providing adequate housing and designing for human needs, also considering contemporary developments such as *home office*. These measures will promote occupants' health and well-being and allow them to thrive in their own homes. Besides the focus on human-centered and social design, green aspects must be considered. As the building industry has an enormous impact on the GHG emissions and thus climate change, there is an urgent need for action. German politics have taken measures, but the current strategy focuses on operational energy. As this only reflects a part of the actual emissions, a more holistic approach, extending to the entire life cycle, is necessary. It would be highly beneficial if performing LCA was obligatory for new projects in the building industry.

Looking into building design requirements, it was found that many social and green aspects overlap, illustrating the strong synergy of both these sustainability pillars. This is also reflected in the use of BSAMs which serve as a guideline for assessing social and green building requirements. The investigated BSAMs fulfilled all green requirements, while some social aspects were only addressed by a few or not at all. The *Level(s)* framework was selected in this assessment as it is very flexible and can be used even at early design stages. Most of the building design requirements were met by *Level(s)* and its inclusion of climate change related aspects is seen as particularly enriching for future building adaptability and resilience. Additionally, aspects of living space and community were taken into account, which were only covered insufficiently in all BSAMs.

During the building assessment, special attention was paid to performing LCA. Here, the integration of BIM was very beneficial for the process as it enabled precise material take-offs and thus more representative LCA results. The tools used in this work, however, had to be mostly exported outside of the BIM program slowing evaluation down. Using an integration within a BIM software would lower error-prone manual inputs and thus enable a more accurate automation process. As *Level(s)* does not provide benchmarks for environmental impacts, there is a lack of guidance for LCA conductors to assess LCA calculations. Therefore, it is advisable to compare the proposed building with other design options. Furthermore, it is worth mentioning that the scope of the conducted LCA in this work is limited to structural building components, leaving out service equipment used for the heating system, ducts etc. For more comprehensive results, these need to be considered.

Regarding the design of the smart building in this thesis, it was found that, if IoT devices are integrated correctly, social and green objectives can be significantly enhanced. This outcome indicates the enormous potential of smart technologies to improve health, well-being and environmental building performance to a level that is not imaginable for traditional buildings. Moreover, IoT devices can make buildings more resilient to future scenarios like pandemics or extreme weather events as the smart system can react to changes more dynamically. However, it should be mentioned that using these devices requires resources in the form of materials and operational energy, which were not included in the scope of the conducted LCA. Analogously to other building equipment extending the scope of LCA would be beneficial. Lastly, the decision of whether to implement a smart building system or not relies on its security against malicious intrusion and data misuse by third parties. Considering the human right to privacy and the large amount of data gathered by IoT devices, it is essential to use an architecture that provides the best protection. The proposed IoTFC, in combination with using the least intrusive technologies, has the potential to fulfill these safety requirements. The responsibility of ensuring user data security lies with smart technology providers and political stakeholders to set standards and regulations.

Overall, the investigation shows that green and social aspects have to be both considered and implemented for designing sustainable buildings and can be further enhanced by using smart building technologies.

Outlook

The use of BIM has proven to be highly beneficial in assessing life cycle impacts. More development is, however, required for further integrating BIM into LCA practice to reduce manual inputs and enhance automation. Additionally, building equipment should be taken into account in the assessment for a more comprehensive LCA.

The same applies in particular to smart devices. Operational energy consumption as well as used materials have to be assessed in LCA to quantify actual benefits and identify shortcomings to avoid rebound effects. Developing a strategy for efficient deployment of sensors, actuators etc., is necessary to reduce the number of IoT devices as far as possible. Furthermore, suitable architectures for the smart building data management should be continuously reevaluated and improved to ensure the highest safety and privacy for occupants, home office employees and patients. Implementing robotics in residential buildings should also be analyzed with regard to the same privacy concerns. This field is still in its infancy and requires more scientific research. Although implementing all this IoT devices bring a lot of advantages, the high dependency on electricity has to be considered. This is in particular important in cases of power cuts or system failure. Research on how to prevent and manage such scenarios is therefore necessary.

In terms of current BSAMs, this investigation showed room for improvement, particularly regarding the social sustainability pillar. Taking into account community and living space aspects is essential for designing appropriately for the environment and human needs. To make a building even more suitable to its users, participation of future tenants of a designed building could be favorable, leading away from a top-down approach to a less hierarchical planning and occupant oriented practice.

Finally, the feasibility of providing a social, green and smart building beyond the design stage needs to be addressed. While the design approach in this thesis showed many benefits, how to finance such a project in practice is a major question. Life cycle costs should be calculated beyond the operational stage and additional acquisition costs of implementing a smart building need to be determined. Regarding the latter, finding ways to integrate low-budget sensors etc. is crucial to ensure that not only the wealthy part of the population but all people can have access to such building services. Another point regarding finances is the affordability of the apartments. Keeping the dynamics of the housing market in mind, regulations need to be adopted to counteract the disadvantage for marginalized households and ensure appropriate renting prices. Other regulations could concern setting a minimum number of occupants in one apartment depending on its size to avoid excess living space. Additional measures such as these are necessary to maintain a holistic perspective on design so that aspirations to create a social, green, and smart building are also met after the design stage.

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Appendix

A Floor plans and views of the building

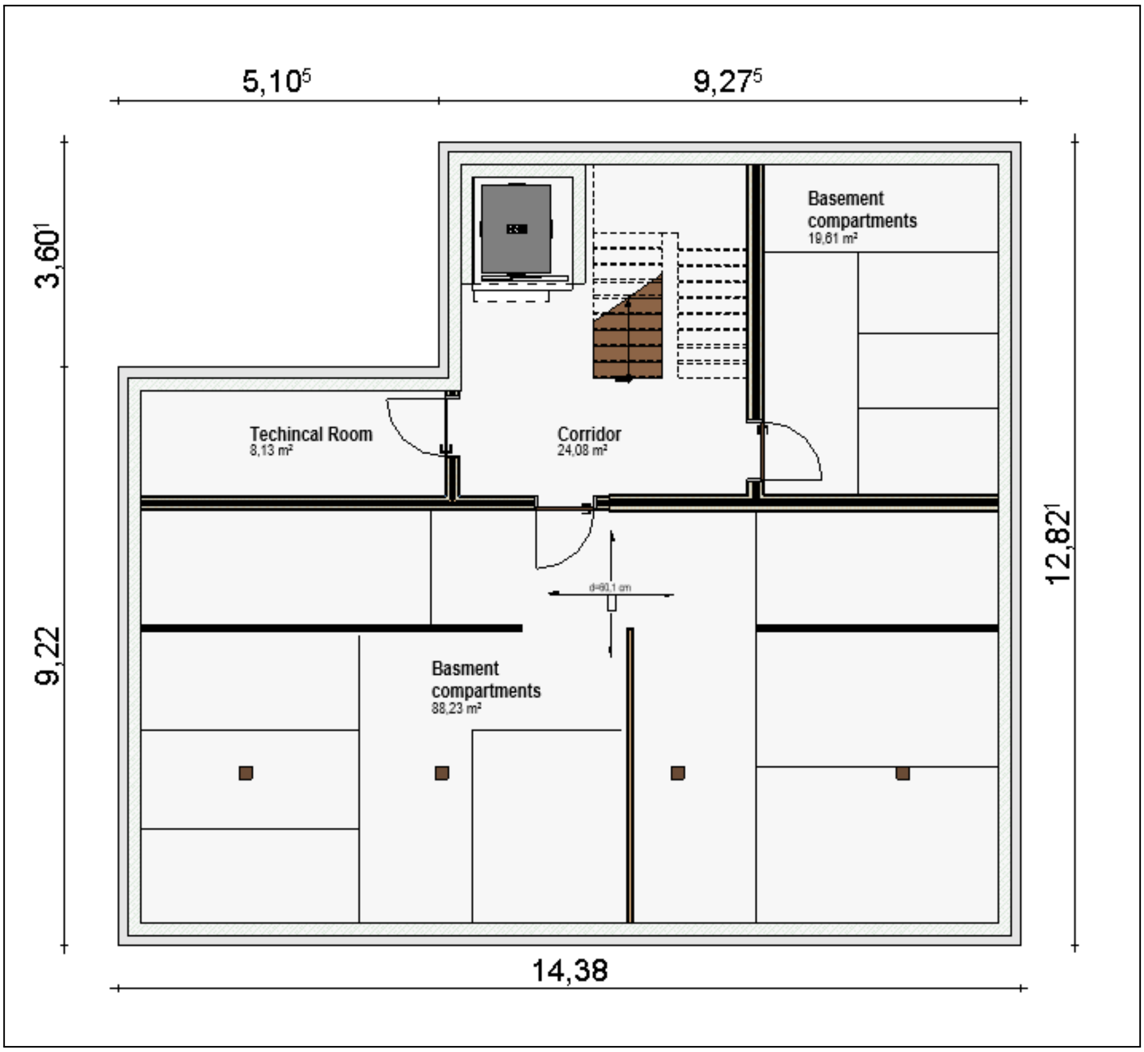


Figure A.1: Floor plan of the basement (screenshot in *Revit*)

Figure A.2: Floor plan of the ground floor (screenshot in *Revit*)

Figure A.3: Floor plan of apartment levels (screenshot in *Revit*)

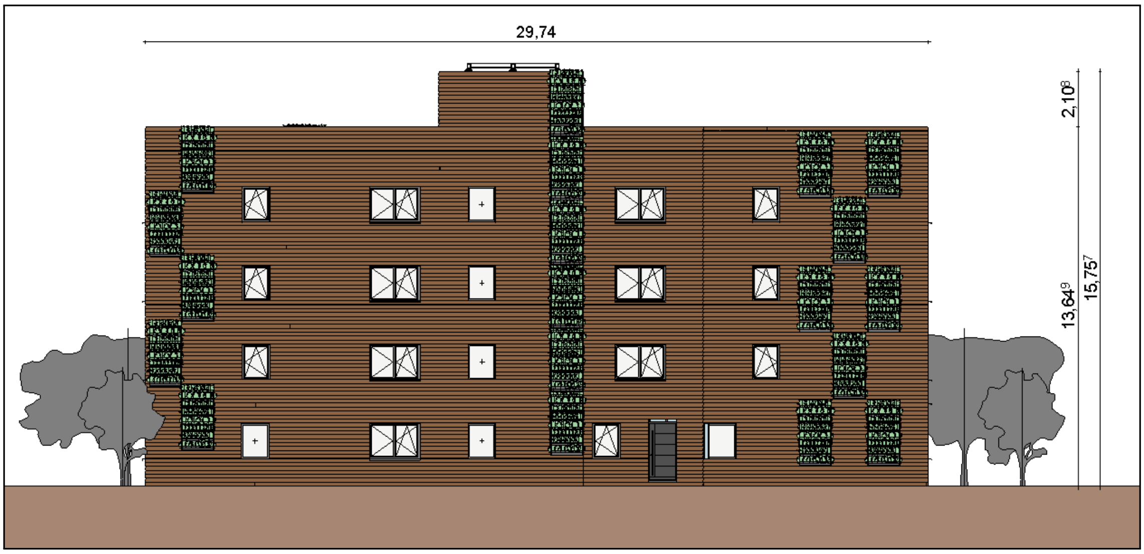


Figure A.4: Northern side view of the building (screenshot in *Revit*)

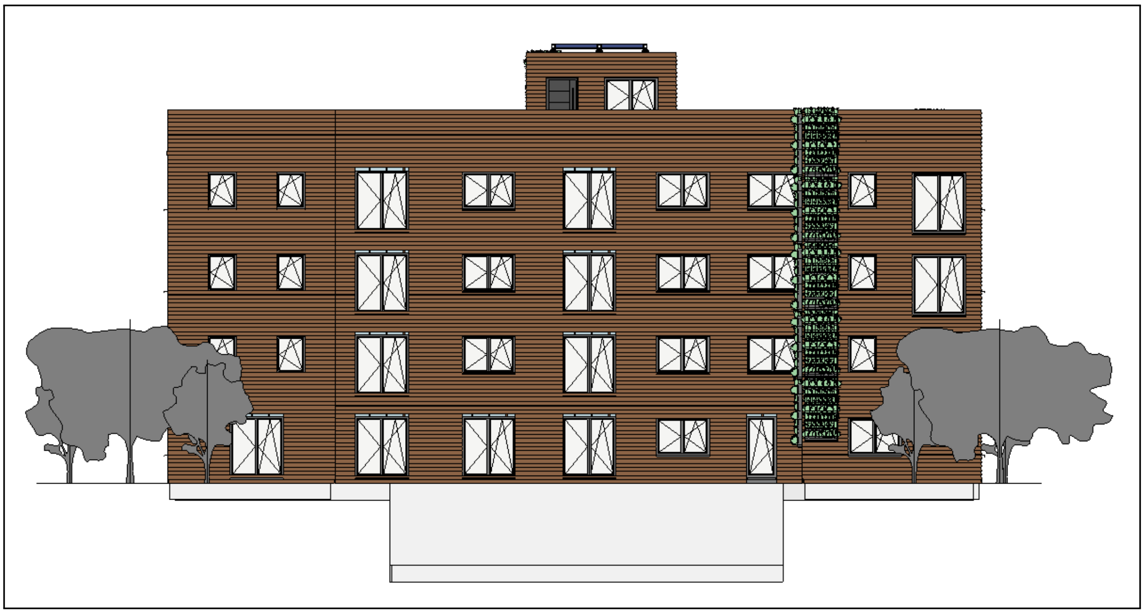


Figure A.5: Southern side view of the building (screenshot in *Revit*)

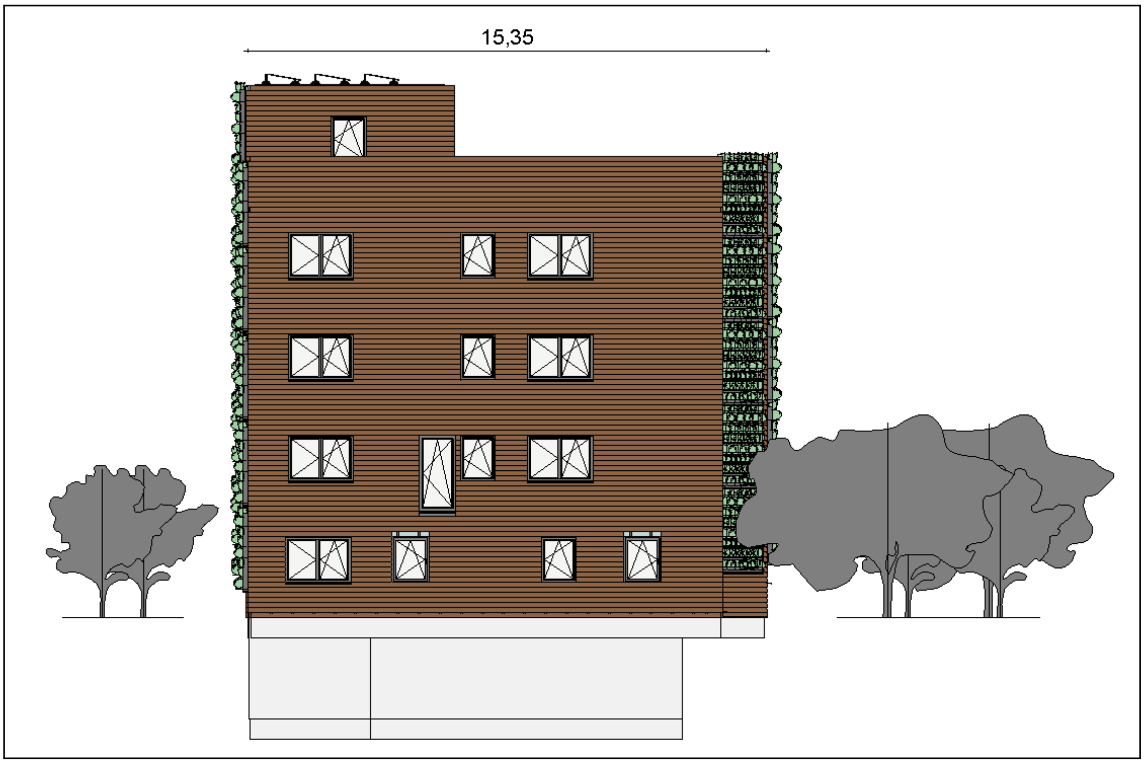


Figure A.6: Western side view of the building (screenshot in *Revit*)

Figure A.7: Eastern side view of the building (screenshot in *Revit*)

B Structure of building components

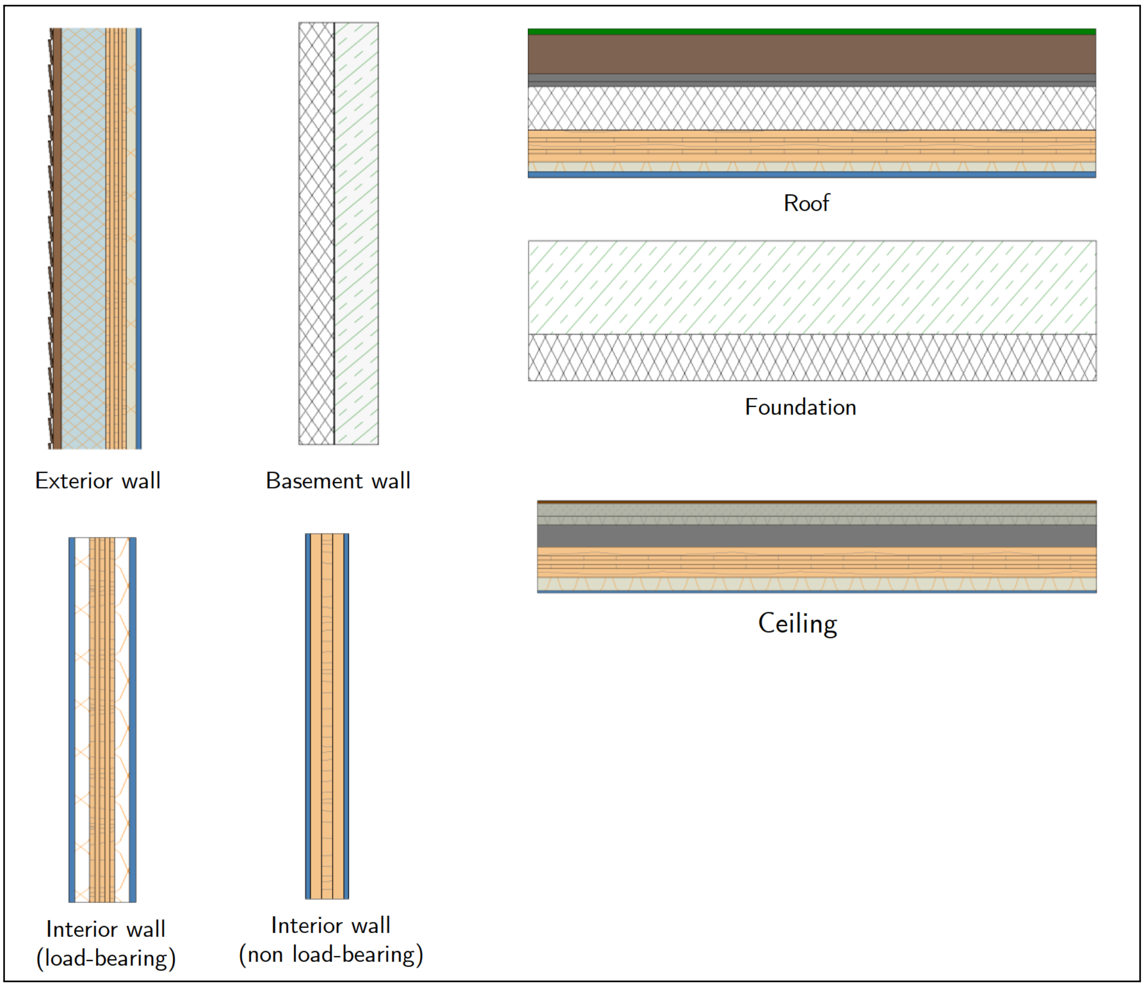


Figure B.8: Main building components (own figure)

Table B.1: Structure of exterior wall above ground level (exterior-interior) (own table)

Thickness [mm]	**Material**
19	Exterior wall cladding
40	Wood lathing (40/60)
220	Wood fibre insulation
100	CLT (5 layer)
50	Mineral wool
25	Gypsum board

Table B.2: Structure of basement walls (exterior-interior) (own table)

Thickness [mm]	**Material**
160	XPS
200	Reinforced concrete

Table B.3: Structure of interior load-bearing walls (own table)

Thickness [mm]	**Material**
25	Gypsum board
60	Mineral wool
100	CLT (5 layer)
60	Mineral wool
25	Gypsum board

Table B.4: Structure of interior non load-bearing walls (own table)

Thickness [mm]	**Material**
25	Gypsum board
90	CLT (5 layer)
25	Gypsum board

Table B.5: Structure of the roof (exterior-interior) (own table)

Thickness [mm]	**Material**
30	Plants
80	Soil
1	Filter fleece
40	Drainage layer (Polyethylen)
10	Rubber granulate mat
1.1	Root Protection layer
2.5	Sealing sheet
220	EPS
-	Sealing membrane
160	CLT (5 layer)
50	Mineral wool
30	Gypsum board

Table B.6: Structure of the foundation (exterior-interior) (own table)

Thickness [mm]	Material
160	XPS
400	Reinforced concrete

Table B.7: Structure of ceilings (top-bottom) (own table)

Thickness [mm]	Material
10	Floor finish (parquet/tiles)
60	Screed
40	Impact sound insulation
100	Lime chippings
-	Trickle protection
140	CLT (5 layer)
60	Mineral wool
12.5	Gypsum board

C Data from *CAALA*

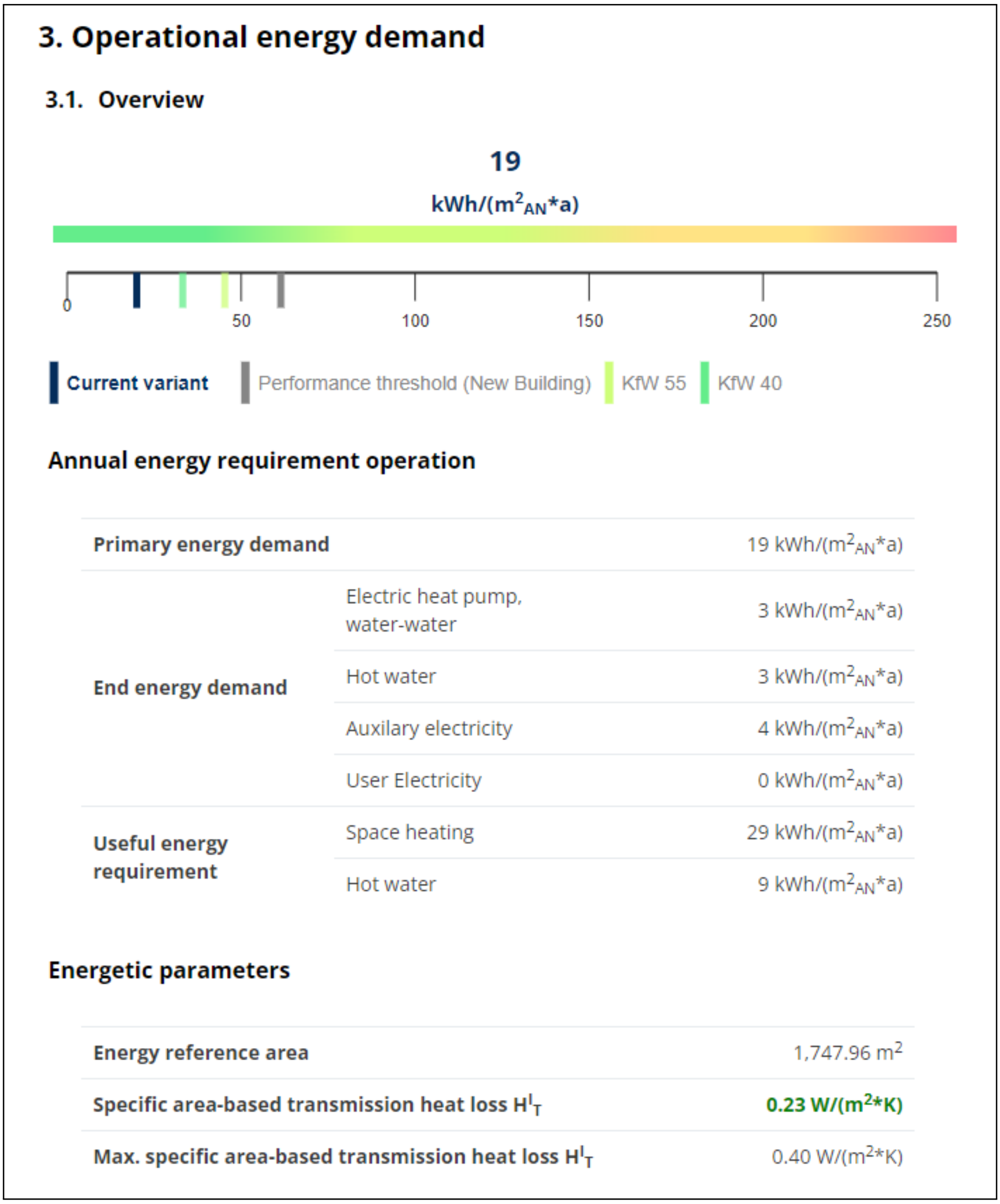
1.1. Object

Model	Multiapartment-buidling_280422_Energy.xml
Scope of analysis	Full Life Cycle
Level of detail	Blueprint planning
Building type	Apartment building
Energy standard	EnEV 2016
Reference study period	50 Jahre
Climate region - reference location	Region 3 - Hamburg

1.2. Geometry

Average floor height	3.00 m
V	5462.36 m^3
GFA th.	1820.79 m^2
NFA	1456.63 m^2
Reference area	1747.96 m^2

Figure C.9: Building data (screenshot in *CAALA*)



3. Operational energy demand

3.1. Overview

Annual energy requirement operation

Primary energy demand		19 kWh/(m^2_{AN}*a)
End energy demand	Electric heat pump, water-water	3 kWh/(m^2_{AN}*a)
	Hot water	3 kWh/(m^2_{AN}*a)
	Auxilary electricity	4 kWh/(m^2_{AN}*a)
	User Electricity	0 kWh/(m^2_{AN}*a)
Useful energy requirement	Space heating	29 kWh/(m^2_{AN}*a)
	Hot water	9 kWh/(m^2_{AN}*a)

Energetic parameters

Energy reference area	1,747.96 m^2
Specific area-based transmission heat loss H'_T	**0.23 W/(m^2*K)**
Max. specific area-based transmission heat loss H'_T	0.40 W/(m^2*K)

Figure C.10: Operational energy demand overview of results (screenshot in *CAALA*)

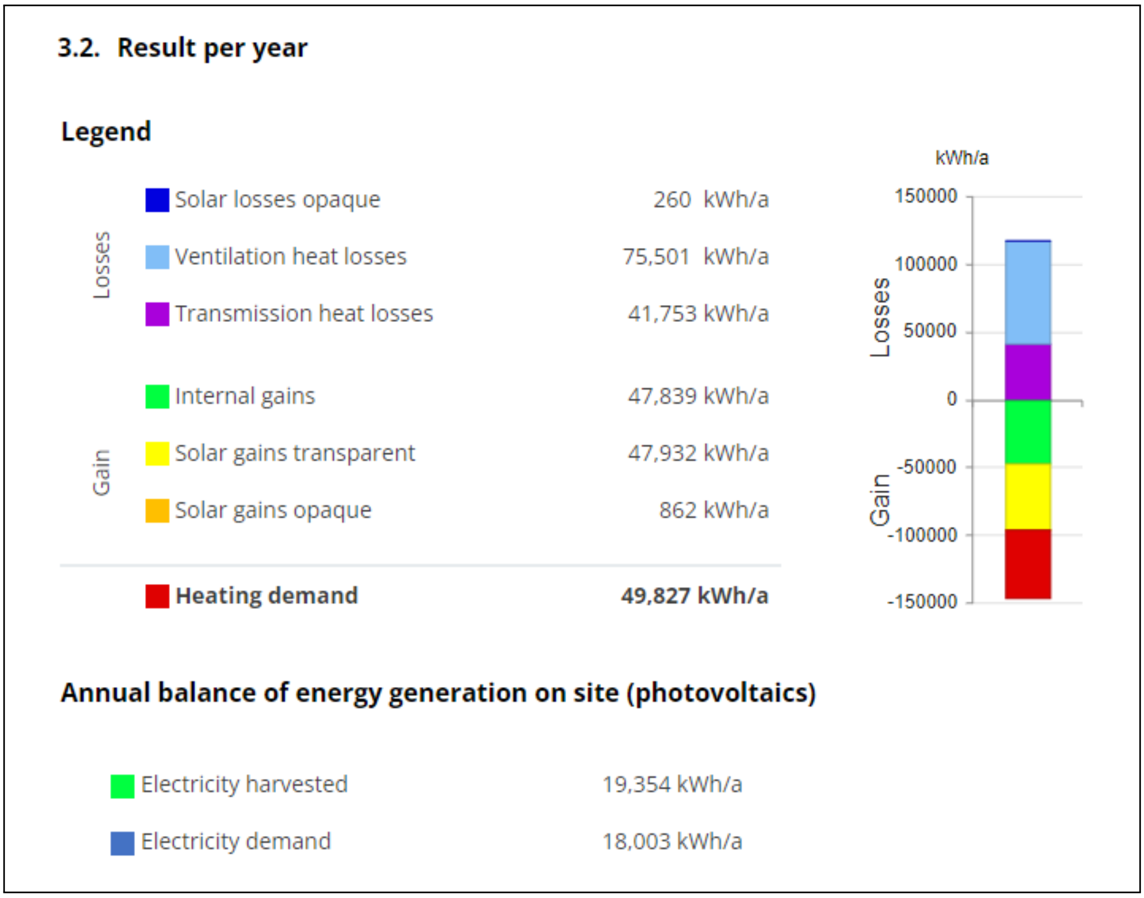


Figure C.11: Operational energy yearly result (screenshot in *CAALA*)

D Data from *One Click LCA*

D.1 Input BOQ, mapped out materials and service life

1. Foundations and substructure 42 Tons CO_2e - 3 %

Materials in the foundations will never be replaced, no matter assessment period length. For BREEAM UK Mat 1 IMPACT equivalent provide the data for site excavation fuel use here, choose resource Excavation works.

Foundation, sub-surface, basement and retaining walls ⇄ Compare answers ▾ Create a group ✥ Move materials Add to compare

Start typing or click the arrow

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers		Service life
Ready-mix concrete, C20/25, 2400 kg ?	172,4	m3	35t - 3%	Foundation + Basement	60	Concrete mixer truck		Not defined	Permanent
Reinforcement for concrete (rebar), ?	3.52	m3	7t - 0,6%	Foundation + Basement	370	Trailer combination, 40		Not defined	Permanent

Figure D.12: Input for foundation and substructure (screenshot in *One Click LCA*)

2. Vertical structures and facade ⓘ 88 Tons CO_2e - 7 %

External walls and facade ⇄ Compare answers ▾ Create a group ✥ Move materials Add to compare

Start typing or click the arrow

Resource	Quantity				CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers		Service life
Damp insulation PA, 0.08 kg/m2 ?	154.21	m2			0,11t - ~0%	Basiswand	430	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	3111.96	m2	x 20	mm	8,2t - 0,7%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	1392.07	m2	x 20	mm	3,7t - 0,3%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	477.99	m2	x 30	mm	2,9t - 0,2%	Basiswand	220	Trailer combination, 40		Not defined	30
Cross laminated timber (CLT), for G ?	372.59	m2	x 30	mm	1,5t - 0,1%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	85.45	m2	x 20	mm	0,23t - ~0%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	2074.64	m2	x 20	mm	5,5t - 0,4%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	955.99	m2	x 30	mm	3,8t - 0,3%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	745.17	m2	x 30	mm	2,9t - 0,2%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	928.05	m2	x 20	mm	2,4t - 0,2%	Basiswand	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	56.97	m2	x 20	mm	0,15t - ~0%	Basiswand	220	Trailer combination, 40		Not defined	60
Wood-fibre insulation board, 0.0 ?	1037.32	m2	x 220	mm	9,7t - 0,8%	Basiswand	350	Trailer combination, 40		Not defined	60
Wood-fibre insulation board, 0.0 ?	152.86	m2	x 220	mm	1,4t - 0,1%	Basiswand	350	Trailer combination, 40		Not defined	60
Extruded polystyrene (XPS), L = 0.0 ?	154.21	m2	x 160	mm	4,9t - 0,4%	Basiswand	430	Trailer combination, 40		Not defined	60
Extruded polystyrene (XPS), L = 0.0 ?	37.86	m2	x 200	mm	1,5t - 0,1%	Basiswand	430	Trailer combination, 40		Not defined	60
Extruded polystyrene (XPS), L = 0.0 ?	31.75	m2	x 160	mm	1t - 0,1%	Basiswand	430	Trailer combination, 40		Not defined	60
Mineral wool (facade insulation), L ?	928.05	m2	x 60	mm	3,9t - 0,3%	Basiswand	60	Trailer combination, 40		Not defined	60
Mineral wool (facade insulation), L ?	1037.32	m2	x 50	mm	3,7t - 0,3%	Basiswand	60	Trailer combination, 40		Not defined	60
Mineral wool (facade insulation), L ?	745.17	m2	x 50	mm	2,6t - 0,2%	Basiswand	60	Trailer combination, 40		Not defined	60
Gypsum plaster board, fire resistan ?	1037.32	m2	x 25	mm	6,5t - 0,5%	Basiswand	60	Trailer combination, 40		Not defined	30
Gypsum plaster board, fire resistan ?	928.05	m2	x 25	mm	5,8t - 0,5%	Basiswand	60	Trailer combination, 40		Not defined	30
Gypsum plaster board, fire resistan ?	745.17	m2	x 25	mm	4,6t - 0,4%	Basiswand	60	Trailer combination, 40		Not defined	30
Gypsum plaster board, fire resistan ?	955.99	m2	x 12,5	mm	3t - 0,2%	Basiswand	60	Trailer combination, 40		Not defined	30
Ready-mix concrete, C20/25, 2400 kg ?	19,19	m3			3,9t - 0,3%	Elevator shaft	60	Concrete mixer truck		Not defined	60
Reinforcement for concrete (rebar), ?	0,39	m3			0,78t - 0,1%	Elevator shaft	370	Trailer combination, 40		Not defined	60
Structural timber, 100 - 240 x 60 - ?	17,38	m3			2,6t - 0,2%	Facade	220	Trailer combination, 40		Not defined	60

Figure D.13: Input for vertical structures and facade (screenshot in *One Click LCA*)

3. Horizontal structures: beams, floors and roofs ⓘ 167 Tons CO_2e - 14 %

Floor slabs, ceilings, roofing decks, beams and roof ⇄ Compare answers ▾ Create a group Move materials Add to compare

Start typing or click the arrow

Resource	Quantity			CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers		Service life
Damp insulation PA, 0.08 kg/m2 ?	365.93	m2		0,52t - ~0%	Basisdach	430	Trailer combination, 40		Not defined	30
Damp insulation PA, 0.08 kg/m2 ?	365.59	m2		0,26t - ~0%	Geschossdecke	430	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	3648.62	m2	x 30 mm	14t - 1%	Brettsperrholz, 2 rows	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	1097.78	m2	x 40 mm	8,8t - 0,7%	Basisdach	220	Trailer combination, 40		Not defined	30
Cross laminated timber (CLT), for G ?	2432.42	m2	x 20 mm	6,4t - 0,5%	Geschossdecke	220	Trailer combination, 40		Not defined	60
Cross laminated timber (CLT), for G ?	731.85	m2	x 20 mm	2,9t - 0,2%	Basisdach	220	Trailer combination, 40		Not defined	30
Soil, compacted dry density, 1650 k ?	363.3	m2	x 200 mm	0,35t - ~0%	Basisdach	40	Dumper truck, 19 ton		Not defined	30
Insulation, EPS solid foam, L = 0.0 ?	365.93	m2	x 220 mm	12t - 0,99%	Basisdach	430	Trailer combination, 40		Not defined	30
Extruded polystyrene (XPS), L = 0.0 ?	365.59	m2	x 200 mm	15t - 1%	Geschossdecke	430	Trailer combination, 40		Not defined	60
PE/PP fleece, 0.5 kg/m2 ?	363.3	m2		0,92t - 0,1%	Basisdach	430	Trailer combination, 40		Not defined	30
Floor screed mortar, cement screed, ?	1157.44	m2	x 60 mm	33t - 3%	Geschossdecke	110	Trailer combination, 40		Not defined	30
Floor screed mortar, cement screed, ?	116.02	m2	x 60 mm	3,3t - 0,3%	Geschossdecke	110	Trailer combination, 40		Not defined	30
Stoneware tiles glazed, 10 mm, 20.0 ?	116.02	m2	x 10 mm	1,5t - 0,1%	Geschossdecke	320	Trailer combination, 40		Not defined	30
Multi-layer parquet flooring, 10.5 ?	1157.44	m2		3,1t - 0,3%	Geschossdecke	220	Trailer combination, 40		Not defined	30
Rock wool insulation panels, unface ?	1157.44	m2	x 40 mm	3,2t - 0,3%	Geschossdecke	60	Trailer combination, 40		Not defined	60
Rock wool insulation panels, unface ?	116.02	m2	x 40 mm	0,32t - ~0%	Geschossdecke	60	Trailer combination, 40		Not defined	60
Damp insulation PA, 0.08 kg/m2 ?	365.93	m2		0,52t - ~0%	Basisdach	430	Trailer combination, 40		Not defined	30
Plastic profile, 980 kg/m3, SBR,/EP ?	363.3	m2	x 10 mm	30t - 2%	Basisdach	430	Trailer combination, 40		Not defined	30
Structural timber, 100 - 240 x 60 - ?	0.023	m3		19kg - ~0%	Holz Träger - rechteckig	220	Trailer combination, 40		Not defined	6
Structural timber, 100 - 240 x 60 - ?	10.42	m3		8,6t - 0,7%	Holz Träger - rechteckig	220	Trailer combination, 40		Not defined	6
Expanded clay aggregate, 715 kg/m3, ?	1157.44	m2	x 100 mm	2,4t - 0,2%	Geschossdecke	110	Dumper truck, 19 ton		Not defined	60
Expanded clay aggregate, 715 kg/m3, ?	116.02	m2	x 100 mm	0,24t - ~0%	Geschossdecke	110	Dumper truck, 19 ton		Not defined	60
Rock wool insulation panels, unface ?	1216.21	m2	x 60 mm	5,1t - 0,4%	Geschossdecke	60	Trailer combination, 40		Not defined	60
Rock wool insulation, for ventil ?	365.93	m2	x 50 mm	2,2t - 0,2%	Basisdach	60	Trailer combination, 40		Not defined	30
Polyethylene foam, L = 0.050 W/mK, ?	363.3	m2	x 40 mm	2,7t - 0,2%	Basisdach	60	Trailer combination, 40		Not defined	30
PE/PP fleece, 0.5 kg/m2 ?	363.3	m2		0,92t - 0,1%	Basisdach	430	Trailer combination, 40		Not defined	30
Geogrid from polypropylene (PP), 0. ?	1157.44	m2		1,5t - 0,1%	Geschossdecke	430	Trailer combination, 40		Not defined	60
Geogrid from polypropylene (PP), 0. ?	116.02	m2		0,15t - ~0%	Geschossdecke	430	Trailer combination, 40		Not defined	60
Gypsum plaster board, fire resistan ?	1216.21	m2	x 12,5 mm	3,8t - 0,3%	Geschossdecke	60	Trailer combination, 40		Not defined	30
Gypsum plaster board, fire resistan ?	365.93	m2	x 30 mm	2,7t - 0,2%	Basisdach	60	Trailer combination, 40		Not defined	30

Figure D.14: Input for horizontal structures, beams, floors and roofs (screenshot in *One Click LCA*)

4. Other structures and materials 18 Tons CO_2e - 1 %

Other structures and materials ⓘ ⇄ Compare answers ▾ Create a group Move materials Add to compare

Start typing or click the arrow

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers		Service life
Structural timber, 100 - 240 x 60 - ?	1.64	m3	0,38t - ~0%	Zusammengebaute Treppe	220	Trailer combination, 40		Not defined	30

Windows and doors ⇄ Compare answers ▾ Create a group Move materials Add to compare

Start typing or click the arrow

Resource	Quantity		CO_2e	Comment	Transport, kilometers		Transport, leg 2, kilometers		Service life
Structural timber, 100 - 240 x 60 - ?	0.94	m3	0,22t - ~0%	TU DF 1 - Rahmenstock	220	Trailer combination, 40		Not defined	30
Structural timber, 100 - 240 x 60 - ?	5.01	m3	1,2t - 0,1%	TU DF 1 - Rahmenstock	220	Trailer combination, 40		Not defined	30
Structural timber, 100 - 240 x 60 - ?	0.6	m3	0,14t - ~0%	TU DF 1 - Rahmenstock	220	Trailer combination, 40		Not defined	30
Steel, stainless, hot rolled, 79 ?	0	m3		Door_SS_The Sliding Door	370	Trailer combination, 40		Not defined	30
Steel, stainless, hot rolled, 79 ?	0	m3		Door_SS_The Sliding Door	370	Trailer combination, 40		Not defined	30
Window glass, single, 7.5 kg/m2 ?	22.47	m2	0,6t - ~0%	Door_SS_The Sliding Door	380	Trailer combination, 40		Not defined	30
Window glass, single, 7.5 kg/m2 ?	10.36	m2	0,28t - ~0%	Door_SS_The Sliding Door	380	Trailer combination, 40		Not defined	30
Triple glazed window, inc ?	221,91	m^2	15t - 1%	Windows	Data by constituent		Data by constituent		Data by constituent

Figure D.15: Input for other structures and materials (screenshot in *One Click LCA*)

D.2 Environmental impact results

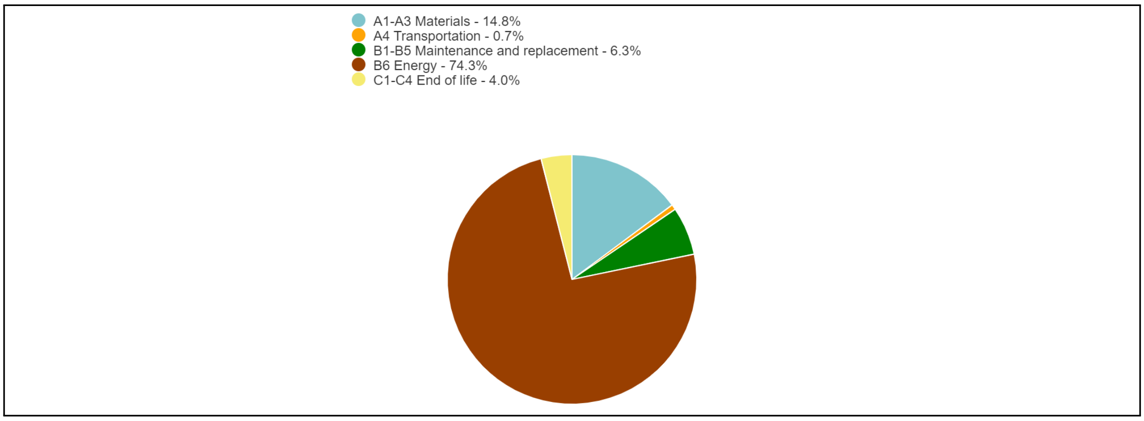


Figure D.16: Global warming potential results (screenshot in *One Click LCA*)

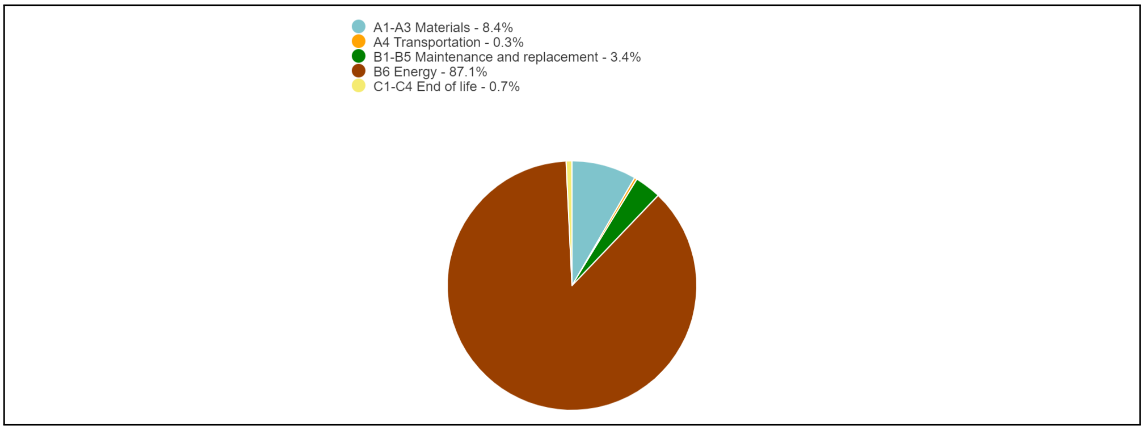


Figure D.17: Acidification potential results (screenshot in *One Click LCA*)

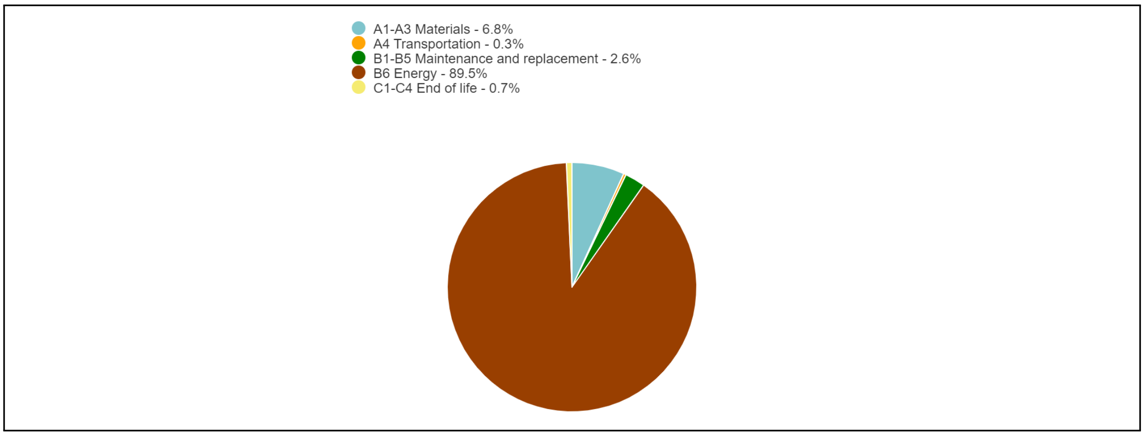


Figure D.18: Eutrophication potential results (screenshot in *One Click LCA*)

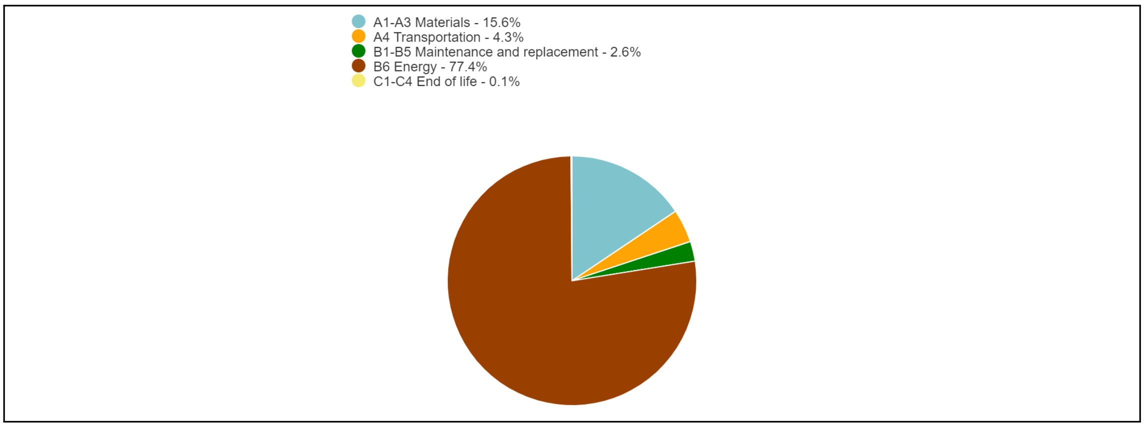


Figure D.19: Ozone depletion potential results (screenshot in *One Click LCA*)

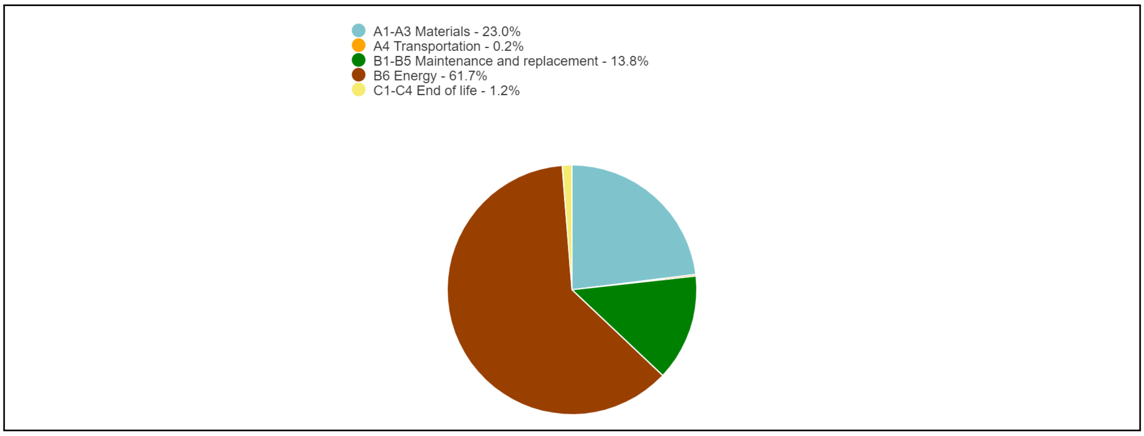


Figure D.20: Photochemical ozone creation potential results (screenshot in *One Click LCA*)

E Room list

Level	Room	Area [m^2]	Level	Room	Area [m^2]
Level -1	Basement compartments	19.51	Level 2	I Living room/ Kitchen	19.39
Level -1	Basment compartments	88.23	Level 2	I Room 1	13.24
Level -1	Corridor	24.07	Level 2	I Room 2	14.02
Level -1	Techincal Room	8.03	Level 2	II Bathroom	5.19
Level 0	Accessible Restroom	4.12	Level 2	II Living room/ Kitchen	22.54
Level 0	Community room	30.06	Level 2	II Room 1	14.02
Level 0	Community room	19.03	Level 2	III Bathroom	1.77
Level 0	Corridor/Gallery	44.93	Level 2	III Bathroom	4.47
Level 0	Coworking	58.33	Level 2	III Living room/ Kitchen	29.12
Level 0	Coworking	13.51	Level 2	III Room 1	13.51
Level 0	Gender neutral Restroom	2.10	Level 2	III Room 2	12.16
Level 0	Laundry room	8.09	Level 2	III Room 3	12.57
Level 0	Library	20.91	Level 2	IV Bathroom	5.80
Level 0	Meeting room	12.50	Level 2	IV Bathroom	2.17
Level 0	Meeting room	16.57	Level 2	IV Living room/ Kitchen	43.18
Level 0	Restroom Men	5.18	Level 2	IV Room 1	12.50
Level 0	Restroom Women	6.04	Level 2	IV Room 2	16.39
Level 0	Sports room	24.94	Level 2	IV Room 3	14.38
Level 0	Staircase	11.71	Level 2	IV Room 4	12.12
Level 0	Study room	17.86	Level 2	Staircase	11.71
Level 0	Technical room	16.35	Level 2	Corridor	21.40
Level 0	Working booth	6.78	Level 3	I Bathroom	5.31
Level 0	Working booth	6.50	Level 3	I Living room/ Kitchen	19.39
Level 1	I Bathroom	5.31	Level 3	I Room 1	13.24
Level 1	I Living room/ Kitchen	19.39	Level 3	I Room 2	14.02
Level 1	I Room 1	13.24	Level 3	II Bathroom	5.19
Level 1	I Room 2	14.02	Level 3	II Living room/ Kitchen	22.54
Level 1	II Bathroom	5.19	Level 3	II Room 1	14.02
Level 1	II Living room/ Kitchen	22.54	Level 3	III Bathroom	1.77
Level 1	II Room 1	14.02	Level 3	III Bathroom	4.47
Level 1	III Bathroom	1.77	Level 3	III Living room/ Kitchen	29.12
Level 1	III Bathroom	4.47	Level 3	III Room 1	13.51
Level 1	III Living room/ Kitchen	29.12	Level 3	III Room 2	12.16
Level 1	III Room 1	13.51	Level 3	III Room 3	12.57
Level 1	III Room 2	12.16	Level 3	IV Bathroom	5.80
Level 1	III Room 3	12.57	Level 3	IV Bathroom	2.17
Level 1	IV Bathroom	5.80	Level 3	IV Living room/ Kitchen	43.18
Level 1	IV Bathroom	2.17	Level 3	IV Room 1	12.50
Level 1	IV Living room/ Kitchen	43.18	Level 3	IV Room 2	16.39
Level 1	IV Room 1	12.50	Level 3	IV Room 3	14.38
Level 1	IV Room 2	16.39	Level 3	IV Room 4	12.12
Level 1	IV Room 3	14.38	Level 3	Staircase	11.71
Level 1	IV Room 4	12.12	Level 3	Corridor	21.40
Level 1	Staircase	11.71	Level 4	Corridor	12.10
Level 1	Corridor	21.40	Level 4	Corridor	12.14
Level 2	I Bathroom	5.31	Level 4	Rooftop	298.09