A New Evaluation Methodology to Identify the Effects of Sufficiency Aspects on the Sustainability of Residential Buildings

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Abstract

Housing has a vast impact on our environment and society. This impact has categories with certain limits. Some of these limitations are given by the planet. They range from resource shortages to climate change. The boundaries in the social field result from the society that we, as citizens of the world, want to have. It includes aspects such as social justice. Strategies can help us to stay within these boundaries. Sufficiency is a promising strategy that focuses on achieving sustainability goals through changes in human behavior. While it has yet to gain much attention concerning residential buildings, some general concepts and criteria have demonstrated their worth in theory. So far, no evaluation system assesses all impacts of housing with consideration of the limitations. An evaluation system based on the Doughnut Economics model of Kate Raworth meets this requirement. This system allows analyzing the effects of sufficiency aspects on housing in a case study. Thereby one learns about the sufficiency aspects of housing. The results additionally give the knowledge to improve the evaluation system.

An examination of strengths, weaknesses, opportunities, and threats for the sufficiency aspects personal living space, energy demand, and low-tech gives an overview. These aspects are tested in a case study on a standard multi-family home which concerns the global warming potential, representing the global environmental impact, and affordability, representing social local factors. All aspects reduce the global warming potential. But none of the applied sufficiency aspects lowers the effect to a level compatible with the evaluation system's boundaries. Besides this, the aspects of personal living space and energy demand improve housing affordability by reduced costs. In general, sufficiency aspects affect housing's social and environmental impact, and the evaluation system helps to understand these effects. Other strategies must accompany sufficiency to reach more sustainability. Further research, application to real-world buildings, and the enhanced evaluation system guide us into strong sustainability in housing.

Kurzzusammenfassung

Der Lebensbereich des Wohnens hat durch diverse Abhängigkeiten großen Einfluss auf Umwelt und Gesellschaft. Die ökologischen Grenzen sind durch die Kapazität unseres Planeten gegeben. Dabei müssen mehrere Kategorien von der Ressourcenknappheit bis hin zum Klimawandel beachtet werden. Die sozialen Grenzen legt die Gesellschaft fest. Dabei werden unter anderem Aspekte wie die soziale Gerechtigkeit beachtet. Um innerhalb der Grenzen zu bleiben, benötigen wir Strategien. Die Suffizienz ist eine von drei Strategien, welche die Nachhaltigkeitsziele durch Veränderungen im Verhalten erreicht. Besonders im Bereich der Wohngebäude hat die Suffizienz erst wenig Aufmerksamkeit erlangt. Einige Konzepte beweisen ihre Wirksamkeit bereits in der Theorie. Es existiert kein Bewertungssystem, welches alle Auswirkungen der Suffizienz auf das Wohnen erfasst. Das in dieser Arbeit entwickelte Bewertungssystem basiert auf dem Doughnut Economics Modell von Kate Raworth. Anhand des Systems werden die Auswirkungen von Suffizienzaspekten auf das Wohnen in einer Fallstudie analysiert. Die Fallstudie erlaubt Rückschlüsse auf die Wirksamkeit der Aspekte und die Eignung des Bewertungssystems.

Die Arbeit untersucht die Suffizienzaspekte persönliche Wohnfläche, Energiebedarf und Low-Tech auf Stärken, Schwächen, Chancen und Risiken. In der Fallstudie wird an einem durchschnittlichen Standard-Mehrfamilienhaus die Wirksamkeit der Aspekte in Bezug auf globales Erwärmungspotenzial und Bezahlbarkeit ermittelt. Das Erderwärmungspotenzial repräsentiert Auswirkungen auf die Umwelt im globalen Kontext. Die sozialen Faktoren werden mit lokalem Bezug anhand der Bezahlbarkeit betrachtet. Alle betrachteten Aspekte reduzieren das globale Erwärmungspotenzial, dabei jedoch kein Niveau erreicht wird, welches mit den gegebenen Grenzen vereinbar ist. Die Aspekte persönliche Wohnfläche und Energiebedarf verringern die Kosten für den Wohnraum. Alle Suffizienzaspekte haben eine Wirkung auf die sozialen und ökologischen Auswirkungen des Wohnens. Das Bewertungssystem kann helfen, diese Auswirkungen zu verstehen. Um die Grenzen einzuhalten, muss Suffizienz von weiteren Strategien begleitet werden. Eine vertiefte Forschung im Bereich der Suffizienzaspekte und ein verbessertes Bewertungssystem werden dazu beitragen, dass Nachhaltigkeit im Wohnungsbau erreicht wird.

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Content

List of Abbreviations

BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung
BREAM	Building Research Establishment’s Environmental Assessment Method
BNB	Bewerungssystem Nachhaltiges Bauen
DEAL	Doughnut Economics Action Lab
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DIN	Deutsches Institut für Normung
eLCA	environmental Life Cycle Assessment
EnEV	Energieeinsparverordnung
GEG	Gebäudeenergiegesetz
GFA	gross floor area
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
PE	Primary Energy
PERT	Primary Energy from Renewable Sources Total
PENRT	Primary Energy from Nonrenewable Sources Total
SDGs	Sustainable Development Goals
SIA	Schweizerischer Ingenieur- und Architektenverein
sLCA	social Life Cycle Assessment

SWOT	strengths, weaknesses, opportunities, and threats
UN	United Nations
LA	living area
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LEED	Leadership in Energy & Environmental Design
VDI	Verband Deutscher Ingenieure

1. Introduction

1.1. Guiding Principle

An increasing number of people worldwide realize that human existence and the health of the earth are interconnected. Germans rate the protection of the environment and climate as the most critical challenges the country faces (Benthin, Gellrich, & Williams, 2019). Nevertheless, the responsible institutions do not stop exploiting our planet's limited resources and form its shape and biological cycles to benefit short-term human needs. These actions lead to a threat to the future of humankind and other species. Most of the earth's states, represented in the United Nations (UN), aim to achieve the 1.5°C target. But the Intergovernmental Panel on Climate Change (IPCC) shows us that more and faster action is needed (IPCC, 2018). The German government is not doing enough to stay within the corridor of the 1.5°C warming (Kobiela et al., 2020). To achieve this target, rapid action, in every field of life, is required.

Within this thesis, I concentrate on the built environment. The construction and real estate sector is the largest consumer of raw materials and energy worldwide (International Energy Agency, 2020). In Germany, the construction sector is responsible for 53.4% of the waste (Statistisches Bundesamt, 2017) and about one-third of the CO_2-emissions (Ürge-Vorsatz, Danny Harvey, Mirasgedis, & Levine, 2007). Even though the literature shows a consensus that a more intense connection and interaction of technology and social studies is essential for sustainability (Jackson, 2012; Paech, 2016, 2020; Precht, 2020), the building sector focuses almost exclusively on technical issues, whereas social aspects have not been given much weight up till now (Figure 1). For this reason, I see a high potential in supporting a healthy future for the planet and humankind by intensively analyzing the connection of social aspects and the built environment.

Figure 1 Imbalance of technology and social aspects in the building sector

Sufficiency is, next to efficiency and consistency, one primary sustainability strategy. It is the strategy closest related to social aspects. The building industry rarely applies this strategy. The rare application derives from the lack of scientific work, built examples, and the psychological effects related to the negative mindset towards sufficiency. Housing has the highest and increasing turnover within the building sector since 2008 (Statista, 2020). Stakeholders in housing do not yet understand the potential of sufficiency and have only a little knowledge about the strategy. Environmental and social indicators allow capturing the full potential of sufficiency aspects in housing. Sufficiency aspects affect many fields and do not focus on improving one environmental impact category alone. So far, there is no appropriate method to evaluate the full impact of human behavior and social aspects. Thus, my motivation is to develop an evaluation system that allows us to understand the interconnections of the social and ecological dimensions. The knowledge about the potential and the balance of social and economic aspects will allow housing companies, architects, and planners to lead the housing sector into a sustainable future actively.

1.2. Objective

German scientists increasingly discuss sufficiency in housing (Kunkel, Steffen, Bierwirth, & Kopatz, 2015), but it is rarely applied (Auer et al., 2020). Scientists state that a building's planning process should implement sufficiency aspects (Lang, 2019; Zimmermann, 2018). Both architects and building planners lack knowledge about sufficiency aspects and miss the motivation to introduce them. The reasons are manifold and reach from inefficiency in economic terms to a lack of regulation, such as laws (Bierwirth & Thomas, 2019). Besides this, stakeholders fear the extent and uncertainties of applying sufficiency. Because of this uncertainty, they hesitate to use the strategy. The uncovering of opportunities for sufficiency in housing will reduce the uncertainty about it.

This thesis shows that sufficiency is crucial to adhere to the limits of the planet and society. These limits are respected if the building's impact does not exceed planetary boundaries and the people living in the building are still able to fulfill their social and individual needs. Since existing evaluation systems only sometimes give strict limit values and do not grasp a residential building's effects to the extent needed, a new evaluation system that aims for strong sustainability with a scientific background is reasonable. This evaluation system focuses on social limits and environmental boundaries. Whether sufficiency aspects allow a building to stay within these boundaries can be shown in a case study. The study examines the effects of sufficiency aspects on selected indicators of the evaluation system. Actors in housing can use this new information and find the motivation to implement the underestimated sufficiency goals.

1.3. Methodology

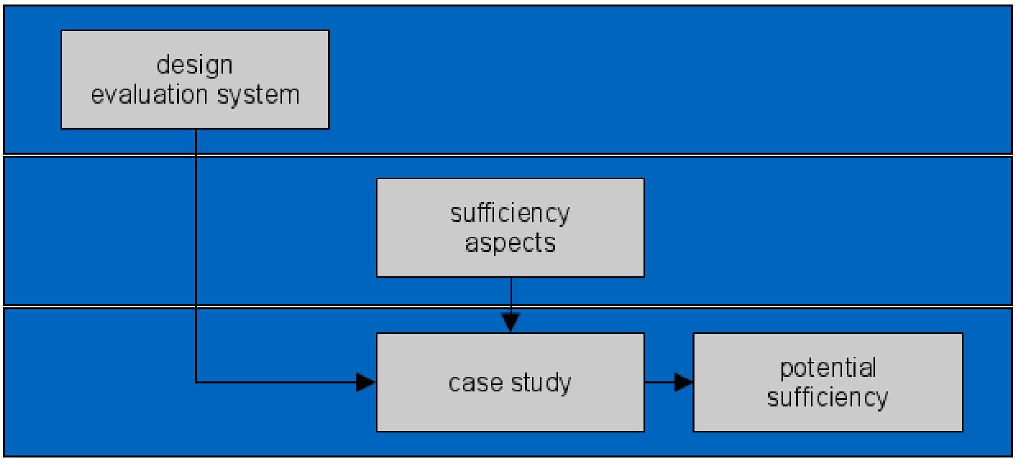

Figure 2 Methodology

Figure 2 shows the methodology. After designing the evaluation system and defining sufficiency aspects, a case study allows evaluating the ideas. The basis for the evaluation system and sufficiency aspects is the literature review. This literature review in chapters 2 and 3 is the theoretical framework and embeds the practical work (Onwuegbuzie & Frels, 2016). Starting from this basis, chapter 2 describes the new evaluation system for housing inspired by Kate Raworth's Doughnut Economics (Raworth, 2017a). The model of doughnut economics comprises indicators for social and ecological impacts. The Doughnut Economics Action Lab (DEAL) used the model to evaluate a city. This existing work allows the transformation of the economic model into an evaluation system of residential buildings.

A benefit analysis helps select material and construction-related sufficiency aspects from Zimmermann's research (Zimmermann, 2018). With the strengths, weaknesses, opportunities, and threats (SWOT) analysis in chapter 4, one gets an idea of each aspect's quality and issues. In the case study (chapter 5), these sufficiency aspects result in several building variants of a standard building. The standard building refers to a building used by the working group for contemporary construction (Arbeitsgemeinschaft für Zeitgemäßes Bauen) (Walberg, Gniechwitz, Schulze, & Cramer, 2014). The case study indicators come from the new evaluation system and identify the effects of sufficiency on housing impact. The study energetic and economic optimization of multi-dwelling units gives the frame for the calculations in the case study (Knallinger, 2018).

2. Evaluation System

2.1. Strong Sustainability

Hans Carl von Calowitz, a German aristocrat, used the term sustainability for the first time for a forestry strategy in the 17th century. Sustainability in forestry is about stability and the ability of a forest to regenerate. Besides this, society developed an understanding of the ecological system and its protection. Rachel Carson showed in her book Silent Spring from 1960 the complexity of relationships within the food chain. She illustrated that the use of pesticides in agriculture has a negative influence on living beings. Her action led to the still-lasting rise of environmental movements and organizations (Radkau, 2011). Along this way, the Brundtland-Report in 1987 formulated today's understanding of sustainability. The report was the basis for the United Nations Conference on Environment and Development in Rio de Janeiro 1992, where the UN has created the foundation for international environmental diplomacy.

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:
>
> The concept of ‚needs ', in particular the essential needs of the world's poor, to which overriding priority should be given; and
>
> The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."
>
> (Brundtland, 1991)

This definition led to the pillars of ecological, social, and economic issues. The Enquete Commission "Protection of human and Environment" (Enquete-Kommission zum “Schutz des Menschen und der Umwelt”) developed a concept of sustainability and describes those three issues as pillars of sustainability (Enquete-Kommission "Schutz des Menschen und der Umwelt", 1998). Pufé (2012) and others state that a change to sustainability dimensions is reasonable because they do not stand next to each other but are connected (Pufé, 2012). The ecological dimension of sustainability is related to nature and environmental systems. These systems support all beings with essential demands, such as land, water, air, and food. The social dimension concerns human interaction, such as how people live together, behave, and where people want to thrive as a community. Finally, the economic dimension is necessary to make this happen and give a frame to humans' interaction. The economy manages resources from the ecology and society. The constitutions of several democratic countries say that the economy aims to support the common good (Felber, 2014).

The UN is working on goal definitions concerning all dimensions and subcategories of sustainability and wants to find a consensus for the international community. The first step was defining the Sustainable Development Goals (SDG) within the 2030 Agenda in 2015 (United Nations, 2015). With the SDGs, the UN aims to raise awareness and make a complex topic more specific and ascertainable. In Figure 3, the Stockholm Resilience Centre shows the SDGs by order of social, economic, and ecologic dimensions of sustainability. This order has the four ecological-related SDGs as the basis for the other dimensions. With aim 17: Partnership for the goals, all SDGs are covered and connected.

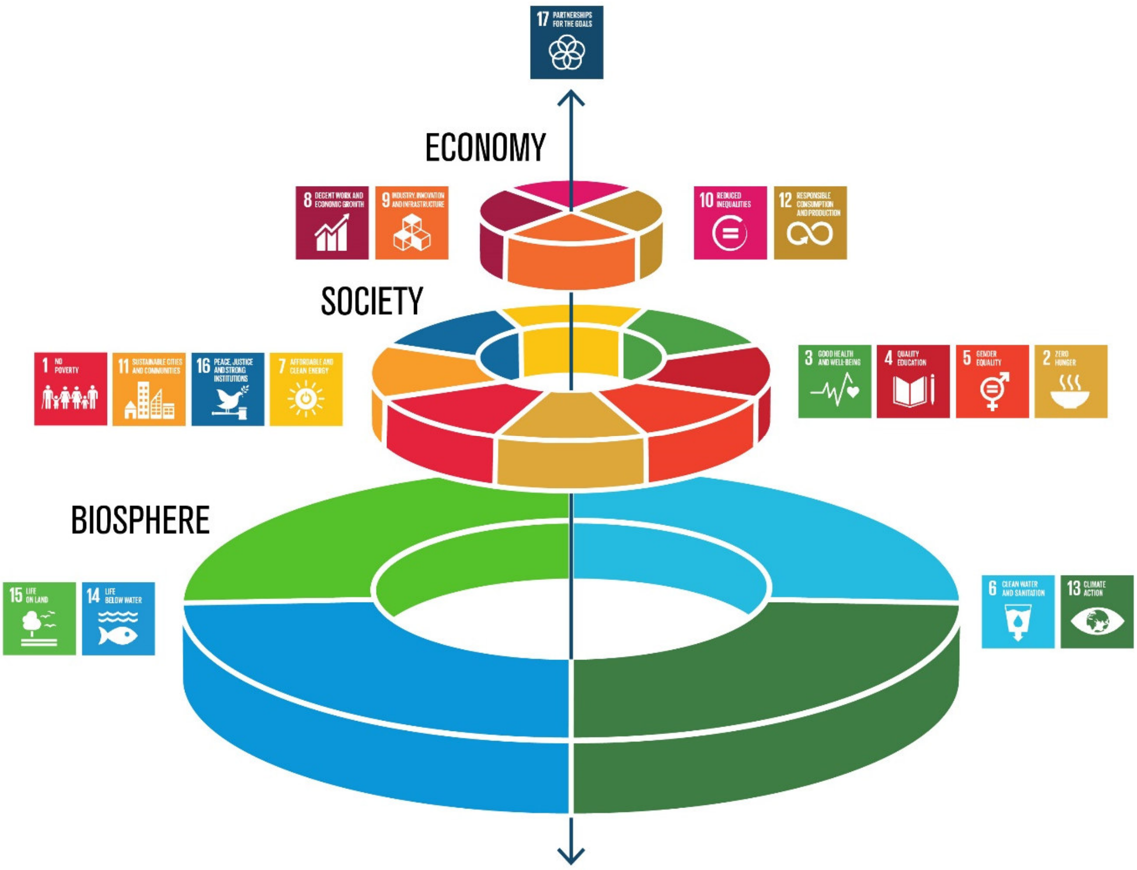

Figure 3 SDG's with sustainability dimensions (Stockholm Resilience Centre, 2016)

The SDGs show the connection of sustainability to various topics. Furthermore, two positions or understandings are contrasting each other: weak and strong sustainability. Scientists talk about weak sustainability if humans and their needs are in the center and substitution of nature capital by economic capital with the help of technology is possible (Döring, 2004; Neumayer, 2013; Pufé, 2012). The total of resource, physical, and human capital is constant, and an exchange between the three is possible. The decoupling of resource usage and economic growth is necessary (Pearce, 1992). Strong sustainability focuses on the environment, and the natural capital stays constant (Döring, 2004; Neto Oliveira, Pinto, Amorim, Giannetti, & Almeida, 2018). Figure 3 implies that the biosphere or the ecological aspect is either the basic or the envelope for the other aspects. Many scientists argue that strong sustainability is the only legitimate way of sustainability (Biely, Maes, & van Passel, 2018; Pelenc, Ballet, & Dedeurwaerdere, 2015; Welzer, 2019). But obstacles like risks, uncertainty, and ignorance counteract this alignment (Neumayer, 2013). The precautionary principle is an argument to support strong sustainability. The principle is about taking action, even if the negative impact is not happening with a hundred percent certainty (Bourguignon, 2016). Some argue that this would be a hindrance to progress and growth. Others found that thriving is possible without growth (Paech, 2020; Raworth, 2017a). If thriving is the aim, growth is not mandatory. A necessity is an economic system and a society that enables and supports strong sustainability (Daly, 1996). Therefore, information about strong sustainability is crucial.

Strong sustainability demands a balance of nature and human action. One can only reach this by staying within the given borders. The limit of the ecology is the framework for action. Humankind is not yet at the stage where unlimited sources of energy and resources are available. Kardaschow (1964) suggests other types of energy utilization within this universe (Kardaschow, 1964). So maybe one day, the limit of the planet will get extended. The use of other sources of energy and resources in the universe will allow this. So far, the planet is finite in size, resources, and especially area surface. The Earth Overshoot Day is a campaign day to illustrate that humankind is already living far beyond the planet's resource capacity. The Global Footprint Network calculates this day each year (Global Footprint Network, 2020). The researchers from the Stockholm Resilience Center classified the ecological limits (Rockström et al., 2019). Nine indicators and their thresholds show the planetary boundaries. The scientists still define thresholds and reduce uncertainties for others.

One can not always define the limits to the social system in numbers. This is why the evaluation of the social dimension needs other evaluation approaches. One approach to evaluating the social dimension is analyzing a persons' well-being and relationships between humans. The Cambridge Dictionary defines well-being as "the state of feeling healthy and happy" (Cambridge English Dictionary, 2020). The feeling of health and happiness can define a limit. Feelings are individual for each person and subjective quality of consciousness (Arnold Elysenck, 1997). With this definition, limits refer to the person. Strict thresholds valid to everyone are hard to define. However, some basics can be found for a specific group in their culture as common sense. Social responsibility and equal chances for development are the frameworks for possible limits. A person's health needs air, water, and food as a basis. Other fields of well-being are connected to the economy as well. The subsistence minimum is the least adequate income to live an appropriate life. In Germany, this minimum is as much as 9,408 € per year in 2020 (Deutscher Bundestag, 2019).

The limits of social and economic aspects result in a limit of growth in the economy. Most of the global north countries have an economic system to achieve an ever-growing gross domestic product. These systems use ideas of the neoclassic. This idea bases on assumptions made in the past, which are maybe not up-to-date anymore (Felber, 2019). An increasing number of economics researchers found that moderate economic growth is essential for a sustainable future (Jackson, 2012; Paech, 2016; Sachs, 1993; Welzer, 2019). This finding is contrary to the steep increase seen since the end of the last century. Meadows (1972) published a book for the Club of Rome in the 1970s, where he showed that the economy's growth is limited (Meadows, 1972). The updates at the 30th and 40th anniversary still show similar results, and the basic ideas of the first book are supported (Randers, 2012). Schumacher and others developed ideas to think about the economy and its application in enterprises differently (1993). The idea was that a small-scale economy could better comply with the given limits. These ideas have not found their way into the mainstream.

There are limits in every dimension of sustainability. This knowledge needs other ways of thinking and new ideas to deal with the accompanying problems. Even if there are no characteristic figures to define the boundaries, they still exist and should not be overshot (Arnsperger & Deibler, 2017; Princen, 2005). The faith in everlasting growth is not the solution for this problem. A radical change with an stabil social system is needed (Pufé, 2012; Welzer, 2019; Welzer & Wiegandt, 2014). To get to this next level in human evolution, one needs transformative action.

2.2. Sustainability in Housing

2.2.1. Housing

Housing describes a basic human need. A house gives shelter from environmental influences for people. Such influences may be the weather condition or wild animals. Humans moved from an ecological system – nature – into a self-build biosphere – dwellings (Auer et al., 2020). But today, housing is even more. A person's expectations concerning his or her home vary widely. This variation starts with safety in terms of personal safety and safety of the belongings (Weidemann, Anderson, Butterfield, & O'Donnell, 1982). It ends with the expression of creativity and self-actualization on top of basic needs (Hasse, 2009). In between, there is a broad field of expectations, dependent on individual preferences. The German government has agreed on democratic values, one of which states that every citizen should reach their housing expectations without threatening others' rights.

The inside of a building has a significant role in everyday life. Pluschke found that Germans spend 90% of their time indoors (1996). Houses, offices, public transport, and cars are regarded as indoor areas as well. By fulfilling basic needs, buildings are the basis for the social and economic life of today. These basic needs include shelter conditions, which must be in the individual's comfort zone. The comfort in temperature ranges from 20 to 26 degrees Celsius depending on the metabolism, clothing, a four other factors (Fanger, 1972). Next to housing, humans have other interests and needs. The need for mobility, for example, is connected to the location of a building. In an urban area, public transport can be sufficient to fulfill mobility needs. Rural areas tend to need individual transportation systems. These dependencies find attention within the evaluation system.

2.2.2. Current Situation in Germany

In Germany, the link between sustainability and housing has already found some attention. The German government has introduced a National Sustainable Development Strategy. In this strategy, the government aims to bring the SDGs into practice and applies them at the national level (Presse- und Informationsamt der Bundesregierung, 2018). This strategy concerns housing as well. Several existing laws and regulations, such as the energy-saving ordinance (Energieeinsparverordnung - EnEV) or the building energy law (Gebäudeenergiegesetz - GEG), already aim for sustainable housing. But the strategy paper calls for actions beyond this. The guide to sustainable building

(Leitfaden Nachhaltiges Bauen), published by the German government, supports the sustainable approach and has been developed further in the last years (Bundesministerium des Innern, für Bau und Heimat, 2019). New governmental buildings will stick to this and thereby serve as role models.

Besides the official regulations and efforts of the government, there are several other approaches. There is scientific research in this field at several universities and institutions. Private persons and companies support sustainability as well. Examples of this are the passive house institute (Passivhaus Institut) or the idea of energy plus houses (Hegger, Fafflok, Hegger, & Passig, 2016). Another example is housing cooperatives like wagnis eG in Munich that focus on sustainability. New concepts that help to reach more sustainability need private initiatives as well. The use of straw as a renewable resource is only one of many examples. Pioneers show that this material can serve as insulation or load-bearing construction (Minke & Krick, 2014). Figure 4 shows an example of a self-supporting straw construction. All these approaches show that sustainable housing in Germany is possible and already exists. But so far, there is no one definition of what sustainable housing exactly is.

Figure 4 Straw construction (Forschungsinstitut für Wärmeschutz e.V., 2020)

2.2.3. Evaluation

Stakeholders have various positions on sustainability in housing today. These positions towards one of Germany's current topics range from acceptance and support to concerns about its relevance and importance. An evaluation system helps to communicate the idea of sustainability in the field. Additionally, such systems evaluate and ensure the quality of buildings concerning sustainable aspects. In Germany, the total number of buildings with a certificate for sustainable buildings rises. The increasing investment volume is 11.5 billion € for green buildings and 39.6 billion € for buildings without a certificate in 2019 (Statista, 2019).

The internationally valid and well-established evaluation systems for sustainable buildings in Germany are the German seal of approval for sustainable building (Deutsches Gütesiegel Nachhaltiges Bauen) from the German sustainable building Council (Deutsche Gesellschaft für Nachhaltiges Bauen - DGNB), the label Leadership in Energy & Environmental Design (LEED) and the Building Research Establishment's Environmental Assessment Method (BREEAM) (Hauser, Eßig, & Ebert, 2010).

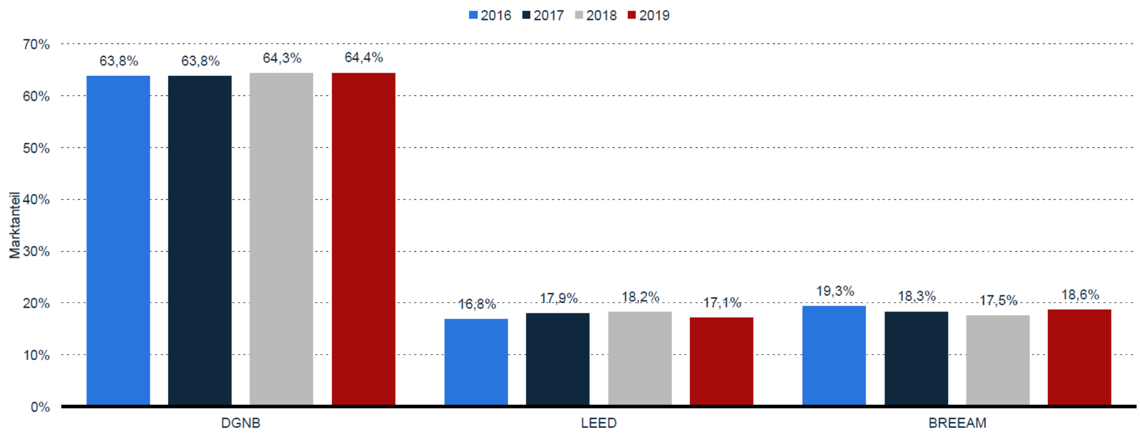

Figure 5 Market shares DGNB, LEED, and BREAM in Germany (Statista, 2019)

Figure 5 shows the market shares of these certificates in previous years. DGNB has the leading share in Germany. The English certificate BREEAM and the North American label LEED are from the first generation. First-generation means that they were introduced in the 1990s and focus on the ecological criteria of the building impact. The German DGNB is from the second generation, based on the first generation (Hauser et al., 2010). The DGNB integrates an economic perspective. This additional view allows a rating of the sustainable quality of buildings based on the three pillars of sustainability (chapter 2.1). Hauser et al. (2010) give an overview and detailed information about existing evaluation systems.

Besides those most common evaluation systems, there are also other less known ones. The German government supports the sustainable building rating system (Bewertungssystem Nachhaltiges Bauen - BNB). This evaluation system is based on research from the Federal Institute for Research on Building, Urban Affairs, and Spatial Development (Bundesinstitut für Bau-, Stadt- und Raumforschung - BBSR). The basis of the DGNB and the BNB is the same. But both systems have developed independently from one another due to disagreement. In Switzerland, Minergie is a building standard from the economy and the government with an integrated certification (MINERGIE Schweiz, 2020). Another evaluation system is the WELL certification which focuses on the well-being and health of the persons in the building (International WELL Building Institute, 2020). In contrast, the living building challenge by the international living future institute aims for buildings as an organism and not as machines anymore. With this approach, buildings fit into nature and do not harm it (Robertson, 2014). The international living future institute focuses on positive aspects and gives positive examples to the building industry.

> *"To be certified as a Living Building, a building must generate its own energy using renewable resources, must capture and treat its own water through ecologically sound techniques, must use only nontoxic, regionally sourced materials, must be healthy and not be harmful to its occupants or its environment, and must be beautiful."*
>
> *(Robertson, 2014)*

The certificates and evaluation systems mentioned indicate the performance with existing standards. They show where the building is better than the average or where the building performs better than the law but do not evaluate planetary and social limits. The third generation could aim at limits within a holistic view of ecological, social, and economic approaches.

2.2.4. Life Cycle Sustainability Assessment

Evaluation systems for sustainable housing often demand a Life Cycle Assessment (LCA) for certified buildings as an essential part or even the evaluation's first criterion (DGNB). Together with the Life Cycle Cost (LCC), this criterion has the highest weight of all criteria (Frank, 2020). An LCA analyzes the impact of a product over the life cycle in impact categories. In the example of the DGNB criterion, the LCA analyzes environmental impacts and is called an environmental Life Cycle Assessment (eLCA). However, the environment is only one dimension of sustainability (chapter 2.1.).

In contrast, Life Cycle Sustainability Assessment (LCSA) allows looking at all three dimensions (Finkbeiner, Schau, Lehmann, & Traverso, 2010). This concept includes eLCA, social Life Cycle Assessment (sLCA), and an LCC (Kloepffer, 2008). One can use this holistic idea for all kinds of products. There is no standard for sLCA, but scientists examine the relevance and application of the assessments (Traverso, 2018). With a uniform approach for the sLCA, a standardization of LCSA is within reach.

The eLCA is standardized and will be improved with current research on the impact categories, for example. The eLCA considers the material and the construction or assembly of a product. Because data collection is standardized, the resulting balance sheet can be used for communication, improvement, and comparison. The two standards making this possible are the 'DIN EN ISO 14040 Environmental management – Life cycle assessment – Principles and framework' and the 'DIN EN ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines'. The standards capture the entire life cycle of a product by defining the following objectives:

"– identifying opportunities to improve the environmental performance of products at various points in their life cycle,

– informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),

– the selection of relevant indicators of environmental performance, including measurement techniques, and

– marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration)."

(DIN EN ISO 14040)

To achieve these goals, an LCA creator must follow these steps according to the DIN EN ISO 14040: *"the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase"*. The named publications give a detailed description of each of those steps. Creating an eLCA leads through an iterative process by fulfilling the steps and requirements.

The product under surveillance in the case of housing is a building. The effects on the ecosystem from the built environment are various and difficult to track. Because of the complexity, the German Institute for Standardization (Deutsches Institut für Normung e.V. - DIN) has introduced the 'DIN EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products' and the 'DIN EN ISO 15978 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method'. They provide a framework for understanding the impact of the life cycle of a building on the biosphere. Figure 6 shows the separation into the phases of production (A1-A3), construction (A4-A5), usage (B), and disposal (C). For additional information, like reuse and recycling, there is phase D. The phases allow a complete record of all effects.

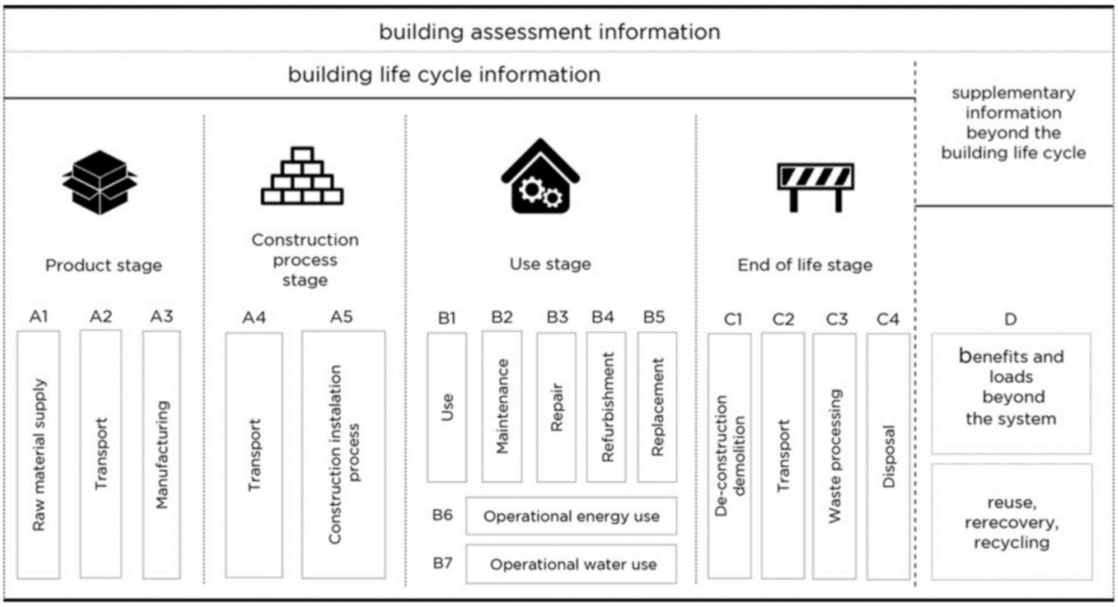

Figure 6 Building life cycle in Soust-Verdaguer, Llatas, and García-Martínez (2016)

These standards' main goal is to support the architect and planner in the conception of a building. Planners can use the early stage eLCA to improve the building's environmental impact to the greatest extent possible (Braune & Ruiz Durán, 2018). The Federal Ministry of the Interior, Building and Community (Bundesministerium des Inneren, für Bau und Heimat - BMI) operates the database OEKOBAUDAT. This database is a source for the input data needed in an eLCA (Figl, Kerz, Kusche, & Rössig, 2019). Scientists use the eLCA as a basis for discussing a building's environmental impacts. Besides reducing the environmental impacts, other aims are to record improvements and raise awareness among the clients and customers.

The Life Cycle Initiative adopts the idea of the eLCA to social and sociological aspects. A result of this is the sLCA. Here the general approach from DIN EN ISO 14040 is adopted with indicators that refer to social criteria (Life Cycle Initiative, 2020). The newly developed method supports social effects assessment (Tokede & Traverso, 2020; Wu, Yang, & Chen, 2014). There is still discussion on which criteria should be taken into account, and the sLCA is not often used yet (Feschet et al., 2013; Jørgensen, Le Bocq, Nazarkina, & Hauschild, 2008). Further work in this field gives the framework to evaluate complex products like buildings in the same way as the eLCA does today.

The LCC concerns the costs of a product. The origin of the term LCC is within the military's investment planning in the United States in the 1960s. Today in science, LCC is widely discussed and focuses on the whole life cycle's cost calculation (Günther, 2006). Tradeoffs between investment costs and upcoming costs are considered (Zehbold, 1996). More money spent in the investment phase may result in fewer costs in the usage phase or vice versa. Knowledge about the product life cycle and the resulting expenditure is essential (Fabrycky & Blanchard, 1991). Several existing methods from business economics allow us to look at them. The upcoming awareness of environmental costs led to new methods for calculation (Günther, 2006). In housing, environmental costs result from CO_2-emission pricing (Schneider-Marin & Lang, 2020). Such expenditures will have an influence on the construction sector in the future. The LCC splits into goal definition, determination of alternatives, information collection, and decision making (Fabrycky & Blanchard, 1991). Within the sustainability context, the LCC is a practical evaluation concerning the economic dimension. The LCC follows the 'DIN 60300-3-3:2004 dependability management – Part 3-3: Application guide – Life cycle costing'. The 'DIN 276:2018-12 Building costs' gives categories for the expenses of a building. It is the basis for total building costs and the accounting of services according to architects and engineers' fee schedules (Honorarordnung für Architekten und Ingenieure). The Association of German Engineers (Verband Deutscher Ingenieure - VDI) gives a guideline for the technical building equipment: 'VDI 2067:2012 Wirtschaftlichkeit gebäudetechnischer Anlagen – Grundlagen und Kostenberechnung'. Further, the directive 2010/31/EU of the European parliament about the energy performance of buildings and the addition Commission delegated regulation (EU) No 244/2012 (European Union, 2012) give a calculation method for cost optima of energy performance. With these tools, an LCC for residential buildings can be created.

The LCSA for buildings lacks information and rules. Especially the sLCA comes with many uncertainties. For eLCA and LCC, there is enough information to start right away. The implementation of the LCSA within laws and regulations could follow the same path that regulations regarding energy demand follow (Schneider-Marin et al., 2020). The motivation to introduce one of the LCA approaches in housing mainly derives from certificates like DGNB. Only a few have used it to look at their environmental impact and draw a conclusion from this (Schneider-Marin, Harter, Tkachuk, & Lang, 2020), even though precisely this is what sustainable housing would need. The LCSA does not recognize the positive effects a building has. The approach is about collecting data and the impact on several fields. The LCSA does not give any limiting figures for the collected data in these various fields. Such limits and a method to define them can be found in doughnut economics.

2.3. Doughnut Economics

Chapter 2.1 presents the limits of growth as well as the limits in every dimension of sustainability. Some scientists in economics develop new ideas for an economy that acknowledges the limits and aims for sustainable development. Felber introduced the Economy for the Common Good, where the common good is in the center of attention (2014). Others suggest a post-growth economy (Paech, 2016). This new idea for the economy is about another focus of work and the production of goods and services. Reduced gainful employment will allow more human resources into noncommercial work. This shift of focus comes with positive side effects for the individual and the community.

Doughnut economics is another approach to tackle the problem of limited growth. This economic system does not focus on the growth of the gross domestic product. Raworth (2017c) based the model on ecological and social limits. Her doughnut model for economics contrasts with other models because humans and ecology's interaction is central in the economic system. The model is about an area within the ecological ceiling and a social foundation. In this area of thriving, humans can develop and live a good and decent life on earth for a long time. The economy must open this corridor and thereby has a leading role.

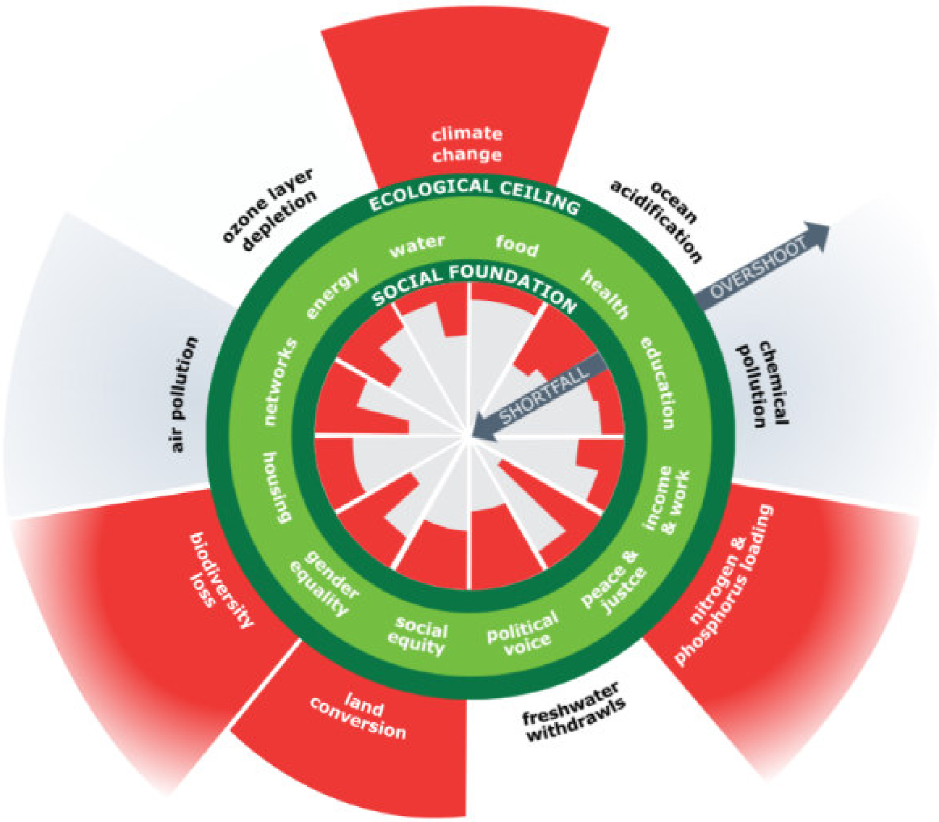

Figure 7 Kate Raworth's Doughnut Economics (Raworth, 2020)

Figure 7 shows us the idea of doughnut economics in a graphic. The green ring, the doughnut, represents the space of action for humans to thrive. Another term for this area is the save and just space for humanity. The outside of the ring shows the ecological impact. The impact is evaluated by the indicators of the planetary boundaries. Rockström et al. (2019) give hints on how to evaluate the overshoot (Rockström et al., 2019). Raworth adopts this idea in her model and uses the same indicators. For example, the loss of biodiversity is measured by the extinction rate with extinctions per million species per year(E/MSY). The boundary to this indicator is <10 E/MSY but with high uncertainty. To improve the uncertainty, scientists need to research and find what the acceptable E/MSY is. In Figure 7, one sees the social indicators inside the ring. The social foundation is measured by indicators related to the SDGs. The indicator population undernourished is related to the second SDG: no hunger. 11% percent of the population on earth is undernourished (Raworth, 2020). The aim is apparent: since each person has the right to food, no person should starve.

Raworth, the developer of the doughnut, had in mind that this idea should spread. A broad discussion about this model for the economy should happen globally. With this discussion, it is possible to find new applications for the model and define a new way of measuring the economy (Raworth, 2020). The DEAL developed principles for putting the doughnut into practice. They base on the seven ways to think like a 21st-Century Economist (Raworth, 2017a). The principles are:

"Embrace the 21st century goal. […]

See the big picture. […]

Nurture human nature. […]

Think in systems. […]

Be distributive. […]

Be regenerative. […]

Aim to thrive rather than to grow. […]"

(Doughnut Economics Action Lab, 2020a)

In practice, the model of Kate Raworth is already in use. It allows to define indicators and evaluate the sustainability of cities. In 2012 the City Think Space has started investigating the City of Kokstad with this basis and developed an urban development plan for the city (City Think Space, 2012). A new sustainable city district of Stockholm: Norra Kymlinge, uses the doughnut for the district's concept (Enander, Kvarnbäck, Lindroos, & Lindmarker, 2017). The city government of Amsterdam and the Doughnut Economics Action Lab applied doughnut economics to the city of Amsterdam (Doughnut Economics Action Lab, 2020a).

2.4. Approach

Within the building sector, researchers with the urban perspective already use doughnut economics. Literature research reveals that the doughnut economy is not yet used in housing. On this scale, the limits of the planet's capacity and social aspects have little attention. Kate Raworth's doughnut economics may solve this problem. A transformation of this economic model into an evaluation system for housing acknowledges the boundary conditions on a planetary scale and focuses on appropriate behavior.

Buildings and especially residential buildings are and will be a product that humans need for their life. If the economics change to a more holistic view, the products, and more specifically the buildings, must do as well. With this perspective, buildings that allow *"every person to lead a life of dignity and opportunity"* are the result (Raworth, 2017b). A tool to evaluate a building for housing with the given boundaries is critical to get us there. One can use doughnut economics as a guideline since it is a *"concise compass for assessment of the current state of human wellbeing"* (Raworth, 2017b). Based on this guideline, buildings will be ready for a 21st-century economy.

The DEAL (2020a) has introduced seven principles for putting Doughnut Economics into practice (Doughnut Economics Action Lab, 2020a). These principles are the framework for the evaluation system in housing. In the first step, principles one and five: to change the aim and be distributive, are stressed. These principles are especially important for the development of the structure. At the beginning of the process, the overall goal to stay within boundaries is most important. This global goal is where the new evaluation system differs from existing evaluation systems. The DGNB, for example, wants to integrate sustainability into the building sector. They want to transform the building sector to take responsible and sustainable action (DGNB GmbH, 2020a). Principle five, to be distributive, opens the evaluation system to everyone. The participating parties gather information and allow acceptance in a broad community.

The researchers of the study Creating City Portraits developed the idea to introduce the look through several lenses on a city (Doughnut Economics Action Lab, 2020a). The authors vary the focus of every lens. This idea is adopted and transferred to the housing sector. Table 1 shows this with the leading question for every dimension.

	Social	Ecological
Global	**In which way does the building acknowledge the well-being and prosperity of humankind?** Social impact categories (Andrews et al., 2009)	**What is the impact of the building on the health of the earth?** planetary boundaries (Rockström et al., 2019)
Local	**How does the building support the well-being and prosperity of building residents?** Maslow's hierarchy of needs (Maslow, 1943)	**Does the building contribute to the health of nature and the biosphere in the immediate environment?** DGNB local environment (Frank, 2020)

Table 1 Fields of evaluation following Doughnut Economics Action Lab (2020a)

The social local field is about the well-being and prosperity of the building residents. Here the person is in focus, and every social need of the person is worth a look. One gains knowledge about this by information about the well-being and an understanding of the capability approach. Individual needs like health are an example of this. The second social field is a global view where the well-being of humankind is in focus. The well-being of humans refers to the social development of everybody on this planet. An indicator here is the number of people under the poverty line. The sLCA is an existing tool to grasp the social impact of products. The ecological local field is about the health of nature and the biosphere next to the building, which considers flora and fauna. The last field is about the ecological global view. The health of the planet and everything on the planet are considered. Climate change is part of this field. The eLCA is a tool to gather information about specific values for given impact categories.

The evaluation system needs dimensions wherein the evaluation will happen. Dimensions for every field allow finding indicators. Figure 8 gives information about how indicators are found in literature and integrated into the evaluation system. The SDGs are superior and connect the indicators. If there is no approved indicator so far, one can follow the structure and define the indicator's stages. The system of levels is defined in the next chapter.

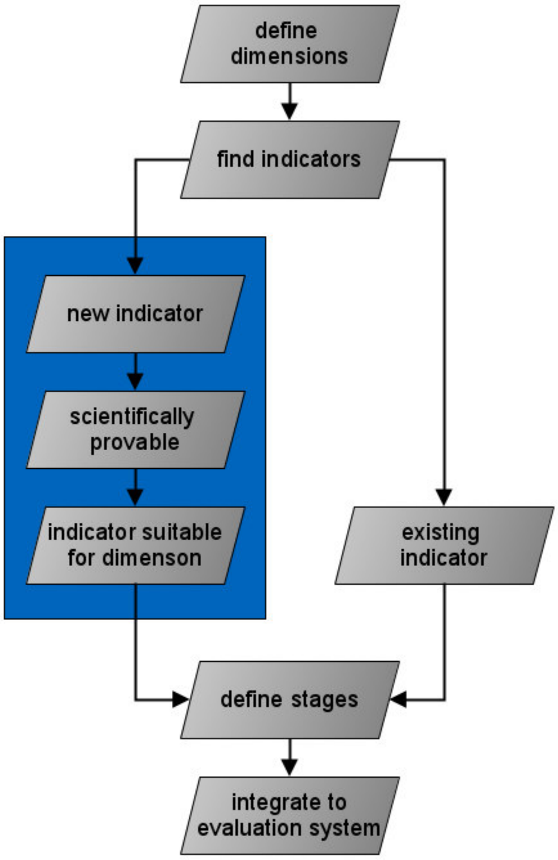

Figure 8 Dimensions and indicators for the evaluation system

The indicators have specific values, but these can change significantly with new scientific research in the corresponding field. Several views from other experts allow a good quality of indicators in the future. This approach contributes to principle five and allows to improve the evaluation system up-to-date.

2.5. Evaluation Process

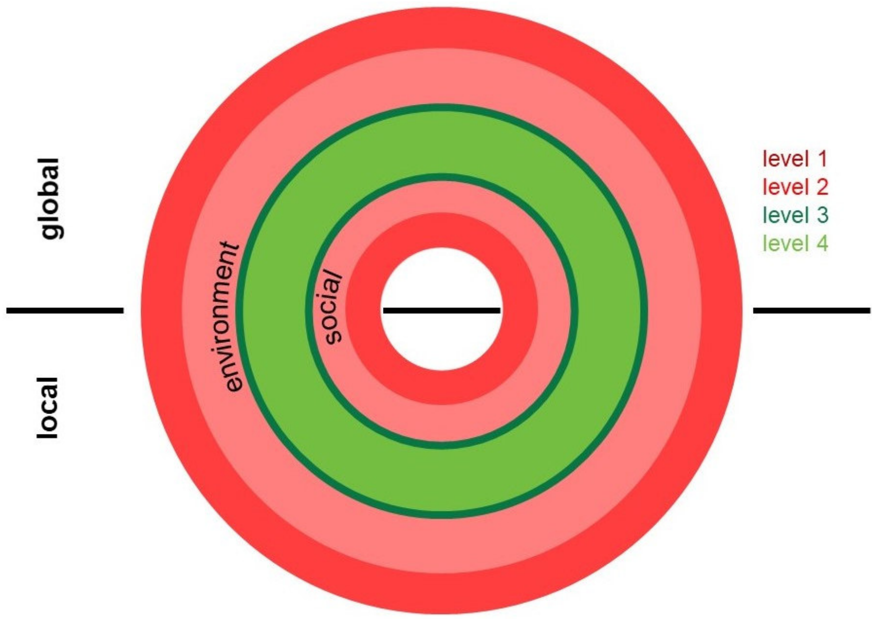

Figure 9 Evaluation system graphic

Figure 9 shows the evaluation system in a graphical description. The green ring is the area of thriving. The upper area of the graphic is global, and below is the local scale. On the outside of the green ring are the environmental aspects. The inside of the ring is the social field. In every field, four levels are possible. A level is a stage on which the indicator is concerning the area of thriving. If an indicator has level one or two, it has not yet reached the area of thriving. The next possible step is level three. The border of the area of thriving is level three. This level is the threshold and belongs to the area that one should aim for according to the first principle of changing the aim. There is another level within the field of thriving. Level four is better than the threshold value. A planner of a residential building should aim to reach either level three or four for every indicator. The two levels in the thriving area enable an exchange between the indicators. For example, one indicator from the global ecological field reaches level four. It is better than the threshold. A social indicator needs effort in this ecological indicator to get to level three. A concise decision against level four in the ecological indicator allows us to reach level three in the social indicator. This way, both indicators stay within the boundaries. Level one and two gives decision-makers a chance to see where effort is needed and where a level within the area of thriving is already likely to reach.

2.6. Ecological Indicators

Residential buildings are the object in the evaluation system, and indicators in the dimensions allow the assessment. With the description of the dimensions comes an example for the indicators. A list of the current ecological indicators can be found in Appendix A. These indicators and dimensions can be complemented or discussed in the further development of the evaluation system. Principle five design to distribute from the DEAL is the corresponding principle.

Ecological Local

The ecological local field uses the dimensions from the DGNB (DGNB GmbH, 2020a). Table 2 shows the related criteria. The DGNB separates these criteria into environmental (ENV), technical (TEC), and process (PRO) quality. Those qualities are the source of indicators. A distinction between the impact on the building and its impact on the environment is needed. Within this field, one evaluates the impact of the building on the local environment. Hazards that threaten the persons living in the building are considered indicators of the social local field.

Dimension	**DGNB criteria**
Local environmental impact	ENV 1.2
Portable water demand and wastewater volume	ENV 2.2
Biodiversity at the site	ENV 2.4
Quality of the building envelope	TEC 1.3
Use and integration of building technology	TEC 1.4
Ease of recovery and recycling	TEC 1.6
Immissions control	TEC 1.7
Mobility infrastructure	TEC 3.1
Construction site / construction process	PRO 2.1

Table 2 Ecological local dimensions and related DGNB criteria

Ecological Global

The doughnut economics indicators and the planetary boundaries of the Stockholm resilience center are used (Rockström et al., 2019). The data acquisition follows a strict guideline, which prevents overlapping and double counting of impacts. The midpoint level categorizes the ecological global impact (DIN 14044:2018-05). These midpoint levels of the standard serve as the dimensions of this field. They are:

- Climate change
- Ocean acidification
- Chemical pollution
- Nitrogen and phosphorus loading
- Freshwater withdrawals
- Land conservation
- Biodiversity loss
- Air pollution
- Ozone layer depletion

The indicator for Global Warming Potential within the dimension of damage to ecosystem diversity influences other dimensions. The German Federal Environmental Agency (Umweltbundesamt) suggests that every person in Germany has a budget of 1.1 tons of CO_2-eq. to stay within the 1.5 °C aim of the UN (Albert et al., 2020). Today 39% of the CO_2-budget is used for housing (Umweltbundesamt, 2020b). This percentage results in a total amount of 430 kg CO_2-eq. as the threshold if today's CO_2-budget is the baseline. One should not exceed this threshold to stay within the area of thriving and thereby stay below a 1.5 °C increase in global warming. The value gives information about the needed reduction. The approach is similar to other indicators of the ecological global field.

2.7. Social Indicators

The social indicators differ in importance, and according to this, they are weighted. The weighting takes the number of submissions raised into account (Raworth, 2012, p. 22). The dimensions and examples for the indicators describe this field of evaluation. In Appendix B, one finds the current list of social indicators.

Social Local

Maslow ranks the needs for an individuum into five dimensions (1943). The dimensions rank here starts from the basic ones:

- physiological needs
- safety needs
- love and belonging
- esteem
- self-actualization

Often a pyramid, the pyramid of needs, shows an order of the dimensions. The overlapping of the needs over time extends this static view. At any one time, one need always prevails. Figure 10 shows this in a graphical description.

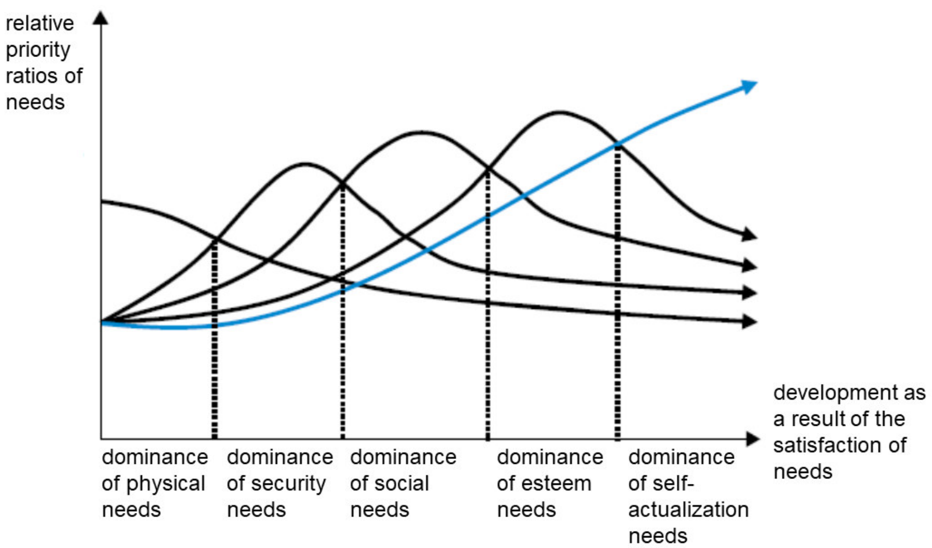

Figure 10 Order of needs (own translation) (Bröckermann, 2016)

The indicators in this field come from the social criteria of the DGNB (Frank, 2020), doughnut economics (Raworth, 2017b), mental health action plan (World Health Organization, 2013), Ottawa charter for health promotion (World Health Organization, Regional Office for Europe, 1986), common good matrix (Felber, 2014), indicators sLCA (Andrews et al., 2009) and Creating City Portraits (Doughnut Economics Action Lab, 2020a).

The indicator: affordable housing is one example of an indicator. Housing must be affordable for all people to meet human safety needs. The needs in connection with housing are shelter and safety. With investment costs for a building and the cost in the usage phase, an assessment is possible. An LCC from the user's point of view makes this possible.

Social Global

The social global field dimensions originate from the Guidelines for Social Life Cycle Assessment of Products (Andrews et al., 2009). These dimensions of Andrews et al. were further developed (Life Cycle Initiative, 2020). Dimensions used in the evaluation system are:

- Human rights
- Working conditions
- Health and safety
- Cultural heritage
- Governance
- Socio-economic repercussion

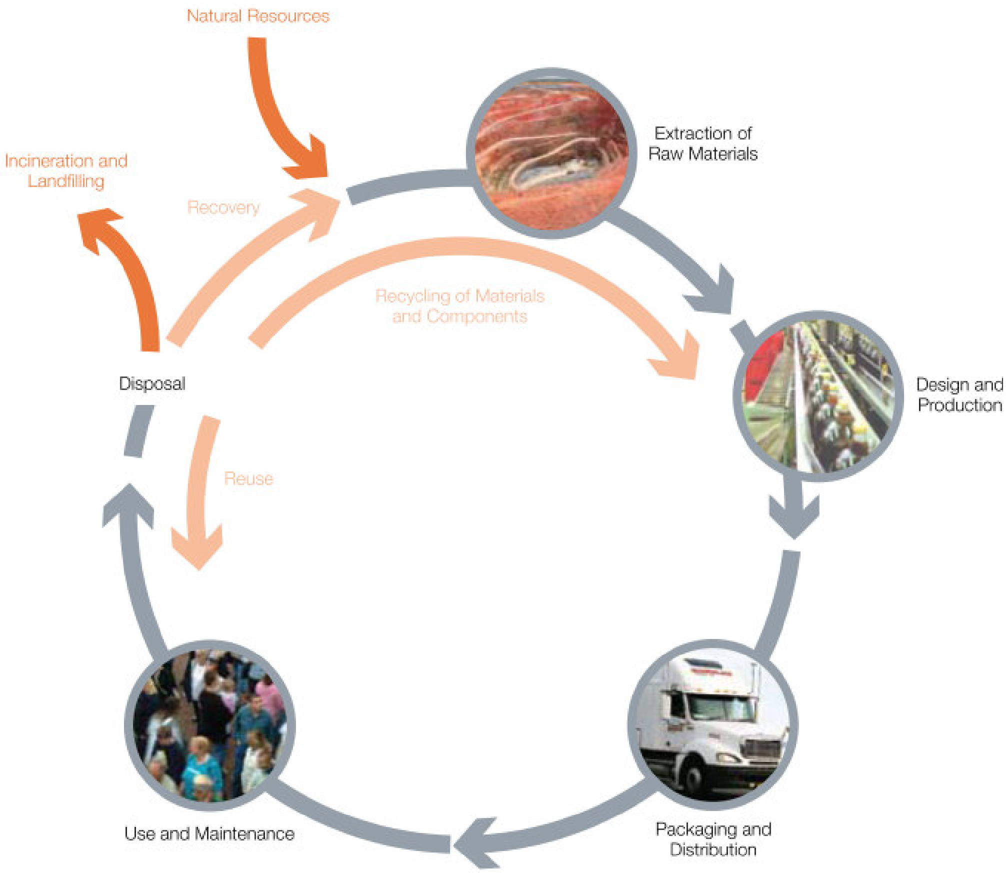

Figure 11 Social global effects within a life cycle (Andrews et al., 2009)

Figure 11 shows a life cycle with social and global effects. Here one sees examples for the dimensions. The extraction of raw materials, for example, has a vast impact on the people's working conditions, health, and safety at the place of extraction. The figure also shows that future life cycles will be circular. The stages of recovery, reuse, and recycling of materials and components are necessary and need attention. Reuse of a product needs distribution, and the human rights of the people working there must be respected.

The Common Good Matrix from the Economy for the Common Good is another source for indicators in the social global dimensions (Felber, 2014). Besides this, indicators from the German strategy for sustainability play an essential role (Presse- und Informationsamt der Bundesregierung, 2018). The German government and the federal statistical office (Statistisches Bundesamt) use these indicators to assess sustainability in the country. Some of them refer to the dimensions above. On an international level, the mapping of social progress is done by the Social Progress Imperative (The Social Progress Imperative, 2020) and the Human Development Report (United Nations Development Programme, 2020).

3. Sufficiency in Housing

3.1. A complementary Strategy

3.1.1. Where to locate Sufficiency?

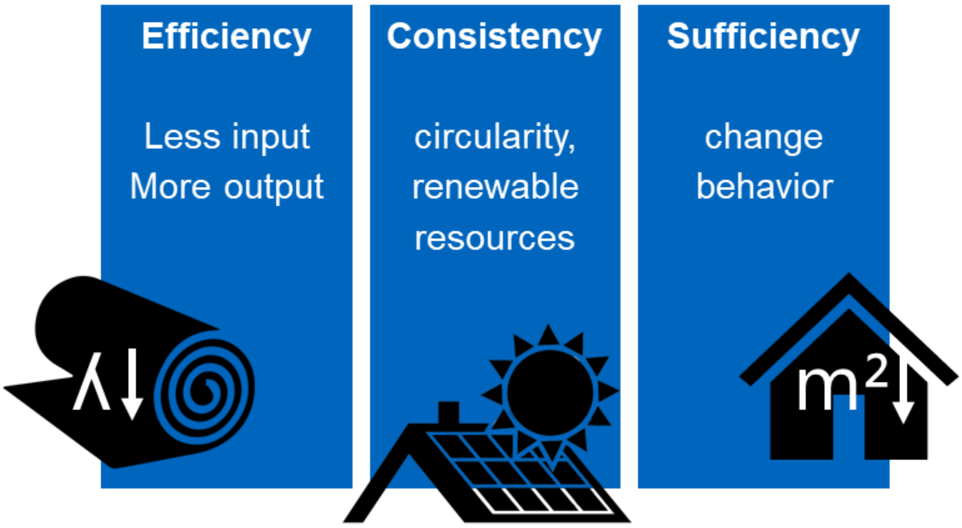

Figure 12 Overview strategies

Sufficiency, efficiency, and consistency are the three superior strategies to reach sustainability (Pufé, 2012). The overview in Figure 12 summarizes the three main strategies with examples from the housing sector. An efficient approach is, for example, the reduction of thermal conductivity within insulation material. With solar power, one can realize consistency, the compatibility of technology and nature. Sufficiency is about a change in behavior according to needs and definitions of having enough. The strategy can be applied by, for example, reducing the used living area. Consistency and efficiency need technological solutions. Sufficiency involves the social aspects even more. Each of these strategies allows an influence on one or more of the dimensions of sustainability.

Efficiency

Efficiency improves the ratio of benefit (output) to effort (input) either by reducing the effort or increasing the benefit. This resource conservation of material, time, or energy results in less impact on the environment. Thus, efficiency will have a crucial role in the future (Kobiela et al., 2020). Several fields and sectors already use efficiency. The building sector aims at high efficiency for several reasons. One reason often mentioned is the cost reduction. But there are other motivations as well. The ecological and social dimensions of sustainability get more important in politics and society than years ago. Because of this, a reduced material and energy demand with the resulting reduction in ecological impact is another goal. Architects, planners, and producers can apply the efficiency strategy in the construction, production, and usage phase.

An example is the insulation of the building. The use of insulation on the outer wall results in less energy demand in the usage phase. Next to this, getting warm rooms or power the electrically driven sun protection must be efficient itself. In the production of the insulation, material-efficient technology causes less effort. This technology, found by engineers and scientists, has improved the performance of expanded polystyrene insulation materials using another heat radiation absorber (Holm, Sprengard, & Treml, 2014). Another absorber causes a change of color. The new material is gray. The improved (gray) expanded polystyrene's thermal conductivity has a reduced radiation share (Figure 13). With this improvement, less raw density fulfills the insulation properties. This reduced raw density means a reduced need for crude oil as the raw material.

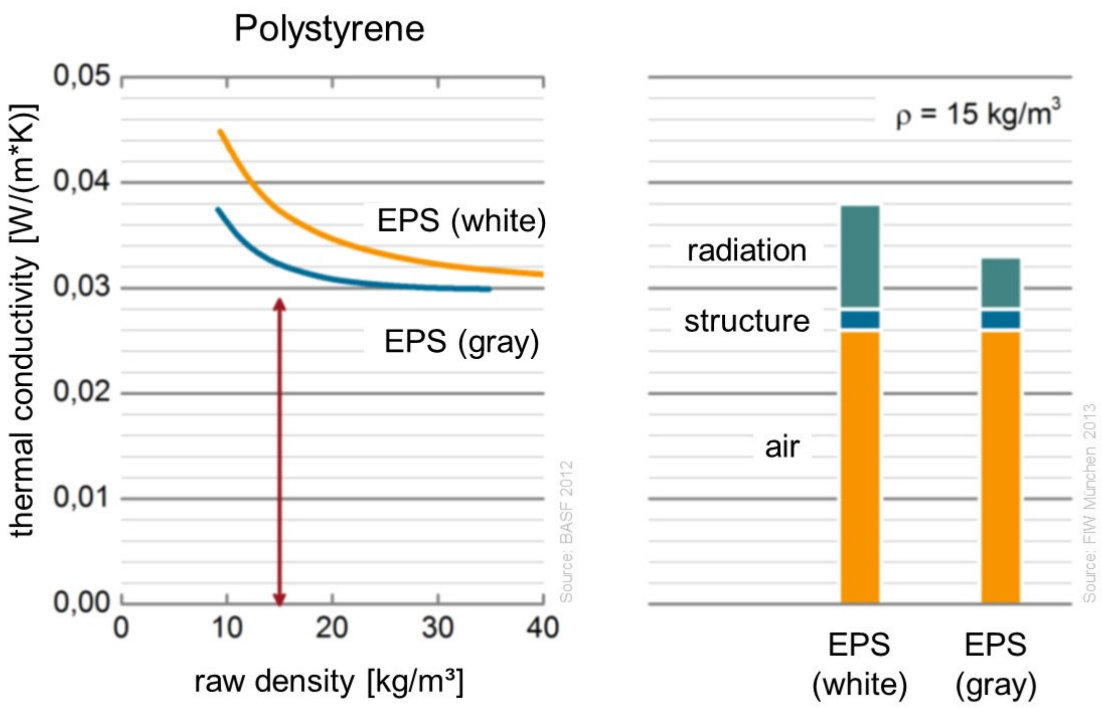

Figure 13 Improved thermal conductivity (own translation) (Holm et al., 2014)

Consistency

The second strategy for more sustainability is the strategy of consistency. This strategy is about circularity. A technological or biological circuit with closed loops for products and energy is the aim (Huber, 2000). Braungart and Mcdonough (2016) have introduced the concept of cradle to cradle (Braungart & Mcdonough, 2016). This concept shows an excellent example of consistency. They also call this the concept of ecological effectiveness. The concept ends up in no more pollution of the biosphere and no waste. A product is either designed for reuse or goes back into the biological circuits. While the cradle to cradle concept was initially applied very generally to a wide range of products, Djahanschah (2019) and others made the case that it is also valid for the building sector (Djahanschah, 2019). A building falls within this framework if the construction and all energy within the material rely on renewable sources. Every process in the production and construction needs to be concerned as well.

Additionally, the energy in the phase of use must come from renewable resources (Hegger et al., 2016). A renewable resource is the sun. Solar gains warm rooms, and sun rays generate power in a photovoltaic plant. The power can be used, for example, to operate the ventilation. The products used for the building are either fully recycled or made from renewable resources that can go back into the biological circuit of rotting and growing. Accordingly, awareness of the toxicity of additives or ingredients is essential. In this way, buildings can reach consistency.

Sufficiency

Sufficiency is the third strategy. It is not yet often used, and the term is not very well known. A detailed investigation and a literature review allow a look at sufficiency in housing.

3.1.2. What is Sufficiency?

Unlike efficiency and consistency, sufficiency is about social transformation. The change is defined as frugality – with a definition of enough – and a limitation of needs. The basic definition of sustainability used nowadays already refers to sufficiency. In 1987 the Brundtland Report mentioned two critical concepts for sustainable development. The first concept sets the focus on needs, and the second concept focuses on limitations (chapter 2.1). With this concept, the Brundtland Report already introduced the strategy of sufficiency. The basic needs of the individual and society are defined. As a next step, necessary limitations for the conservation of present and future needs are applied. By recognizing these limits, one must find solutions to stay within limits. Such solutions can be found in technology and society because those are the fields that give the limits. A possible social solution is to deal with the behavior of society. That is what sufficiency does.

The sufficiency strategy requires a behavior change (Linz et al., 2002; Princen, 2005). The behavior aims to stay within the environmental and social boundaries (chapter 2.1) by reducing demand for goods, energy, and other resources. Actions compliant with sufficiency derive from *"the sense that, as one does more and more of an activity, there can be enough and there can be too much* "(Princen, 2005, p. 6). Stengel (2010) extended the idea and said that the behavior is intrinsically motivated and not imposed by others (Stengel, 2010). But Jackson (2012) argues that institutions or politicians' laws or regulations will and should result in sufficient behavior (Jackson, 2012). The self-limitation and the regulation associated with sufficiency are conscious and oriented toward the strict ecological limits for every person on this planet (Arnsperger & Deibler, 2017). One can derive both positive and negative perspectives from this definition. Heyen et al. (2013) provide waiver and eco dictatorship as examples for fear and defense reaction in opposition to good life and liberation from excess as promises (Heyen et al., 2013). All scholars agree that sufficiency results in a resource reduction and comes from a behavior change. From here, literature interprets the term sufficiency differently. The list of definitions in Table 3 describes what sufficiency is and what it is not[1].

[1] The quotations in the table are translated by the author of the thesis.

This is sufficiency	This is not sufficiency
"liberation of abundance "(Paech, 2016)	People who act less resource-intensive because they are poor (Winterfeld, 2020)
“the right measurement“ (Oekom e.V. - Verein für ökologische Kommunikation, 2013)	“Sufficiency does not determine a state but describes a task.” (Linz et al., 2002)
"tighten one's belt "(Winterfeld, 2020)	lack or excess (Linz, 2004)
"The intelligent handling of resources we have is one main task of sufficiency." (Linz, 2004)	directed against technical progress. (Princen, 2005)
Deceleration, unbundling, decommercialization and clearing out (Sachs, 1993)	"The goal of sufficiency is not asceticism, voluntary poverty, or the lifestyle of today's subcultures." (Linz et al., 2002)
"Sufficiency is a class of principles sensitive to critical environmental risks, to the needs of management and self-management, when it is otherwise all too easy to evade responsibility for such risks. Sufficiency is an idea, a principle, indeed an ethic for sustainability." (Princen, 2005, p. 19)	
"The principle of sufficiency […] is also linked to the examination of questions about the 'optimal' or 'right' measure for the good life and the search for a balance between material and immaterial as well as quantity and quality. "(Jenny, Wegmann, & Ott, 2013, S. 1).	
„Frugality“ (Genügsamkeit) (Paech, 2020)	

Table 3 Definitions sufficiency (own translations)

According to Princen (2005), the paradox with sufficiency is that the environmental issues are already evident, but the appropriate action is missing (Princen, 2005). Sufficiency is about searching and learning (Linz, 2004). It is a process that every person and institution must go through, but to follow it in practice is difficult. The strategy covers a fast and interdisciplinary approach to fulfill the SDGs and reach strong sustainability with acceptable ecological impact. One sees that knowledge about sufficiency can lead to more success for the strategy.

3.1.3. Why is Sufficiency needed?

Neither efficiency nor consistency alone will achieve a sustainable future within the boundaries of the model of doughnut economics (Alcott, 2008; Linz et al., 2002; Linz, 2004; Pufé, 2012). Efficiency and consistency show their effect in theory, but there are limitations and problems in the application.

The efficiency strategy often comes with a rebound effect, which means that achieved savings are compensated, if not compensated, by a change in behavior (Peters, Marth, Semmling, Kahlenborn, & Haan, 2015; Pufé, 2012; Sonnberger & Gross, 2018). The rebound has at least two classifications: the direct and the indirect rebound effect (Sonnberger, 2020). The indirect rebound deals with improvement in one field and increased demand in another field. With the direct rebound effect, the improvement and the increased demand are in the same field. A higher room temperature because the heating plant is efficient is an example. The result is more energy consumption. This effort can be higher than the saving of the more efficient heat plant. The rebound effect overcompensated the savings due to a behavior change – more heat demand. The energy demand of buildings has reduced due to governmental approaches and other initiatives like the passive house institute. Thereby, reducing the energy demand down to zero and even producing energy within a house (Plusenergiehäuser) is possible (Erhorn, 2019). Here, the rebound effect shows its impact. The more efficient a house is, the more likely the inhabitants change their behavior because its technology is improved (Sonnberger, 2014). For example, the person in the house chooses a higher room temperature. This higher temperature causes additional energy effort. The fact that the average living area is increasing since 1969 underlines this phenomenon as well. This development has overcompensated the savings of reduction of energy consumption until 2005 (Kopatz, 2016). In total, this is not reducing the consumption to the forecasted amount.

The building report from the German energy agency (dena-Gebäudereport) of 2019 shows that the laws and regulations today are not sufficient to reach the aims of the German government concerning the energy efficiency of buildings (Deutsche Energie-Agentur GmbH [dena], 2019). Kobiela et al. (2020) conclude in their work about the feasibility of CO_2 neutrality until 2035 that if trends stay the same, Germany will not reach the aim to stay in the CO_2 emission budget in the building sector (Kobiela et al., 2020). Scientists have focused on research about this effect (Auer et al., 2020; Moeller, Weber, Schröder, Bauer, & Harter, 2020; Santarius, 2012). Politicians can act against the rebound effect with taxation (Font Vivanco, Kemp, & van der Voet, 2016). An example of this is an appropriately designed cap-and-trade system and energy and carbon taxation.

The strategy of consistency still has a long way to get implemented. An example is the German energy transition (Energiewende), which aims to increase renewable energy use by industry and individuals. The renewable energy law (Erneuerbare Energien Gesetz) is a tool used by the government. The net energy production from renewable resources so far is at 40% (Fraunhofer Institut für Solare Energiesysteme ISE, 2019). At this level, the German energy production industry is on the right track but still has a long way to reach 100% renewable energy. New technologies are needed. Within this action, politics and the consumers play a significant role (Sterchele et al., 2020).

The households and the building industry – responsible for the building's construction – follow the consistency approach only to a minor extent. The application of the consistency strategy would result in no waste and deposition on landfills. By 2018 settlement waste is contributing 50.3 t (12%) to the total volume of waste. Building and demolition waste has a share of 228.1 t (55%) (Umweltbundesamt, 2020a). Within the last years, these numbers even raised slightly. Consistency in material usage is far from complete implementation. So far, there are approaches to do so. The Environmental Protection Encouragement Agency wants to apply the concept of cradle to cradle to housing (EPEA GmbH, 2020). A tool for closed circuits can be the building circularity passport and Building Information Modelling. With this modeling, a computer model integrates all information about a building and material. Since the building material is known, planners of future buildings can reuse the resources for their buildings. The examples of waste and the lack of documentation of used material show that there is still a long way to integrate consistency fully. What comes more, the technology is not yet able to reach the perfect closed loop (Arnsperger & Deibler, 2017; Linz et al., 2002).

Combining the three strategies is essential, and each strategy's strengthsust be used (Arnsperger & Deibler, 2017; Behrendt, Göll, & Korte, 2018). It is not only about putting them next to each other but about intelligent combinations and profit from synergies (Behrendt et al., 2018; Heyen et al., 2013). Especially efficiency needs to be guided by sufficiency (Sachs, 1993). Sufficiency can give the framework, and efficiency improves the processes. The combination in the correct order of application can lead to good results. The example of energy in the building sector is based on a proposal of the DGNB

(DGNB GmbH, 2020b). In the first step, saving energy through a change in behavior (sufficiency) reduces the total demand for energy. An example is to turn off the light as often as possible. The second step is about energy productivity and an efficient provision of the lasting energy demand (efficiency). Appropriate technical building equipment allows this. In the last step, renewable energy covers the energy demand (consistency). A photovoltaic system on the roof of a building can do this. This idea of a combined application of the strategies is not yet broadly used. Especially the first step of sufficiency is rarely fully implemented or skipped. All three strategies' correct order with a balanced effort allows synergy (Behrendt et al., 2018). This example shows that sufficiency has a specific relevance within the strategies for sustainability.

Sufficiency can tackle the rebound effect of efficiency (Peters et al., 2015) and can be a solution accompanied by a comprehensive consistency concept (Sterchele et al., 2020). But sufficiency can come with an indirect rebound effect as well (Sonnberger, 2020). This indirect rebound effect must be considered by looking for solutions. Chapter 4.3 gives more information on the rebound in sufficiency. Besides this, a sufficiency approach, such as not consuming, is immediate and directly influences resource use (Paech, 2016). In this way, one can apply fast to environmental problems. Sufficiency is only barely used, but the need for it is present.

3.1.4. How to introduce Sufficiency?

The economy, politics, companies, and institutions are the actors who can apply sustainability strategies such as sufficiency, consistency, and efficiency. They know more about the application of efficiency and consistency than they know about using the strategy of sufficiency. Sustainability experts claim that research on applying and implementing sufficiency is needed (Paech, 2020; Princen, 2005). A look into the obstacles and chances gives information on how to implement the strategy in housing. The most important actors to allow the integration of sufficiency are civil society, companies, science, and politics (Schneidewind, 2018). Princen (2005) gives responsibility to the indium, society, and companies (Princen, 2005). The upcoming chapter presents investigations on an individual, societal, and economic level. They show obstacles and chances for sufficiency related to these levels.

Obstacles

Stengel (2011) names five barriers to sufficiency: costs, consumerism, conventions, responsibility, and capitalism (Stengel, 2010). In chapter 3.1.2, one finds that sufficiency is about the intrinsic motivation for behavior change. Because of this reason, the individual is a significant factor. His or her mindset is the key to the strategy of sufficiency. The personal fear of change should not hinder this potential (Linz, 2004). Hindrances on the individual level reach from insufficient motivation to missing knowledge. The people lack the knowledge of how to act sufficiently (Princen, 2005). Acting according to the strategy of sufficiency is about present action influencing future needs.

Besides this, there is the psychological rebound effect: With moral acting in one field, the person allows him or herself to act less moral in another field (Heyen et al., 2013). An example could be that a person even sells his car out of motivation to live a more sustainable life but uses the money gained to buy a new, larger apartment. This action might even overcompensate the positive effect of living without a car. Another hindrance on an individual level is that the person must have the possibility to act consistently with the sufficiency strategy. Products wrapped in plastic, for which there is no plastic-free alternative, are a typical example (Bohnenberger & Leuser, 2020; Heyen et al., 2013). These products force behavior that does not conform with the strategy of sufficiency. A politically forced abandonment could solve this problem and help the person to act sufficiently. The legislators need to back up the abandonment with reasons. The last obstacle on the personal level is that the sufficiency solutions do not come within products, like efficiency or consistency. A product does not conform with the strategy of sufficiency itself (Arnsperger & Deibler, 2017). This is the reason why one cannot buy a sufficiency solution. Sufficiency does not fit with consumption.

The societal view bears some hindrances for sufficient action as well. Society influences the action of every individual. If many people adopt the idea of sufficiency, others will do as well (Heyen et al., 2013). Sufficiency is not visible, and this causes problems (Wilk, 1997). The example of consumption illustrates this. One can not see not if someone is not consuming. What one can learn from the COVID-19 pandemic is that people save others by avoiding social contact. The result is not evident to the individual, but in a bigger societal context and a statistical view, every avoided contact saves life (Fuhrmann & Barbarossa, 2020).

The mindset the western society brings at least hinders sufficiency in two ways. The first hindrance is the claim to be the best. This expectation and the resulting mindset can be found in education and working life. Acknowledge borders and limits, thereby, is a step back (Linz et al., 2002). These thoughts hinder sufficiency and should not be the motivation for action (Welzer, 2019). Another mindset is the belief in technical solutions. The focus of society on solutions within technology hinders us from finding solutions within the behavior. Both mindsets hinder sufficiency. Behrendt et al. (2018) and others argue that sufficiency needs a cultural change (Behrendt et al., 2018). Not only culture but also politics need to change. Politicians do not want to interfere with personal or economic freedom (Heyen et al., 2013). So far, they lack ideas to introduce sufficiency (Bohnenberger & Leuser, 2020). Politicians sometimes act against sufficiency by introducing subsidies (Burger & Köder, 2016).

Figure 14 shows the three sustainability strategies as a function of economic success and their impact on the environment. Sufficiency reduces economic revenue. With constant productivity, point C is reached, where the ecological impact is reduced to an acceptable level. Our current economic system needs the economy's growth as an essential part (Jackson, 2012). According to the graphic, sufficiency reduces revenue. This reason is why the economy seldom uses sufficiency.

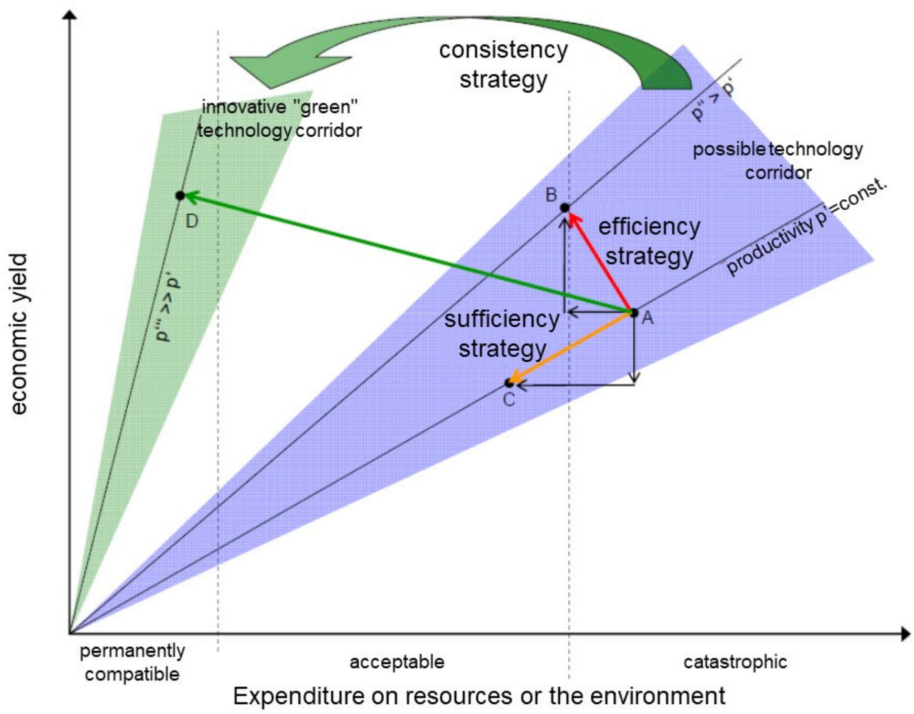

Figure 14 Effect of strategies (own translation) (Hartard, Schaffer, & Giegrich, 2008)

Sufficiency and an economy of infinite growth do not fit together (Jackson, 2012; Lange, 2020; Linz, 2004; Mincyte, Kütting, Goldblatt, & Princen, 2007). Especially in times of crisis, more consumption has a positive effect on the economy. This is counterproductive to sufficiency (Linz, 2004). Even publications of actions for strong sustainability and cleaner production do not talk about sufficiency at all (Neto Oliveira et al., 2018). There is a lack of knowledge in this field. Information about products compatible with sufficiency strategies and the adequate application of these products is needed (Arnsperger & Deibler, 2017).

Another hindrance is that it is hard to measure sufficiency. Efficiency instead can be measured. Without measuring, the economy cannot grasp sufficiency and deal with this strategy (Zimmermann, 2018). These are why actors on the market will not act sufficiently without external norms and constraints (Arnsperger & Deibler, 2017). The capitalistic economy hopes that technical solutions will solve all environmental problems and thus sticks to the dogma of growth (Christ, 2020). The non-existing will for a transformation hinders sufficiency.

„In history the society has introduced things like: moderation, frugality, prudence, temperance, reverence even if the people would think that more is always a good thing. "

(Princen, 2005, p. 7)

Thoughts of sufficiency are not new. Therefore, the historical context of individual behavior, societal dependencies, and economic issues are important to consider. The path dependency of technology, for example, is a factor that hinders sufficiency (Berkhout, 2002). The historical context should not be a part of this thesis. The obstacles are reasons not to apply sufficiency strategies or maybe give a framework where it appears not to be possible.

Chances

As for the obstacles, the same levels categorize the chances. These are the individual, social, and economic levels. Chances will show us how sufficiency influences these levels positively and the reasons for the actors to introduce sufficiency. The individual level is considered first. An example of the positive effects of sufficiency for the individual is using a bike for commuting. That kind of sufficient mobility has a less environmental impact and contributes to the health of the person riding the bike (Stengel, 2011). An example of housing is affordability. A person can afford to live in a more expensive area if he or she reduces the living area. With this reduction, housing costs for the individual decrease (Bierwirth & Thomas, 2019). Fewer costs allow us to live in another district in the city or to afford other expansions. In this case, the rebound effect must be concerned. There are not only positive effects of sufficiency. One must deal with less space, for example. If the person is willing to accept this negative side, he or she may feel empowered. This can help the person to a happy and good life (Linz et al., 2002; Welzer & Wiegandt, 2012). Philosophy discusses the good life (Sen & Nussbaum, 1993). Sufficiency approaches need this definition of a good life. This good life has limits that result in general rules for everyone (I.L.A. Kollektiv & Gesellschaft für Ökologische Kommunikation mbH, 2019). This definition and the limits for a good life allow for some people to live a better life through reduction. Getting rid of unnecessary stress and live an eco-social lifestyle can cause relief and has a lot to do with personal aims and lifestyle (Bohnenberger & Leuser, 2020; Linz, 2004).

Society will profit from and can contribute to sufficiency. In contrast to the existing and accepted life plans and goals, sufficiency makes the relation between material needs and non-material requirements more comprehensible. It leads to a new understanding of wealth (Linz et al., 2002). This understanding allows other life plans to become more accepted — for example, having less and being happy. A cultural change is required here. So far, the idea of a good life from the mainstream perspective involves the ever-ongoing financial prosperity growth. To change this, politicians can support a bearable ecological consumption and reduce the costs for sufficiency (Bohnenberger & Leuser, 2020; Diefenbacher & Zieschank, 2011; Heyen et al., 2013; Stengel, 2011). This cost reduction supports people who already act sufficiently. On the other hand, the active support of sufficiency will lead to more sufficiency action (Bierwirth & Thomas, 2019). The promotion of alternative housing projects in several cities in Europe is an example of this. There is still inequality in social and ecological justice (Hornberg, Bunge, & Pauli, 2011). High-income households have the most significant carbon footprint (Ivanova & Wood, 2020). Sufficiency is the strategy that tackles inequality (Bohnenberger, 2020b; Bohnenberger & Leuser, 2020; Ivanova & Wood, 2020). To get there, one needs distributive justice and accepted sufficiency, which laws and regulations can support.

Social issues are related to the economy. Profit maximization and efficiency are currently the only focus of our economy if one wants to solve environmental problems (Mincyte et al., 2007). One solution is that companies should get no support if they do not act sufficiently (Bohnenberger, 2020a; Heyen et al., 2013). With a reduced income tax and increased tax on material, sufficiency approaches will be used more often (Lange, 2020). Companies themselves can contribute to sufficiency by offering products and services that allow the customer to act sufficient (Arnsperger & Deibler, 2017; Heyen et al., 2013). Sufficiency sometimes even is a cheaper and faster solution to problems than efficiency and consistency (Heyen et al., 2013). From an economic view, reduced energy demand can be cheaper than the installation of wind parks. Companies need to be more open in their thinking, referring to the sufficiency approach.

Personal happiness and the good life are reasons for a person to start with sufficiency. If one wants to keep going with sufficiency, a broader action at the institutional level is needed. Incentives for sufficiency integrated by the government could be the next step. These incentives can be similar to energy-efficient buildings' incentives (Darby & Fawcett, 2018; Heyen et al., 2013). The scientific community can develop best practice examples. The positive mindset towards sufficiency supports the strategy in a broad field (Linz, 2004; Welzer, 2019; Zell-Ziegler & Förster, 2018). The attitude and the integration of sufficiency in ecological thinking (SDG Watch Europe, 2020) bring more acceptance of political measures. This acceptance can result in the awareness of sufficiency in every field. One of these fields must be housing.

3.1.5. Excursus: Sufficiency and the COVID-19 Pandemic

On the 11th of March 2020, the World Health Organization declared a pandemic caused by the COVID-19 virus (World Health Organization, 2020). This status led to various actions by the governments of every country of the world to encounter this crisis. The reactions differed from country to country, but most of them caused restrictions for the population. The restrictions caused changes in behavior. In the early stages of the pandemic discussions, started about the connection of the decided measures with sustainability. Because of strict lockdowns, the environment had time to refresh again, and several news agencies showed the ecological impact. This impact appeared to be significant. There were clean canals in Venice, clean air, and no noise pollution due to less traffic in the streets and no air traffic. All these were snapshots. The COVID-19 Pandemic cannot be taken as an example to conclude a positive effect on the environment. Besides this, there have been more negative than positive impacts on society as well.

The scientific discussion about the connection of these effects due to the lockdown and sufficiency started almost immediately. This topic filled online conferences. Examples are the network meeting by the research network for sufficiency in Germany on the 20th of March 2020 and diversity instead of waste (Vielfalt statt Verschwendung) by eco.ch on the 25th August 2020. This revealed relations and research potential for sufficiency in this crisis. Life was sufficient almost immediately. The people only had the chance to have few social contacts. The idea of what is enough, how much traveling is necessary, and what one needs for a good life was raised. From this moment on, people thought differently about what is necessary for them in life. There was a shift in focus. At the conference, diversity instead of waste, Prof. Dr. Dominik Georgi gave an insight into a survey. The survey had one thousand participants in Switzerland. Prof. Dr. Dominik Georgi found that ecological awareness and more time in nature during the crisis caused a more sustainable consumption (eco.ch - Das Schweizer Forum für nachhaltige Entwicklung, 2020b). These results are an example of a positive effect that came with the crisis. Whether this effect remains after the pandemic is open. But there are many other effects as well. The people who suffered the most under the actions against the virus's spreading have already been the socially disadvantaged ones (eco.ch - Das Schweizer Forum für nachhaltige Entwicklung, 2020a).

The earth overshoot day has moved about three weeks later than in the year before (Global Footprint Network, 2020). This trend allows the assumption that a changed behavior improves environmental problems. Still, it is not enough for the planet to regenerate from the problems that already exist. Social injustice became even worse. A long-term approach to social awareness and ecological orientation is needed. Sufficiency will be a part of it. One reason is that individuals already recognize that their action has an impact. The behavior change does not need technical help. Besides this, the strategy can be used right away and will have an instant effect on sustainability. With this lesson learned from the COVID-19 pandemic, sufficiency may get more attention in the following years.

3.2. Current Situation in Germany

The potential of sufficiency discussed in chapter 3.1 is not the only argument for sufficiency. Another argument is, for example, the future orientation. Since the land consumption will be restricted to 30 hectare per year until 2030 in Germany the need for new buildings must be reduced (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2020). Other ways of creating new rooms like living areas or offices are needed (eco.ch - Das Schweizer Forum für nachhaltige Entwicklung, 2020b). Sufficiency will enable us to tackle this problem.

Sufficiency is about how little is enough and what is needed (chapter 3.1.2). The critical goal of sufficiency in housing is to reduce demand for new construction and housing space in general (Lorek & Spangenberg, 2019). Bohnenberger found four strategies for sufficiency in housing. Those are:

"1. Reduction of housing space from the 'wanted' to the 'needed' amount.

2. Substitution of housing needs.

3. Flexibilization of temporal and spatial supply and demand of housing.

4. Optimization of the spatial and temporal match of housing consumption."

(Bohnenberger, 2020a)

The first strategy is to think about the space a person needs to live. Shared spaces or the public realm can realize the substitution of housing needs. Next to this, the housing needs should be covered flexibly and optimized.

Several actors within the housing can apply and support the strategy of sufficiency (chapter 3.1.4). The actors involved in housing need to learn how to apply sufficiency. The legislator has the power to give a framing for sufficiency in housing. However, so far, no law or regulation prescribes the implementation of sufficiency in the building sector (Bierwirth & Thomas, 2015). Regulation of the consumption of living areas is one example. Such regulation is not attractive and, because of this, hinders the politicians from introducing such laws.

Figure 15 Tiny house, Vernon BC, Canada (Dream Big Live Tiny Co., 2020)

Individuals limit themselves in their area because of internal motivation (Lorek & Spangenberg, 2019). Some people participate in the tiny home movement. They reduce their needs and thereby reduce the impact on the economy. Several associations like the Small House Society or others participate in this development (Small House Society, 2020; Tiny Houses Consulting UG, 2020). Sometimes this development contradicts the official laws. For example, if the building law does not allow the construction at specific sites (Tiny Houses Consulting UG, 2020). Other approaches are the concepts of building cooperatives with a focus on sustainability. Wagnis eG in Munich is an example. The cooperative members plan, build, and live together in a social and ecologically sustainable way (Wohnbaugenossenschaft wagnis eG, 2020).

A company or planning office can orient towards the direction of sufficiency. They can help the consumer to act adequately. The BBSR forecasted that besides spectacular architecture, there would be a focus on buildings that deal with the appropriate size (Auer et al., 2020). Architects and planners will have the chance to design buildings that do less harm to the environment and promote positive social effects (Auer et al., 2020). The questioning of today´s comfort measures might allow this new design. Concerning the materials within a building, they cannot be sufficient. However, products can be compatible with sufficiency; they cannot act sufficiently (Arnsperger & Deibler, 2017). There is still analysis and research to be done until sufficiency is used to the same extent as the other housing strategies. This research can be either about how to change behavior or how to offer sufficiency conform housing.

3.3. Aspects of Sufficiency in Housing

Aspects of sufficiency in housing show the application of the strategy. Zimmermann (2018) shows a list of sufficiency aspects in the housing sector (Zimmermann, 2018). He scanned the literature for aspects and categorized them. He aimed to find parameters that allow the evaluation of sufficiency. Some of these parameters are described in chapter 4 in detail. The analysis he did comes with a detailed description. Table 4, on the next page, lists these aspects with the German expression and a suggestion for an English name. The order is due to the naming in literature, with the first aspect as the most mentioned one. The description of the aspects summarizes the specific information.

Aspect (German)	**Aspect** (English)	**Description**
Personenfläche	Personal space	The area one person inhabits within a building. A commonly used area is included. **Example**: reduction of rooms needed.
Gemeinschaft-liches Wohnen	Community living	Shared rooms for several uses reduce the area. The motivations to do so are various. **Example:** shared flats, cluster housing, and functional rooms.
(Energie-) Nutzerverhalten	energy user behavior	Behavior and tools that influence energy demand. **Example**: heating, warm water.
Flächeninan-spruchnahme	Land use	A human-made construction or object causes a reduced land coverage. **Example**: building and infrastructure, density in cities.
Mobilitätsinfra-struktur	Mobility infrastructure	Personal mobility is related to the building. **Example**: bicycle parking.
Anpassbarkeit	Adaptability	Future needs can be fulfilled with the flexibility of a building to adapt. **Example**: Variation in the use of the building.
Bestand statt Neubau	Renovation	The need for new buildings is reduced due to the reuse of existing buildings.
Ausstattung / Einrichtung	Equipment / Furnishings	The improvement of things needed to make a building habitable. **Example**: reduction in maintenance, recycling, and minimalism.
Ausbau / Konstruktion	Expansion / Construction	Materials and constructions used in the building. With the concern about the quality and demand.
Standort	Location	The place of a building allows short distances, regional and local structure.
Nutzungsdichte (zeitlich)	Density of use	Increase the intensity of use with multi-use and multiple functionalities.
Soziales	Social	The building is a place where social interaction, sharing, communication, and encounters happen.
Partizipation	Participation	The user is included in the planning and during the lifetime of the building.
Subsistenz	Subsistence	People in a building live self-sufficient. **Example**: Grow food next to the building.
Lowtech	Low-tech	One uses simple building technology and passive systems.
Eigentumsstruk-tur/Finanzierung	Ownership/ Financing	Alternative concepts for the financing of housing. **Example**: cooperatives.
Bedarfsplanung	Demand planning	A planning tool that allows planning referring to the needs of the inhabitants.

Table 4 Aspects of sufficiency in housing by Zimmermann (2018)

4. Analysis of Sufficiency Aspects

4.1. Approach

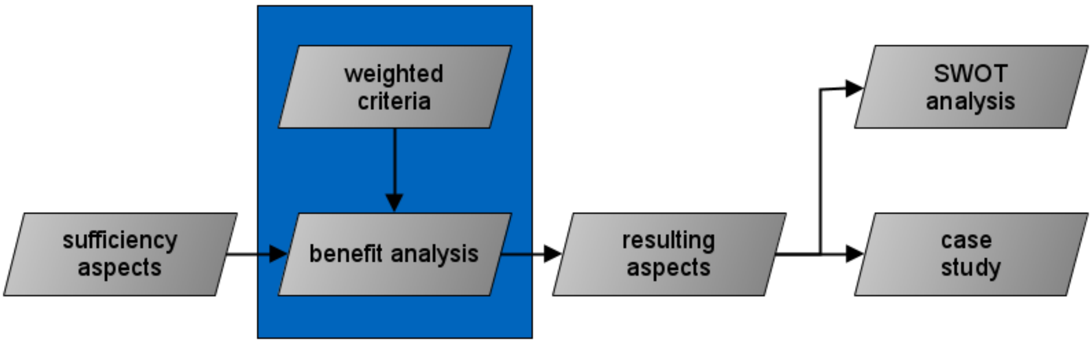

Figure 16 Flow chart benefit analysis and SWOT analysis

Zimmermann (2018) describes tools for sufficiency in housing and factors on which sufficiency can be evaluated (Zimmermann, 2018). The SWOT analysis focuses on aspects that correspond to material and technology. Figure 16 shows the process for finding these aspects. The benefit analysis is critical for this process. Zangemeister (2015) gives an example of the benefit analysis (Zangemeister, 2015). His work is the template for the benefit analysis of the sufficiency aspects. The aspects of personal space, community living, energy user behavior, expansion/construction, low-tech, and demand planning are selected with weighted criteria (chapter 4.2). These criteria have a leading question to clarify their extent (Appendix C). A SWOT analysis examines every selected sufficiency aspect and gives information on integrating sufficiency aspects in housing. The economic focus of the SWOT analysis is transformed into an analysis related to sufficiency aspects in housing.

A SWOT analysis is used in business economics to develop a strategy for organizations. Albert Humphrey invented the approach at the Stanford Research Institute in the 1970s. With this strategic planning technique, the planner analyzes the company and develops a new strategy. A division into four categories of research is part of the SWOT analysis. There is one category for each letter: strengths, weaknesses, opportunities, and threats (Friesner, 2008). Strengths and weaknesses have an internal origin (Bamberger & Wrona, 2013). The investigation for the category of strength focuses on both positive aspects from the past and successful activity. Weaknesses and the resulting increased effort indicate an opposing side. The categories of opportunities and threats are future-oriented and external (Bamberger & Wrona, 2013). Opportunities look towards trends. The threats show where the new strategy or the organization is in danger and where it is likely that risks, problems, and hindrances will occur. This analysis is the basis for a new strategy that uses the strengths to reach opportunities, avoids weaknesses, and prepares for threats (Weissman, 2015). Bamberger and Wrona (2013) and Weissman (2015) give the structure for the SWOT matrix (Bamberger & Wrona, 2013; Weissman, 2015). Strength and opportunities support the sufficiency aspect. Weaknesses and threats hinder the introduction and application of the sufficiency aspect.

4.2. Technology and Material related Aspects

Criteria	Factor
Building technology	20%
Quantitative evaluation	15%
Building envelope	25%
Related to the EnEV (DIN 4108 and 4701-10)	28%
Related to material	13%

Table 5 Criteria and the corresponding factor

Table 5 shows the criteria and factors for the benefit analysis found in an iterative process. The factors for the criteria result from a pairwise comparison (Appendix C). The factors are compared to all others. The most important one gets a high rating. If both criteria are equally important, both get the same rating. This rating results in the factor which gives a weighting of the criteria.

Sufficiency aspect	Result benefit analysis
Personal space	2.0
Community living	0.5
energy user behavior	3.8
Land use	0.8
Mobility infrastructure	0.3
Adaptability	0.9
Renovation	1.5
Equipment / Furnishings	0.4
Expansion / Construction	2.3
Location	0.4
Density of use	0.0
Social	0.0
Participation	0.0
Subsistence	0.6
Low-tech	4.2
Ownership / Financing	0.0
Demand planning	3.4

Table 6 Rated sufficiency aspects Zimmermann (2018)

Table 6 shows the aspects found by Zimmermann (2018) with the result of the benefit analysis. Every aspect is evaluated with the criteria from Table 5. The numbers in Table 6 show the degree of fulfillment with a weighted evaluation. The evaluation range is from zero, no accordance, to five, maximal accordance. The highest accordance is found in personal space, community living, energy user behavior, expansion/construction, low-tech, and demand planning. The aspect of demand planning is a tool to integrate sufficiency in the planning process (Zimmermann, 2018). Because the relation to the other three aspects is constant, demand planning is used and applied in every aspect.

4.3. SWOT Matrices

Personal Living Space

For this aspect, community living and personal space merge in personal living space. Community living allows reducing the space for one person without the necessity of reducing the common area (Kenkmann et al., 2020; Prytula, Rexroth, Lutz, & May, 2020). A decrease in living space reduces the negative impact on the environment because this space must not be built, heated, or cooled. With this, the need for new residential buildings decreases (Fuhrhop, 2020). This aspect has particular relevance. Kobiela et al. (2020) argue that one out of three leading questions is the question about how much living space is enough (Kobiela et al., 2020). One can not answer the question about which area is needed the simple way, mainly because it is related to the question of the good life in chapter 3.1.4. Nevertheless, some boundary conditions and benchmarks have been defined (Zimmermann, 2018).

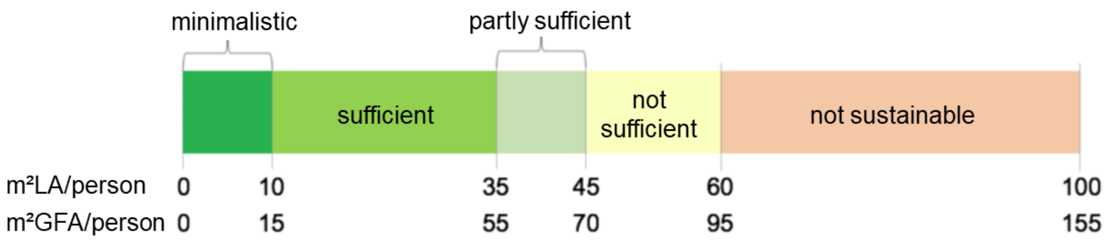

Figure 17 Benchmarks personal living space (own translation) (Zimmermann, 2018)

Figure 17 shows benchmarks for personal living space and provides information about the living space demands that can range from sufficient to unsustainable behavior. The graphic scale uses the living area (LA) and gross floor area (GFA). The discussion about whether this is appropriate or not is not part of this work.

	Helpful	**Harmful**
Internal origin	Strengths: • Positive side effects • Evaluation simple • Reduction of built area, material, and energy • Multi-use of areas	Weaknesses: • Variety of personal needs • Health issues • Rebound effects
External origin	Opportunities: • Broad application results in a sound reduction • awareness for living area and reduced needs • reduced costs • Tiny House Trend	Threats: • Status symbol • An increasing effort for the residents • Economic interests

Table 7 SWOT matrix personal living space

Table 7 shows the SWOT matrix for the aspect of personal living space. The strengths of the aspect are within in several fields. Most important are the positive side effects of a reduction of the area needed for one person. The effects come from the individual and societal levels. A positive aspect of living together is that it is possible to share tools and other goods (Schopp, 2017). The social relation of inhabitants and the acceptance of life concepts increases. The benchmarks in Figure 17 allow the evaluation. The reduced area in a building reduces the impact on the environment. Besides smaller rooms, the multi-use of rooms and areas (Figure 18) allows this reduction (Fuhrhop, 2020; Kenkmann et al., 2020).

Figure 18 Community space in inclusive living cologne (Prytula et al., 2020)

Weaknesses are resulting from the aspect itself. The appropriate area depends on personal needs, which makes it hard to assign value to every person. Planners need to deal with this complex situation. He or she must integrate the person living in a building into the planning. Another problem concerns the health of persons. If more people live in a small area, it is more likely that one person spreads disease to others. The COVID-19 pandemic shows this problem since the virus spreads over the air via aerosols. Besides this negative effect on the sharing of rooms, there are adverse side effects of a person's behavior. This is the indirect rebound effect in sufficiency. Reduced area causes cheaper flats (Kenkmann et al., 2020), which allows a person to spend more money on other things if the income stays the same. The basic rent for a flat in a Munich district (Schwabing-Freimann) is 11,781 €/year [2] for a living space of 52.5 m², which is not sufficient according to Figure 17. A flat with 22.5 m² is sufficient and costs 5,049 €/year [3]. The exact flat sizes cause a GWP of 3.07 tCO_2-eq./a [4] and 1.32 tCO_2-eq./a [5] on average. The money saved (6,732 €/year) can be spent on a flight from Munich to Sydney and back, resulting in 20.68 tCO_2-eq (atmosfair gGmbH, 2020). Thereby the saving in GWP (1.75 tCO_2-eq.) is overcompensated by far.

Opportunities of the personal living space are the awareness of actual needs. A reduced area raises awareness of consumption. A reduction in total consumption may be the result (Ellsworth-Krebs, 2020). The previously mentioned tiny house movement is an example of this (chapter 3.2). This movement and the aspect of personal living space have the same motivation. The synergy effect between the two is conceivable. Besides this, living in a reduced space comes with fewer housing costs if the framework and conditions stay the same (Kenkmann et al., 2020). These reduced costs allow social justice because more people can afford to live in an appropriate shelter (Bohnenberger, 2020b). Another factor is that old persons live in prominent places and cannot move from there because other places' price would be way higher. One example to solve this is where a person lives in a flat, pays a reduced rent, and helps the other person. Both profit from help and reduced costs.

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[2] The basic rent in Munich Schwabing-Freimann of 18.70 €/(m²*month) is based on meinestadt.de (2020). This is an average value from the evaluation of 300 sources.
[3] Ibid.
[4] With the average living space of 46.7m² per Person in Germany from Statista (2020) and the GWP of 2.75 tCO_2-eq./year for Housing and power of the CO_2-Rechner of the Umweltbundesamt (2020b).
[5] Ibid.

A threat to the aspect of personal living space is the trend to bigger buildings and flats. This trend and the fact that housing can act as a status symbol lead to increasing demand. In the COVID-19 pandemic, the flats and houses got more important to the individual (Weißmüller, 2020). Another threat is that one person has more effort if he or she wants to use rooms for several purposes. The need for communication with others increases, and there is an effort to modify furniture. The need for economic growth threatens the reduction of personal living space. The maximization of profit is not compatible with small cheap flats because more square meters allow a higher profit.

Energy Demand

The energy demand relates to the behavior of the user in the usage phase of a building. Within this phase, the user influences the building performance. Thermal comfort, for example, needs much energy in the usage phase (Matzat, 2020). The comfort and temperature vary from person to person (Lorek & Spangenberg, 2019). Fanger developed an evaluation system for thermal comfort (Fanger, 1972). A planner or engineer needs to build a building that the user can control. Personal behavior can only influence the energy demand if the user can influence settings within the building.

	Helpful	**Harmful**
Internal origin	Strengths: • direct influence on primary energy consumption • implementation is simple • empowerment of the user	Weaknesses: • Individual needs • User knowledge • acceptance and commitment of the user
External origin	Opportunities: • demand reduction technically possible • interactive elements • communication can influence the behavior	Threats: • user responsibility • Abandonment can lead to refusal • Various changes needed

Table 8 SWOT matrix energy demand

Table 8 gives an overview of the sufficiency aspect of energy demand. The energy demand of a person directly influences the primary energy in the usage phase. One can reduce this energy demand, for example, by lowering the temperature (Bierwirth & Thomas, 2019). Most of the buildings already existing allow the user to intervene in the temperature. The individual needs are met with the empowerment of the user. He or she decides about energy and, for example, temperature reduction. With this, the aspect can contribute to the self-determination of a person.

Weaknesses of the energy demand aspect are related to individual needs. There may be adverse effects of the application of the sufficiency aspects of energy demand as well. A possible negative effect comes from the personal comfort range. If there are two people in one room, both can feel comfortable with different room temperatures. At least one unsatisfied person is likely. Besides this information about interrelations is needed. The user needs to accept and commit himself or herself to sufficient energy demand. This commitment is not easy to get. For example, if a person does not think about his or her impact on the energy demand at all.

Architects and planners can influence the reduction of needed energy (Brischke et al., 2016). This reduction can happen, for example, with water-saving fittings. They reduce the need for water and therefore the need for warm water and energy for the water pump. A way to tackle the rebound effect on energy savings is a human building communication element. A traffic light-like installation can show the energy demand. Consumer awareness rises. This interaction can have another positive effect: the user identifies herself or himself with the building. Furthermore, communication between the user and the planner can give the option for a reduction of the energy demand.

A threat to the aspect of energy demand is the responsibility of the user. Several methods need to be applied by the resident. Maybe the resident does not like to have this responsibility. This abandonment may lead to the refusal of the importance and hinder the will to change.

Low-tech

The institute for energy in Voralberg (Energieinstitut Voralberg) defines low-tech buildings as robust in their construction, simple to repair if necessary, and open to exchange parts (Energieinstitut Voralberg, 2020). Planners integrate low-tech by avoiding complex technology, developing integrated solutions, designing solutions with reduced maintenance needs, and planning the building appropriate to the requirement (Auer et al., 2020; Bochart, 2017). A low-tech solution either concerns the technical building equipment or the construction (Auer et al., 2020). Within this work, the low-tech aspect refers to the construction and the aspect buildup/construction. A low-tech construction comes with fewer layers, fewer composite materials, and uses a material with few production stages (Nagler, 2018). The construction change causes reduced resources depending on the investigated indicator (Gauer & Kurzrock, 2017). The user of the building has no direct influence on low-tech construction.

	Helpful	**Harmful**
Internal origin	Strengths: • Reduced technology • Usability increased • Maintenance reduced • carbon storage in material	Weaknesses: • more planning effort • Adaptability worse
External origin	Opportunities: • Extended lifetime • easy assembly • increased quality	Threats: • Negative side effects • The comfort of the user not satisfied

Table 9 SWOT matrix low-tech

Simple construction and a low-tech building envelope offer advantages in several fields. This construction meets the requirements of the user despite the reduction. Often this construction does not influence the optical appearance of a building. The user and planner have no restrictions in this respect. Besides this, the usability of a building increases. One example is a construction that adjusts the humidity of the air. Clay as plaster for inner walls can have this effect (Auer et al., 2020; Sauer, Kapfinger, & Rauch, 2017). Clay takes up humidity from the air and gives humidity back to the air in periods of dry air. The construction avoids additional technology for humidity control. The user benefits from the automated process because he or she does not need to adjust anything. In comparison with complex constructions, simple construction allows an easy replacement. A pure wooden wall, for example, is monolithic and therefore easy to maintain and renew. Another advantage of wood in a specific dimension is carbon storage within the wooden construction (Holzforschung München, 2010). Other materials for low-tech construction are concrete or bricks.

Besides this strength, some weaknesses come with the low-tech aspect. The effort in planning is higher than with a conventional construction (Nagler, 2018). There are no guidelines or standards on how to implement low-tech in construction. Every building needs a new idea for a low-tech design. If the low-tech approach should be successful, such standards are needed. The possible problem is that buildings with low-tech construction are not adaptable and flexible anymore (Nagler, 2018). Reasons are uncertainties in the planning or that the planning only fits specific circumstances.

A low-tech wall is more manageable to prefabricate than a complex wall (Nagler, 2018). Besides prefabrication, the handling on construction site and parts' weight is reduced. Reduced handling results in less damage on the site and improves the quality of the building process. A low-tech wall is fast to build, and this is why the weather has no significant influence on the building site. The less complex the constructions are, the longer the lifetime can be (Brischke et al., 2016). There is no need for new constructions because all construction parts stay undamaged and can be used for an extended period.

There are several threats to the aspect as well. Low-tech construction does not allow every building design (Auer et al., 2020; Nagler, 2018). Architects are not free to plan the buildings according to their idea. Nagler revealed that windows must have a particular form for low-tech construction (Nagler, 2018). This unflexible frame might hinder creative design. It is not possible to build a window with a new shape. Architects are maybe less willing to introduce the aspect because of this. If low-tech should be introduced, the comfort of a user still needs to be satisfied. The user does not accept a building not compatible with his or her needs. If the low-tech approach should be successful, it still must meet the need of the user.

5. Case Study

5.1. Approach

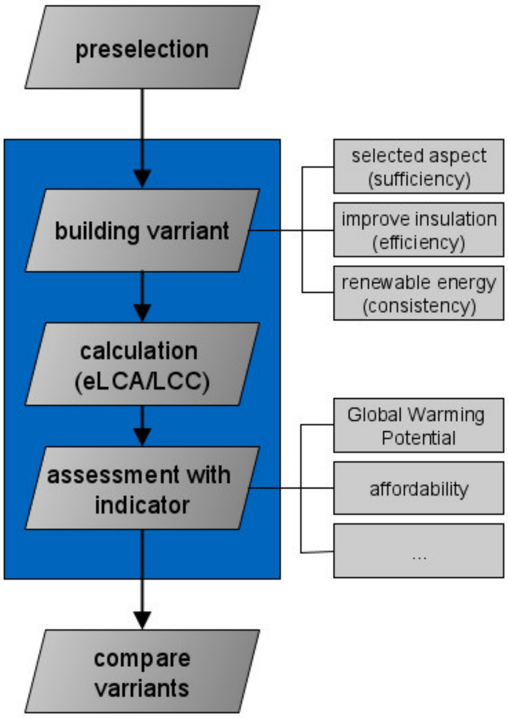

Figure 19 Flow chart for the case study

The case study deals with a multi-family home. The study shows whether sufficiency and other aspects contribute to staying within the area of thriving. The global warming potential (GWP) indicator for the building relates to the ecological global field. Besides this, the costs for the building envelope represent the indicator of affordable housing. Figure 19 displays the case study process, which starts with the preselection. The preselection results in the standard building (chapter 5.2). On this standard multi-family home, sufficiency, efficiency, and consistency approaches are applied. This application results in several variants of the building (chapter 5.3). Chapter 5.4 describes the calculation approach for the building. The outcome of all variants is compared with values for the indicators from the evaluation system.

Figure 20 Exemplary illustration type-building (Walberg et al., 2014)

The standard building is an average German multi-family home. In Figure 20, one sees an exemplary illustration of the building. The representative building is called a type-building. Such buildings give more general statements than specific buildings, and they base on statistics, the market situation, and a building and cost controlling view (Walberg et al., 2014). The type-building used in the case study is based on research of the consortium for contemporary building (Arbeitsgemeinschaft für Zeitgemäßes Bauen - ARGE//eV) in the study optimized housing (Optimierter Wohnungsbau) (Walberg et al., 2014). The building has 12 flats with a living area of 880 m² (usable building area: 1,064 m²), a gross volume of 3,325 m^3, and a building envelope area of 1,411 m². Appendix D gives further information and plans for the type-building.

5.2. Preselection

For the case study, a preselection of material for the building envelope and the heating system results in a standard building with a building envelope made from light concrete bricks and a gas condensing boiler with a heat recovery system. The wall type results from the lowest impact on the environment. This impact is defined as the GWP and primary energy (PE) based on the phases defined in chapter 5.5. One finds an exemplary construction in Table 13 in chapter 5.4. Appendix E lists all construction variants for every wall type with their data for the LCA. Values for the calculation come from the ÖKOBAUDAT.

Figure 21 shows the GWP for all variants in the wall types and the corresponding U-value (Appendix E). The concrete wall's (Stahlbeton - SB) regression line has the highest values because steel and concrete have high GWP values. The sand-lime brick (Kalksandstein – KS) is high as well. The solid wood wall from cross-laminated timber (Holzmassiv – HM) and the wall made from light concrete bricks (Leichtbeton – LB) come with low GWP values. In Figure 21, the values for the LB wall vary because the type of used bricks varies. Some of these variants integrate additional insulation, which results in a variation of the U-value. The brick wall (Ziegel – ZI) and the aerated concrete (Porenbeton – PB) have average values for the GWP within the considered reach of the U-value.

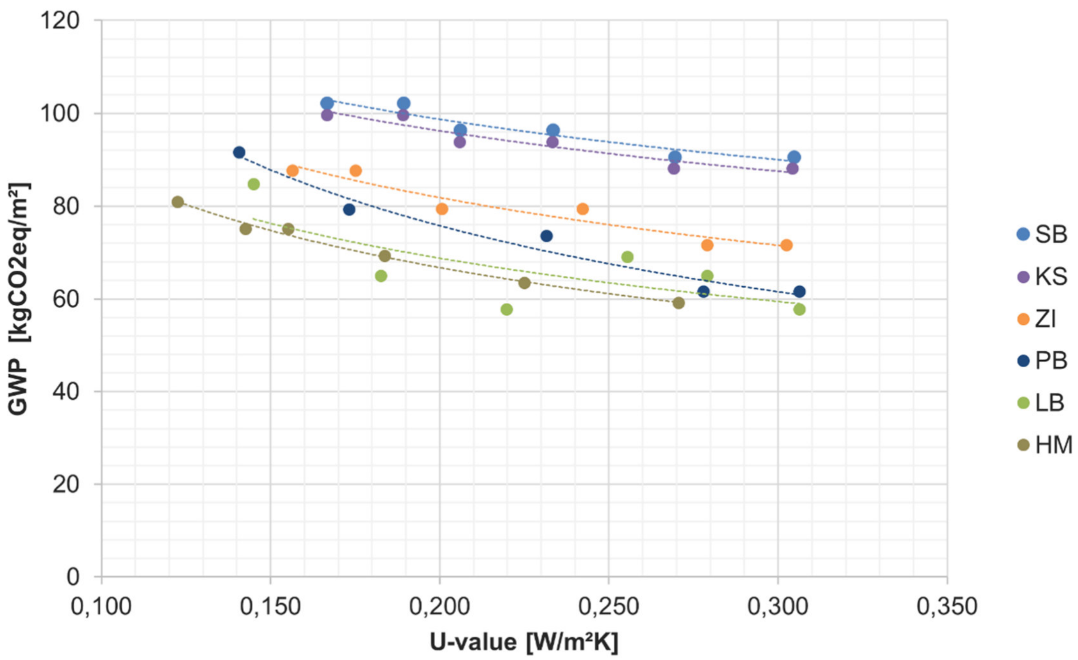

Figure 21 GWP outer wall per U-value

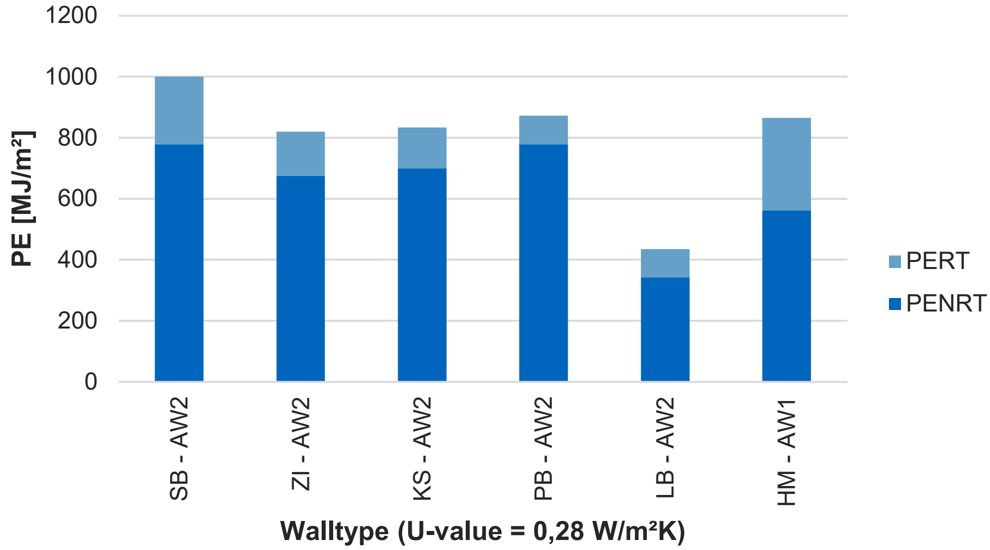

Figure 22 Primary energy per specific wall type

The second factor for the preselection is PE. Figure 22 shows the PE for specific wall types. The PE splits up into primary energy from renewable sources total (PERT) and primary energy from nonrenewable sources total (PENRT). These wall types have a reference U-value of 0.28 W/(m²K). The SB, KS, ZI, PB, and HM wall have high values for the PE. These values are in the range of 800 MJ/m² to 1,000 MJ/m². Reasons for these higher values are the effort of energy in the production of the material. Cement within the concrete and the other materials besides wood causes a relatively high energy effort (Schneider, Romer, Tschudin, & Bolio, 2011). The brick material additionally needs much energy for the process of drying in industrial production. Especially in this field, many research and development of new methods can cause fast changes (Cabeza et al., 2013). The study uses the ÖKOBAUDAT data. Therefore other product-related values are considered separately. The high value of the brick wall is the layer of light plaster on the outside. The light plaster has a total PE of 9,907 MJ/m³, and the lime plaster has 2,703 MJ/m³. This difference may result from supplements and binders that have a high value for PE as well. The ÖKOBAUDAT dataset for timber has a high PENRT. The wood drying process is energy-intensive; the dataset is a general one and does not consider specific production properties. One reason for a lower PERT is the energy mix for power.

The study uses a light concrete brick wall because of good results in GWP and PE. One square meter of this light concrete brick wall with the U-value of 0.28 W/(m²*K) causes a GWP of 65 kgCO_2-eq./m² and uses a total PE of 435 MJ/m². A wall from light concrete bricks needs no reinforcing steel. The production of reinforcing steel is energy-intensive (98,807 MJ/m³) and has a high GWP (5,365 kgCO_2-eq./m³)[6] , and causes high total values for the reinforced concrete wall. The light concrete bricks have a density of 800 kg/m³, which is low compared to sand-lime bricks' density and the brick wall (2,000 kg/m³). More material means more impact on the environment. A reason for the reduced impact of light concrete bricks is the drying. The drying process runs without any additional energy. The light concrete bricks dry in high-rack storage for 24-36 hours, and the hardening at another storage location takes 28 days[7]. The dataset does not specify the binder used for the raw material.

The case study calculation deals with specific information about the heating plant, heat gain, and heat demand. An analysis of the frequency of use of several heat generation systems reveals that the gas condensing boiler was the most used system in 2018 (dena, 2019). The gas condensing boiler with solar heating for drinking water and a heat recovery system is used in the case study.

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[6] These numbers result from the values in Appendix E, are based on the ÖKOBAUDAT, and concern a raw density of 7,850 kg/m³.

[7] Information from the technological description in the dataset: ‘Mauersteine aus Leichtbeton aus natürlichen Zuschlägen - Hohlblock - (de)’ from the ÖKOBAUDAT.

5.3. Building Variants

The building variants for the case study derives from an application of aspects. This application changes the standard building with preselected properties. In chapter 4.2, one finds the selection of sufficiency aspects. Next to these aspects, the strategies of efficiency, consistency, and lifetime extension are applied. Table 10 gives an overview of all building variants with the modified values. The description of all building variants in this chapter gives information about the used values. Appendix F shows the calculation values, including separation of area per wall with their orientation, area of building parts, and volume.

variant	adjustment	standard	modified
1	-	-	-
2	reduced personal living space	46.7 m²/person	23.35 m²/person
3	indoor temperature reduced	19°C	18°C
4	low-tech building envelope	light concrete	cross-laminated timber
5	variant 2, 3, and 4 combined		
6	efficiency: reduced U-Value	0.28 W/(m²*K)	0.145 W/(m²*K)
7	consistency: renewable res.	fossil gas	biogas
8	building lifetime extended	50 years	80 years

Table 10 Variants of the standard building

Variant 1

Variant 1 is the standard setup for the building. The values refer to the EnEV specifications (Table 11) and the preselection (chapter 5.2). The gas condensing boiler generates heat for the room temperature, and an exhaust air system ensures the building's ventilation. These specifications remain the same for the upcoming buildings if not declared otherwise.

specification	**max. value** [W/(m²*K)]	**value** [W/(m²*K)]
transmission heat loss H_T' (freestanding, area > 350m²)	0.50	0.433
external wall: light concrete brick wall	0.28	0.279
External wall to earth	0.35	0.324
wall and ceiling to not heated rooms	0.35	0.359
roof	0.20	0.194
windows	1.3	1.3
external doors	1.8	1.8

Table 11 Specification of the standard building

Variant 2

The second building variant deals with the aspect of personal living space. One person is using less living space. Today the average German lives on 46.7 m² (Statistisches Bundesamt, 2020), which results in 19 persons in the standard building. The assumption of halved personal living space results in 23.35 m². Zimmermann (2018) shows that this value is sufficient (chapter 4.3). With this assumption, the total living area of the building is 443.65 m². This floor area results in a reduced building envelope area of 422.6 m² and a reduced window area of 111 m². Building 2 has three floors. The roof and cellar do not change.

Variant 3

In this building variant, the energy demand of the building is concerned. The aspect of energy demand focuses on the inner temperature of the building. The inside temperature of the building is lowered from 19 °C down to 18 °C on average by changing the inhabitants' behavior. Matzat (2020) describes in her work that the practice of heating is complex, but a change in habit referring to the heating is possible (Matzat, 2020). This habit change influences the calculation referring to the DIN 4108 and results in higher values for heat loss.

Variant 4

The fourth building variant deals with the low-tech in construction and material. The outer wall material is changed from a light concrete brick to wood made from cross-laminated timber. The use of wood in the external wall allows a two-layer construction used in the study built simple (Nagler, 2018). With this change, the building's effort is reduced, and the wooden construction is responsible for insulation and the transfer of load.

Variant 5

The fifth variant of the standard building is a combination of all three sufficiency aspects. The combined building has 23.35 m² for one person, a room-temperature of 18 °C, and cross-laminated timber construction for the external wall.

Variant 6

The efficiency approach results in a more efficient building envelope. More efficiency in the light concrete brick wall's insulation property is realized by reducing the thermal conductivity from 0.1 W/(m²*K) to 0.55 W/(m²*K). The material of the outer wall stays the same. The result is a reduced transmission heat loss of 0.367 W/(m²*K).

Variant 7

Building variant 7 uses the strategy of consistency. The energy used is from a heating plant powered by energy from renewable resources alone. The gas for heating is from biogas, gained from biomass via a synthetic natural gas process. The case study does not concern changes in the cost calculation because of the changed fuel.

Variant 8

The changed behavior concerning the housing habits allows increasing the building's lifetime from 50 to 80 years in this variant. The habit needs action by the user and the owner of the house. The planning process of such a building needs to include durable material. The case study does not consider this kind of material in the eLCA.

5.4. Calculation and Validation

The case study's basis is an existing calculation structure in the programming language R for costs and energy demand from energetic and economic optimization of multi-dwelling units (Knallinger, 2018). This structure is extended with calculations needed for an LCA. The result is the GWP for the usage phase and the used material. The GWP in the usage phase results from the DIN 4108-6 and the energy demand in DIN 4701-10 (chapter 5.3). The method is adequately precise for the comparison of variants.

The values for costs base on the calculation atlas for shell construction and expansion in new buildings (Sirados Kalkulationsatlas 2018 für Roh- und Ausbau im Neubau) (WEKA MEDIA GmbH & Co. KG, 2018) and Construction costs for new construction elements (BKI - Baukosten Bauelemente Neubau 2017) (Spielbauer, 2017) (Knallinger, 2018). One finds the information about the costs in Table 12. This table shows the variants with different U-values according to the wall type.

		reinforced concrete (SB)	brick (ZI)	sand-lime brick (KS)	aerated concrete brick (PB)	light concrete brick (LB)	cross-laminated timber (HM)
1	Costs [€/m²]	237.03	153.22	203.98	132.41	141.39	297.00
	U-value [W/(m²*K]	0.31	0.30	0.30	0.31	0.31	0.27
2	Costs [€/m²]	240.86	169.33	207.81	137.41	156.61	304.72
	U-value [W/(m²*K]	0.27	0.28	0.27	0.28	0.28	0.23
3	Costs [€/m²]	246.67	189.04	213.62	154.39	160.61	313.76
	U-value [W/(m²*K]	0.23	0.24	0.23	0.23	0.26	0.18
4	Costs [€/m²]	252.02	223.55	218.98	237.37	189.88	323.40
	U-value [W/(m²*K]	0.21	0.20	0.21	0.17	0.22	0.16
5	Costs [€/m²]	268.33	248.80	235.28	259.02	215.35	328.75
	U-value [W/(m²*K]	0.19	0.17	0.19	0.14	0.18	0.14
6	Costs [€/m²]	273.09	272.12	240.04	-	223.68	349.82
	U-value [W/(m²*K]	0.17	0.16	0.17	-	0.15	0.12

Table 12 Costs and U-values for the variants of the buildings

The evaluation of the GWP in the usage phase considers the primary energy factors of the heating plant. Here the nonrenewable values of the energy consumption are decisive. The primary energy factor for renewable resources is zero. Future scenarios can use this factor. The thesis refers to the EnEV and thus on the DIN 4108-6 with the DIN 4701-10. The introduction of the GEG on the first of November 2020 changed the basis for the energy demand calculation. The now required DIN 18599 calculation looks more closely at the interaction of heat plant and building envelope. Upcoming research will use the DIN 18599.

Knallinger (2018) compared the results for energy and costs with the literature (Knallinger, 2018). The results are valid because they fit into the range of previous research. A detailed calculation of the GWP validates the new computation method. Table 13 gives the needed information for the construction. In the case study's scope, one finds the framework for the validation (chapter 5.5.). Data for the GWP of the light concrete wall come from the ÖKOBAUDAT.

Layer	d = Thickness [m]	n = Exchange []	GWP [kgCO_2-eq/m³]	Dataset	Dataset name
Interior plaster	0.015	1	408.22	Lime inside plaster	Kalk-Innenputz (de)
Light concrete brick	0.3	-	66.96	Lightweight concrete masonry blocks from natural aggregates - hollow block	Mauersteine aus Leichtbeton aus natürlichen Zuschlägen – Hohlblock - (de)
Mineral wool	60% of the brick	-	72.36	Mineral wool	Mineralwolle (Fassaden-Dämmung)
Light plaster	0.02	1	931.32	Lightweight rendering mortar	Putzmörtel-Leichtputz (de)

Table 13 Construction light concrete wall with U-value 0.28 W/(m²*K)

$$GWP\left[\frac{CO_2-eq.}{m^2}\right]=\sum d\,[m]*GWP\left[\frac{CO_2-eq.}{m^3}\right]*(1+n[])$$

$$=\ 0.015*408.22*2+0.3*66.96*1+0.3*0.6*66.96*1$$

$$+0.02*931.32*2\ \left[\frac{CO_2-eq.}{m^2}\right]$$

$$=65.04\ \frac{CO_2-eq.}{m^2}$$

The calculation uses values from Table 13 and gives a valid result. Walther (2019) calculates a similar value of 70 CO_2-eq./m² GWP for the light concrete wall (Walther, 2019). The case study refers to the calculation above.

5.5. Scope of eLCA and LCC

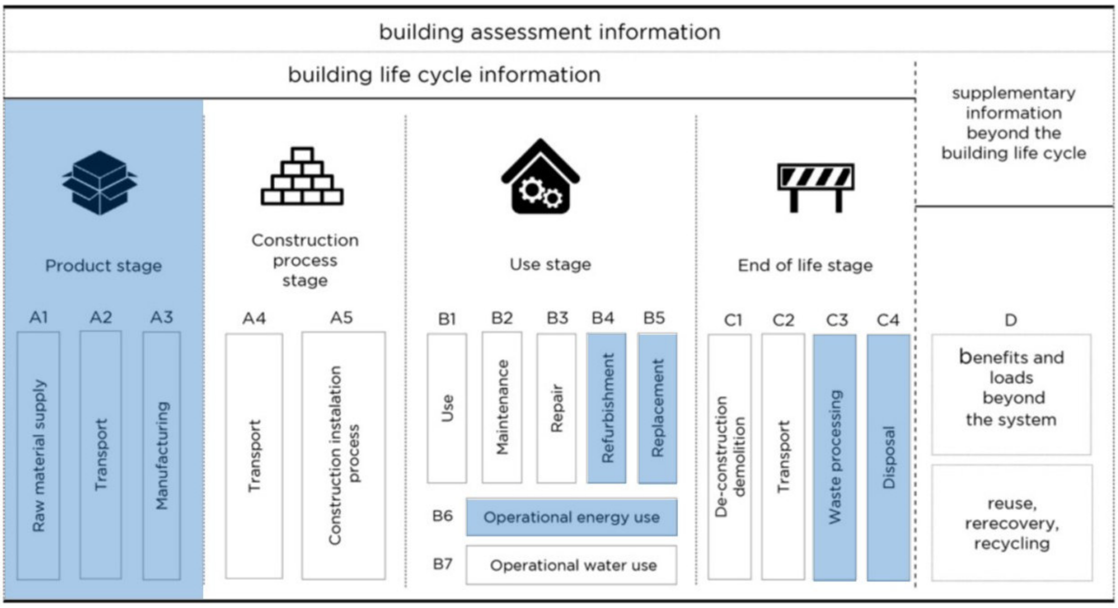

Figure 23 Scope LCA (Soust-Verdaguer et al., 2016)

The focus of the case study is on the building envelope. The interior fittings, interior walls, and technical building equipment is not included. In the eLCA, GWP and primary energy are determined. The case study looks at the phases of production (A1-A3), replacement/refurbishment (B4/B5), operational energy use (B6), and waste processing (C3-C4) according to the DIN 15978. Phase B6 concerns the energy for heating alone. Figure 23 displays the extent of the eLCA, and the blue marks indicate the used phases. This extent refers to the definition of grey energy by the swiss association of engineers and architects (Schweizerischer Ingenieur- und Architektenverein - SIA). In the standard SIA:2032, gray energy within buildings is the sum of those phases. The study excludes the transport and the operation at the building site. Concerning material, windows, doors, sanitary or electrical installation, interior components, and the heating plant are excluded. In the study, the LCA quantity comes from the building parts of the building envelope, roof, and cellar.

The reference service life for the material is taken from the table Useful life of components for life cycle analyzes according to the assessment system for sustainable building (Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem Nachhaltiges Bauen) from the BBSR (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2017). The lifetime of the building is 50 years. This time results in the number of replacements of the layer. Schneider-Marin et al. argue that an eLCA for buildings should implement the phase of usage (2020). Information about the materials used comes from the database ÖKOBAUDAT. The values integrate the heat demand and heat gains within the usage time (phase B6). This calculation follows the calculation method of the EnEV. Within the result, the values separate impact from the material and the use.

For the specific material used in the construction, generic data is used. Specific values would probably allow lower values. This chance for lower values is the case in the sand-lime brick dataset. A positive value is possible within the wooden construction because the wood can either be transformed to energy or recycled to make other building materials out of it (Cascade). But the study does not consider the recycling potential (phase D). Another unique thing about wood is that the production can use energy from production waste. For the light concrete brick wall, the dataset bricks from light concrete with natural supplements (Mauersteine aus Leichtbeton aus natürlichen Zuschlägen) is combined with the dataset for mineral wool (Mineralwolle).

Concerning the LCC, the outer wall's variation is responsible for changes in the costs of the building. Knallinger (2018) did the LCC by introducing the capital costs and energy costs within the usage phase (Knallinger, 2018). The Calculation atlas for shell construction and expansion in new buildings gives the costs of the building envelope. In this case study, the focus is on the investment costs for the building envelope. The usage phase is excluded.

5.6. Results

Appendix G lists the results for the case study. Table 14 shows the results for the standard building per year and year and person as an example. The GWP value splits into the GWP from the building envelope and GWP from the usage phase. The PE from the building envelope splits into PERT and PENERT, and the PE from the usage phase is also listed separately. Additionally, the costs for the building envelope for the related building are the last line.

		standard building	
		per year	per year and person
GWP [$kgCO_2$-eq.]	building envelope	2367.99	124.63
	use	13967.71	735.14
	total	16335.70	859.77
PE [MJ]	PERT building envelope	941.28	49.54
	PENERT building envelope	6,005.05	316.05
	total building envelope	53,069.15	2,793.11
	use	60,145.79	3,165.56
	total	113,214.94	5,958.68
		total	per person
costs [€]	building envelope	276,192.34	14,536.43

Table 14 Results standard building

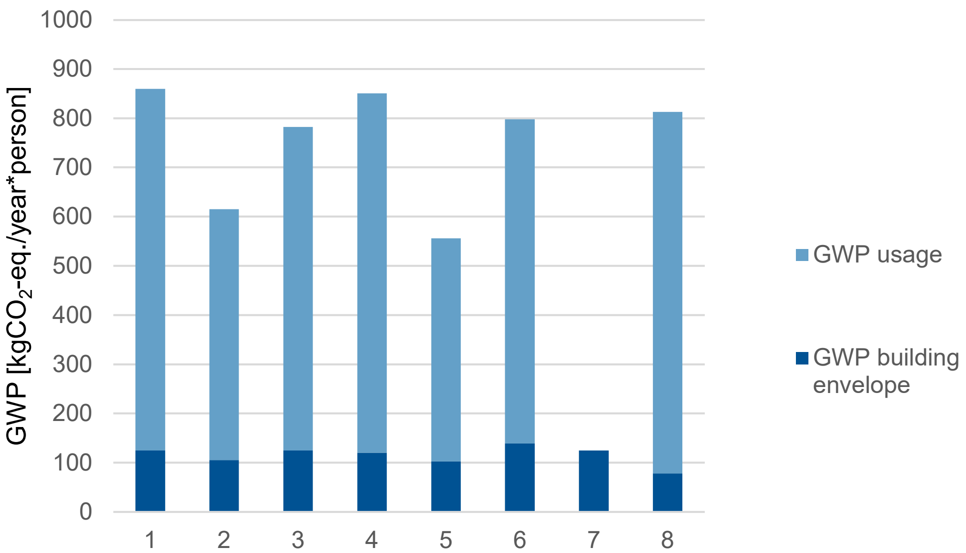

Figure 24 GWP per year and person for all variants

Figure 24 shows the GWP per year and person for every building variant. The range of GWP is from 124 to 860 kgCO_2-eq./year*person. Building one is the standard variant of the building and has the highest value for GWP. The building with the lowest GWP of 124 kgCO_2-eq./year*person is the building with renewable energy for the usage phase. With this assumption, renewable energy covers the energy demand and does not have any CO_2-emissions. In every other variant, GWP from the construction only has a minor role in the total GWP emission. Combining all the sufficiency aspects results in 556 kgCO_2-eq./year*person - the lowest GWP of these options. Within the sufficiency aspects, the personal living space causes a reduction of the GWP by 245 kgCO_2-eq./year*person. This value stands for saving about 2.2 percent of the total GWP-budget one person used in 2020[8]. The reduction comes from less heat demand and less embodied energy.

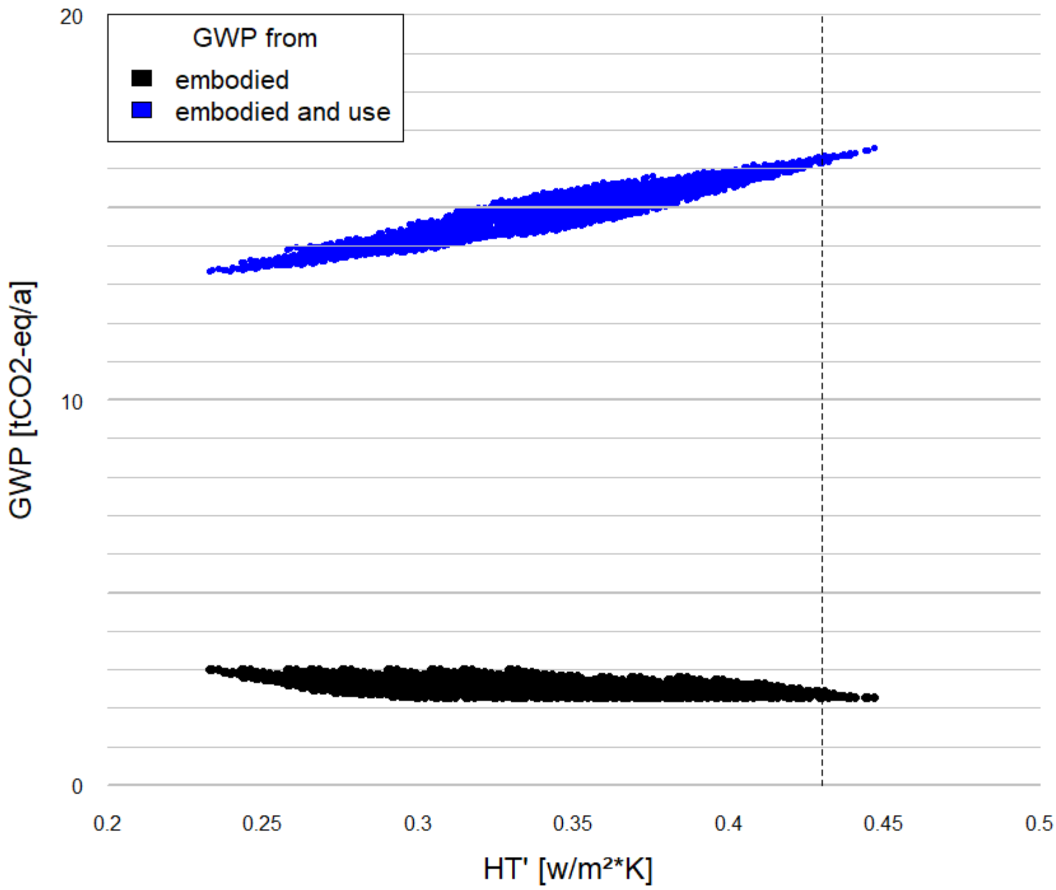

Figure 25 GWP for the standard building per transmission heat loss

[8] The Federal Environment Agency (Umweltbundesamt (2020b)) identified the average CO_2-budget per person in Germany to 11.17 tCO_2-eq./year.

The GWP for the building varies within the construction of the light concrete brick wall. Figure 25 gives an overview of the GWP results of the light concrete wall and the related transmission heat loss. The transmission heat loss depends on the variation of the U-value of the construction. The dashed line is the wall's standard variation with a transmission heat loss of 0.43 W/m²*K. The variation of the GWP embodied in the building envelope is not significant. The main impact comes from savings in the usage phase. An improvement of the insulation property of the outer wall thereby causes a reduction of the total GWP. The total of about 16 tCO_2-eq./a reduces to about 13.5 tCO_2-eq./a. Every building variant can reach this reduction of 15 percent by the improvement of the building envelope.

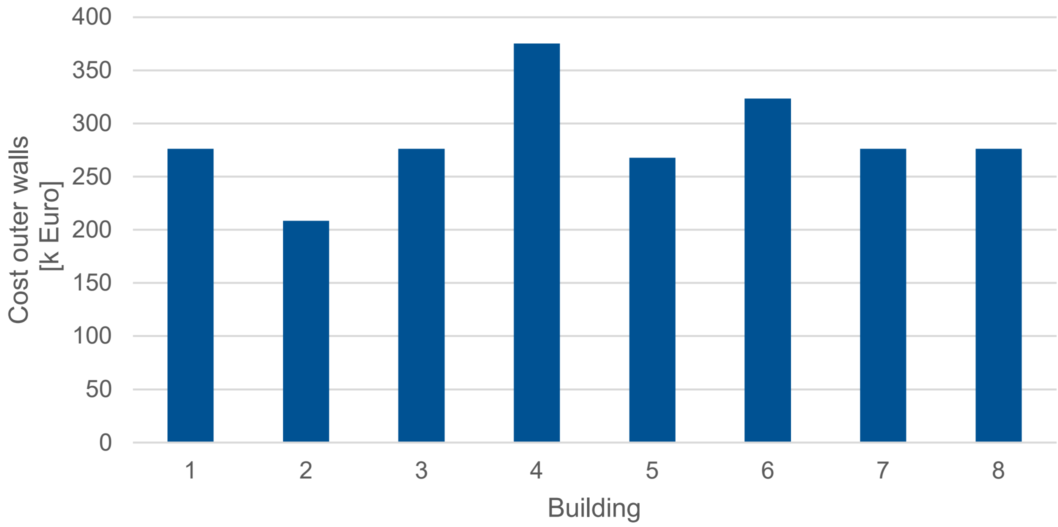

Figure 26 Total cost outer walls

The second indicator analyzed is affordability. In the case study, the focus is on the price of the building envelope. One sees the price range from 208,000 € to 375,000 € for the building envelope in Figure 26. An application of the aspect of personal living space in building two results in the lowest costs. One reason is a reduced building envelopes area. This reduced area needs less material and less effort for the assembly. The most expensive building is variant four that has an outer wall made from cross-laminated timber. This cross-laminated timber needs more effort for the assembly and an installation layer on the inner side. Both cause a higher price. Another reason is that the wooden construction needs an increased thickness to reach the same U-value as the other constructions. Wood is more expensive than insulation and other construction material.

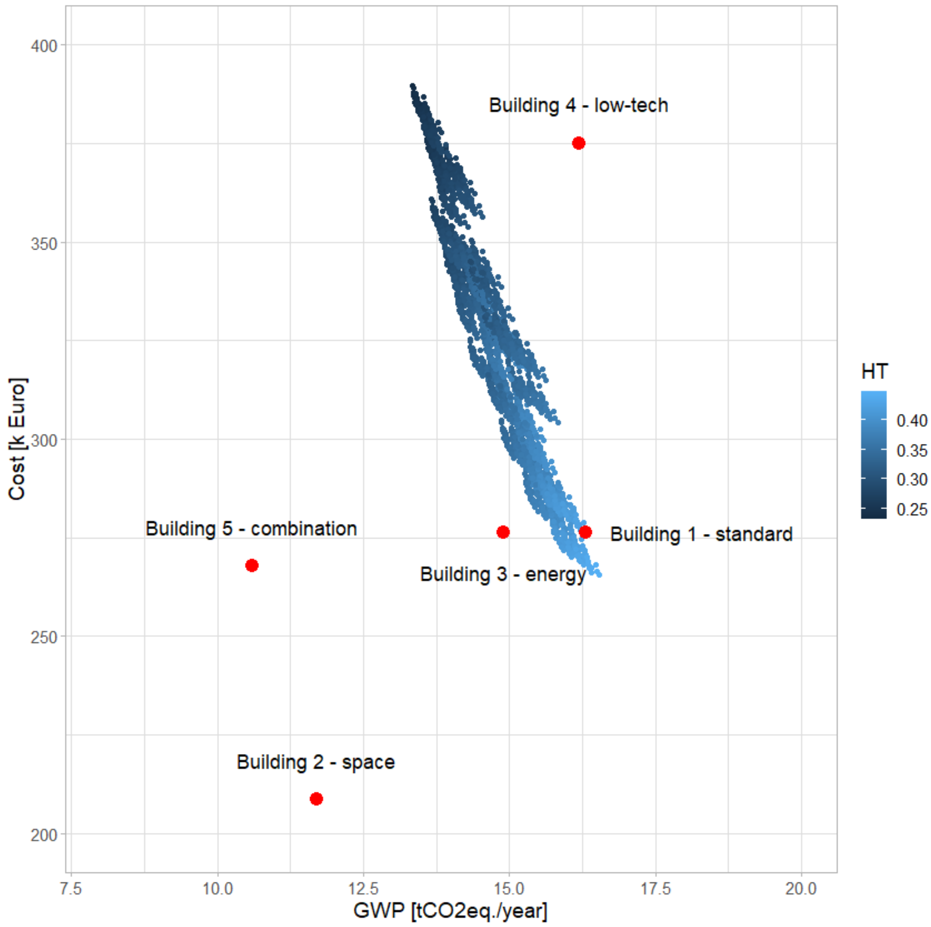

Figure 27 Total costs per GWP for sufficiency aspects

The two indicators are related to each other. Figure 27 shows their relation. The total GWP for the building envelope and from use in tCO_2-eq./year is on the x-axis. The range is from 7.5 to 20 tCO_2-eq./year. The y-axis displays the investment costs caused by the building envelope in €. The range for the buildings with the applied sufficiency aspects is from 200,000 € to 400,000 €. A dot cloud gives information about the variation of the standard building. These variations differ in the construction. With more and improved insulation material, the transmission heat loss decreases. One can apply this change of the building envelope to every building with the applied sufficiency aspects. The building's low-tech variant has high values in costs and only a very slight reduction in the GWP. With the combination of all three aspects, the high costs of the low-tech approach are compensated. The reduction of the living space allows the best results for both indicators. This variant results in the best reduction of GWP. Within this scope and the given framework, this variant has the most negligible impact on both indicators.

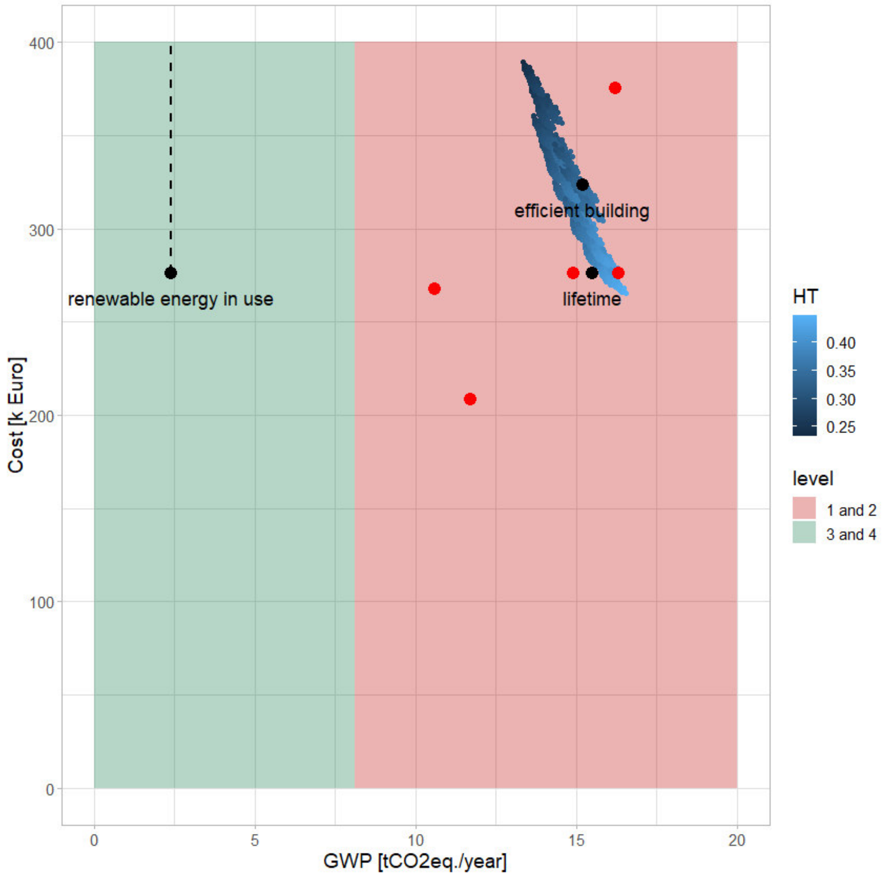

Figure 28 Total costs for the building envelope per GWP

The red marks in Figure 28 show the sufficiency aspects. The diagram ranges from 0 to 20 tCO_2-eq./year and from 0 to 400,000 €/year. The background of the diagram refers to the evaluation system. The green color indicates the area of thriving (levels 3 and 4), and red indicates the area outside the boundaries (1 and 2). The building with a higher efficiency lies within the range of the other approaches. It has a better value for the transmission heat loss, and this way, one reduces the GWP in the usage phase. However, there is more embodied GWP in the material. The efficient building is more expensive than most sufficiency variants which perform better in terms of affordable housing. The variation of the lifetime has neither a significant influence on the costs nor on the GWP. This low impact comes because the lifetime only influences embodied GWP per year. Lifetime extension reduces the GWP to 15.4 tCO_2-eq./a in total, which is 0.9 tCO_2-eq./a less than the standard variant.

The consistency strategy's building variant deals with renewable energy and allows a reasonable reduction of GWP to 2.3 tCO_2-eq./year. This lasting GWP is from the embodied energy. The costs do not include the cost of the heating plant. The dashed line stresses that there are costs for this technology not observed.

6. Discussion

The case study shows that today's standard building is not within the acceptable ecological boundaries. Therefore, this building needs optimization. The application of sufficiency aspects is one strategy to do so. Within these applied sufficiency aspects, the best result comes from the reduction of personal living space. The ecological indicator is reduced by about 30%, and the social indicator is reduced by about 25%. The temperature reduction by one degree allows savings in the ecological indicator of about 6%. This reduction agrees with the literature (Calì et al., 2016) but is not enough to stay within the given boundaries. Consistency is the solution that brings the GWP value into the area of thriving within the evaluation model. In this case, the embodied GWP is remaining.

The building variants have several limitations. Within the second building variant, the reduction of the personal living space results in three floors. This assumption changes the cubic volume, which has an impact on the heat demand and heat loss. For the heat demand, a more compact building is better. Whereas, for the cooling demand, which will increase in the future, the more compact building can negatively affect (Menti, Serge Mattli, & Hönger, 2020). Therefore, a simulation of several building volumes and the consideration of future climate data makes sense. In building four, the wooden construction's positive effect as a sink for carbon is not within the investigation's scope, and thus the positive effect is not considered. This has an impact on the GWP (Bund Deutscher Architekten, 2019). The consistency variant does not consider the new heating technology price because the case study only looks at the building envelope's investment costs. Investment costs for a heating system powered by renewable energy can be higher than those of conventional technology (dena, 2019). Besides this, the required mechanical parts for another heating system may cause more GWP in the production. Additionally, the impact on, for example, the biodiversity at the site can be affected negatively. New research could go into detail about this broader view. The efficiency approach in the case study causes higher costs in the building envelope. These higher costs come from the insulation material with less thermal conductivity. However, the savings in the usage phase are not concerned due to the scope of the case study. Significantly if the price of energy rises due to emission pricing, the total costs will rise.

The reduced number of indicators limits the broad view and the holistic approach to the effects of the selected sufficiency aspects. The effects on other impact categories, for example, the area used, will differ (Petroche et al., 2015). The case study focuses on the thermal building envelope and excludes the costs of interior walls, interior fittings, and the building's technical building equipment. Specifically, the technical building equipment can cause half the building's ecological impact (Weißenberger, 2016). Another research must consider the impact of the technical building equipment.

The new evaluation system, used in the case study, assesses residential buildings' impact on social and ecological aspects. The evaluation system has high potential because global problems and local solutions can be linked. This link is more evident than other evaluation systems. For example, the global scale limitations are related to local material and, therefore, the building scale. This way, a more sophisticated discussion about sustainability in housing is possible, both in resource use and energy use in the usage phase. The evaluation system allows us to be flexible with the indicators' fulfillment if the indicator stays within the defined boundary. The example in chapter 2.5 shows this. Next to that, the system allows freedom of choice. The planner or architect can still decide how to stay within the boundaries. The strategies for this are sufficiency, efficiency, and consistency (chapter 3.1.1).

There are some limitations to the evaluation system. A detailed elaboration can only be found for a few indicators so far. A detailed analysis of the values is needed. For some indicators, both ecological and social, no limit values have been found yet by science. Research in the corresponding field will give new perspectives and limitations. Besides the missing research, some of the indicators are abstract and not widely known. The contribution to ocean acidification of building material, for example, is not easy to understand. Broader awareness and an understanding of ecosystems will help. Education in this expertise can help us to get there.

7. Conclusion and Prospect

This thesis shows the effects of sufficiency aspects in a case study using the new evaluation system indicators. Sufficiency aspects can be introduced right away and do not need any further development. There is no barrier in the form of investment costs, and they have an immediate impact. The obstacles derive from other fields (chapter 3.1.4). The SWOT Analysis gives us detailed information about some of the sufficiency aspects of housing (chapter 4). An extension of the SWOT Matrix is the basis for concepts to tackle the threats and obstacles. These solutions need to focus on the whole planning process and the life cycle of the building. Within the case study (chapter 5), the focus is on GWP and affordability. The influence of personal heating habits has only a small impact on these indicators. The reduction of the personal living space instead is resulting in a considerable reduction of GWP. A low-tech approach for the construction results in an increase in GWP. The discussion gives reasons for this. The solution with the application of consistency shows promising results. For a general statement, one must consider other indicators as well. Efficiency is needed because one cannot take endless energy from renewable resources so far. Energy saving is the key to support every person on the planet with decent access to energy.

Most of the tested aspects allow a cost reduction of the building envelope, which positively affects affordability. The LCC in the case study does not concern pricing of ecological impacts, for example, of CO_2-emissions. Since this pricing will happen in the future, this is an exciting field of further research. The results show that sufficiency aspects have environmental and social impacts. Therefore, especially sufficiency aspects help to reach the area of thriving in several indicators. The strategies of efficiency and consistency, which focus on technical solutions, reduce the ecological indicators.

A policy that strengthens sufficiency and prevents non-sustainable action will increase the importance of sufficiency aspects in housing. Actions by politics, housing stakeholders, and architects should not forget about the heat demand in the usage phase, even if the personal living space has more potential for climate change and affordability. Sufficiency in housing is more than the aspects analyzed in this work. There are alternative ways to cover the need for housing. Examples are shared housing or renovation. This change in behavior concerning housing habits results in a reduced need for new buildings and positively affects sustainability.

The evaluation system based on doughnut economics differs from other evaluation systems. It is about actual ecological and social borders on the global and local scale. The social aspects like affordability integrate the economic dimension. One may name this an evaluation system of the third generation (chapter 2.2.3). The new evaluation system gives room for improvement, for example, concerning the indicators. The evaluation system's improvement happens with a broad discussion in the Doughnut Economics Action Lab (Doughnut Economics Action Lab, 2020b). A broad discussion by several stakeholders and a test of the evaluation system in the field gain additional information and increases acceptance. The holistic evaluation of several strategies' impacts allows us to find the strategies with the best result.

Furthermore, a more holistic application of the evaluation system is conceivable. Housing is only one field of the impact of an individual. The extension to an individual's needs allows setting his or her focus. Such needs are mobility and food. One could shift expenses within the boundaries between the needs. The evaluation system could work similarly to the CO_2 calculator of the German Federal Environment Agency (CO_2 Rechner des Umweltbundesamt), but for all indicators.

The evaluation system follows the precautionary principle, and the aim is strong sustainability. These considerations cause strict limits and make it even harder to justify them within the capitalistic economic view. The discrepancy between economic interests and sustainability needs further investigation. Adjustments to the economic system are necessary. This work focuses on housing sufficiency aspects but reveals that cooperation of the three superior sustainability strategies is required. The evaluation system accompanies the journey into a sustainable housing sector. In this way, housing within given boundaries will be the future and allows a good life for all of us (Figure 29).

Figure 29 Housing within boundaries (Eli Pautz)

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9. List of Figures

10. List of Tables

Appendix A

ecological indicators

Ecological local indicators

indicator	dimension	description	source and related work
criteria matrix	environmental impact	The matrix contains several substances and aspects that are considered. Defined Values give information about the number of substances.	DGNB - ENV 1.2 local environmental impact
emission	environmental impact	What is the quantity of emissions at the site? The negative impact on nature and humans should be minimal. Minimize the demand for products etc., with negative emissions. Maximize the circularity capacity. Other related factors like mobility are concerned here as well.	DGNB: TEC 1.7 - Immissions control; TEC 1.3 - the quality of the building envelope; TEC 1.4 - Use and integration of building technology; TEC 1.6 - Ease of recovery and recycling; Common Good Matrix
environmental behavior	environmental impact	The inhabitants refer to environmentally friendly behavior. This reaches from waste treatment to awareness for pollution.	Common Good Matrix
land coverage	life on land	This concerns the coverage of the area on the site. Less coverage is rated positively.	DGNB - ENV 2.3 Land use
Biodiversity at the site	life on land	Is the building contributing to or hinder biodiversity?	DGNB - ENV 2.4 Biodiversity at the site
water at the site	water	The water used and distributed of the building. This indicator concerns wastewater and water demand.	DGNB - ENV 2.2 Portable water demand and wastewater volume

Global ecological indicators

indicator	dimension	description	source and related work
global warming potential	climate change	The indicator measures the Global Warming Potential with the CO_2-equivalent of the related gas. Life Cycle concerned.	Planetary Boundaries: Exploring the Safe Operating Space for Humanity
carbonate ion concentration	ocean acidification	Ocean acidification causes problems for marine ecosystems.	Planetary Boundaries
emissions and their effect	chemical pollution	The effect of chemical pollution can be various and needs further research to the extent.	Planetary Boundaries
amount of nitrogen and phosphorus	nitrogen & phosphorus loading	Both biochemical cycles need to stay within a range that is bearable.	Planetary Boundaries
consumptive blue water use	freshwater withdrawals	The use of water influences climate patterns and has diverse effects on ecosystems.	Planetary Boundaries
percentage land converted	land conversation	The soil and area covered not by water are essential in this indicator. Overuse of this system can result in global problems.	Planetary Boundaries
extinction rate	biodiversity loss	The extinction rate is a value with high uncertainties. This indicator is important because of ethical reasons and the need within ecosystems.	Planetary Boundaries
particulate concentration	air pollution	There are effects on human health, as well as on the water system and other ecological systems.	Planetary Boundaries
stratospheric O3 concentration	ozone layer depletion	A stable ozone layer is needed to allow life on earth.	Planetary Boundaries

Appendix B

social indicators

Social local indicators

indicator	dimension	description	source and related work
water	physiological	The amount of water needs to be sufficient for drinking and cleaning.	Kate Raworth Doughnut Economics; Ottowa Charter for Health Promotion,
nutrition	physiological	The amount of food for the person - in terms of calories and other ingredients	Kate Raworth Doughnut Economics
physical health	physiological	The human body needs certain circumstances to stay physically healthy. A building can contribute to this circumstance, either positive or negative. Healthy food and water are included. Comfort referring warmth and cold for the person in a building.	Ottowa Charter for Health Promotion, 1986; DGNB SOC1.2 - Indoor air quality; DGNB SOC1.1 - Thermal comfort; DGNB SITE 1.1 - Local environment
mental health	physiological	Mental and physical health is the foundation for all other needs. The building avoids the negative impact on the residents.	Comprehensive mental health action plan 2013-2020-2030 (WHO)
education	safety	Is there a chance to use an education system? This indicator is a foundation for all upcoming needs.	Kate Raworth Doughnut Economics
income and work	safety	Can the building contribute to this indicator?	Kate Raworth Doughnut Economics
energy	safety	Is there sufficient energy amount from renewable resources?	Kate Raworth Doughnut Economics
shelter	safety	The house needs to give enough shelter from the environment.	Kate Raworth Doughnut Economics; DGNB SOC 1.7 - Safety and security
affordable housing	safety	The costs of housing must stay affordable for the inhabitants. Are the contracts and the rent fair?	Kate Raworth Doughnut Economics; DGNB ECO1.1 - Life Cycle Cost;
fire safety	safety	Does the building follow the official regulation and maybe more?	DGNB TEC 1.1 - fire safety
recreation	safety	The building and the rooms can help to recreate.	common Good Matrix; DGNB SOC 1.6 - Quality of indoor and outdoor spaces; DGNB SITE 1.4 - Access to amenities

visual safety	safety	The building provides safety in terms of visual properties.	DGNB SOC 1.4 - visual comfort
acoustic safety	safety	The acoustical and sound properties contribute to a safe space for the residents.	DGNB SOC 1.3 - Acoustic comfort; DGNB TEC 1.2 - Sound insulation
communication	love/belonging	An offline and online network allows communication and mindful contact within the building.	Kate Raworth Doughnut Economics; Common Good Matrix; DGNB PRO 2.4 - User communication
human dignity	love/belonging	Ethical relations between housing stakeholders.	Common Good Matrix
Identification	love/belonging	Identification with the building.	DGNB ECO2.2 - Commercial viability
gender equality	esteem	No gender is separated. Gender policy for the building.	Kate Raworth Doughnut Economics; Common Good Matrix
inclusion	esteem	Are all kinds of persons included (for example, disabled, ill, or older people)? Other inhabitants provide help for all people.	Common Good Matrix; city portraits: Lense Local Social; DGNB SOC 2.1 - design for all
Solidarity and social justice	esteem	Inhabitants Contribute to and are solidary with the community within the city.	Common Good Matrix
transparency and co-determination	esteem	Ownership or rental system of the flats the building is transparent, and inhabitants participate.	Common Good Matrix
political voice	self-actualization	Persons within the building should have a political voice and should be able to use this.	Kate Raworth Doughnut Economics; Common Good Matrix
culture	self-actualization	Does the building allow to be creative and either take part in culture or to be culturally active? Rooms for artists etc., and integration in the Baukultur at the site.	DGNB PRO 1.6 - Procedure for urban and design planning; SITE 1.2 - Influence on the district
independence	self-actualization	Every person in the building is doing his or her lifestyle.	city portraits: Lense Local Social; DGNB TEC 3.1 - Mobility infrastructure; DGNB SITE 1.3 - Transport access
creativity	self-actualization	Is the person able to unfold creative potential? Participation within the usage phase and in the planning phase.	DGNB SOC 1.5 - user control; DGNB PRO 1.4 - Sustainability aspects in tender phase; DGNB SITE 1.4 - Access to amenities

Global social indicators

indicator	dimension	description	source and related work
comply with human rights by the United Nations	human rights	Every process and every stakeholder allow to comply with human rights and do nothing against them.	Common Good Matrix; Guidelines for social life cycle assessment of products
reduced inequalities	working conditions	Is every Person treated equally, independent of any category? No child or forced labor, fair salary	Common Good Matrix; Kate Raworth Doughnut Economics
responsibility for workers	working conditions	Does the company care about the rights, health, and safety of its workers?	Common Good Matrix, Guidelines for social life cycle assessment of products
transparency of the work	working conditions	The workers should know what they work on and what their product is used for.	Guidelines for social life cycle assessment of products
health and safety through the life cycle	health and safety	Health and safety for consumers, workers, and all stakeholders	Common Good Matrix; Guidelines for social life cycle assessment of products
no destruction of cultural heritage	cultural heritage	The heritage that is there is a specific location or site needs protection and conservation.	Guidelines for social life cycle assessment of products
contribute to new cultural heritage	cultural heritage	New ideas should not be suppressed.	Guidelines for social life cycle assessment of products
governmental action	governance	The government cares about the indicators and gives rules and laws that allow complying with them.	Guidelines for social life cycle assessment of products
Solidarity and social justice	socio-economic repercussions	Products and services avoid social injustice.	Common Good Matrix
socially responsible funds	socio-economic repercussions	Use of funds concerning social and environmental impacts.	Common Good Matrix

Appendix C

Benefit analysis

Criteria for the benefit analysis

These criteria are used to find the aspects of sufficiency related to technology and material. The leading questions allow an evaluation of every aspect of sufficiency.

Nr.	Criteria	Leading question
1	Building technology	Has the aspect a direct impact on the construction or the heating plant?
2	Quantitative evaluation	Is there a value that allows evaluating the aspect?
3	Building envelope	Is the aspect related to the building body? Has the aspect an influence on size, shape, or construction?
4	Related to the EnEV (DIN 4108 and 4701-10)	Does the aspect influence heat demand or loss? Are the calculations within the EnEV influenced?
5	Related to material	Has the aspect an influence on the material? Is the aspect related to the use of the material?

Pairwise comparison of the criteria

This pairwise comparison results in a factor that is used to weight the criteria.

	Building tech.	**Quanti-tative**	**Building envelope**	**EnEV**	**Material**	**Sum**	**Factor**
Building tech.		3	1	1	3	8	20 %
Quanti-tative	1		1	1	3	6	15 %
Building envelope	3	3		2	2	10	25 %
EnEV	3	3	2		3	11	28 %
Material	1	1	2	1		5	13 %

Analysis

Aspect	Criteria (evaluation: 0-5)					Result
	1	**2**	**3**	**4**	**5**	
Personal space	0	5	5	0	0	2.0
Community living	0	0	2	0	0	0.5
energy user behavior	2	5	5	5	0	3.8
Land use	0	5	0	0	0	0.8
Mobility infrastructure	0	2	0	0	0	0.3
Adaptability	2	0	2	0	0	0.9
Renovation	2	0	2	2	0	1.5
Equipment / Furnishings	2	0	0	0	0	0.4
Expansion / Construction	2	0	5	0	5	2.3
Location	2	0	0	0	0	0.4
Density of use	0	0	0	0	0	0.0
Social	0	0	0	0	0	0.0
Participation	0	0	0	0	0	0.0
Subsistence	0	0	0	0	5	0.6
Low-tech	5	5	5	2	5	4.2
Ownership structure/ financing	0	0	0	0	0	0.0
Demand planning	5	0	5	2	5	3.4

Appendix D

Standard building

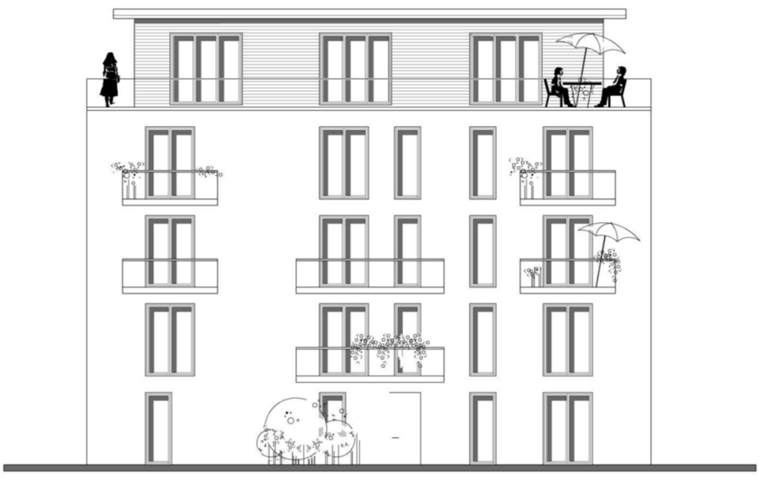
Data standard building

The standard building from the 2014 study "Optimierter Wohnungsbau" form the *Arbeitsgemeinschaft für Zeitgemäßes Bauen* (Walberg et al., 2014, p. 12) defines a multi-family home. The information results from statistics and the market situation.

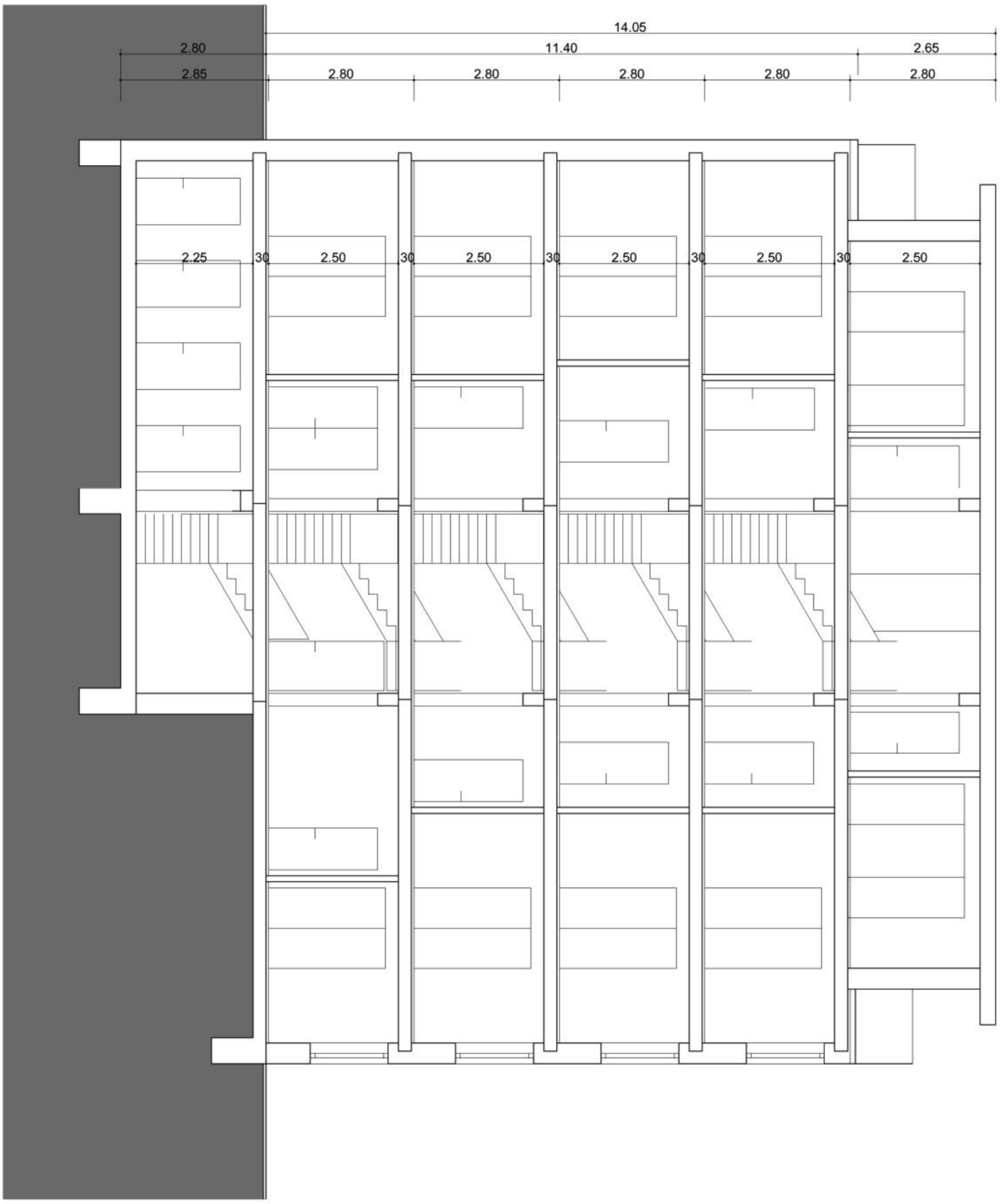
- Usable Building Area: 1,064 m²
- Living space: ca. 880 m²
- Volume: 3,325 m³
- Enveloping surface: 1,411 m²
- Enveloping surface / Volume ratio: 0.42

Design and plan

Ansicht Eingang



Ansicht Garten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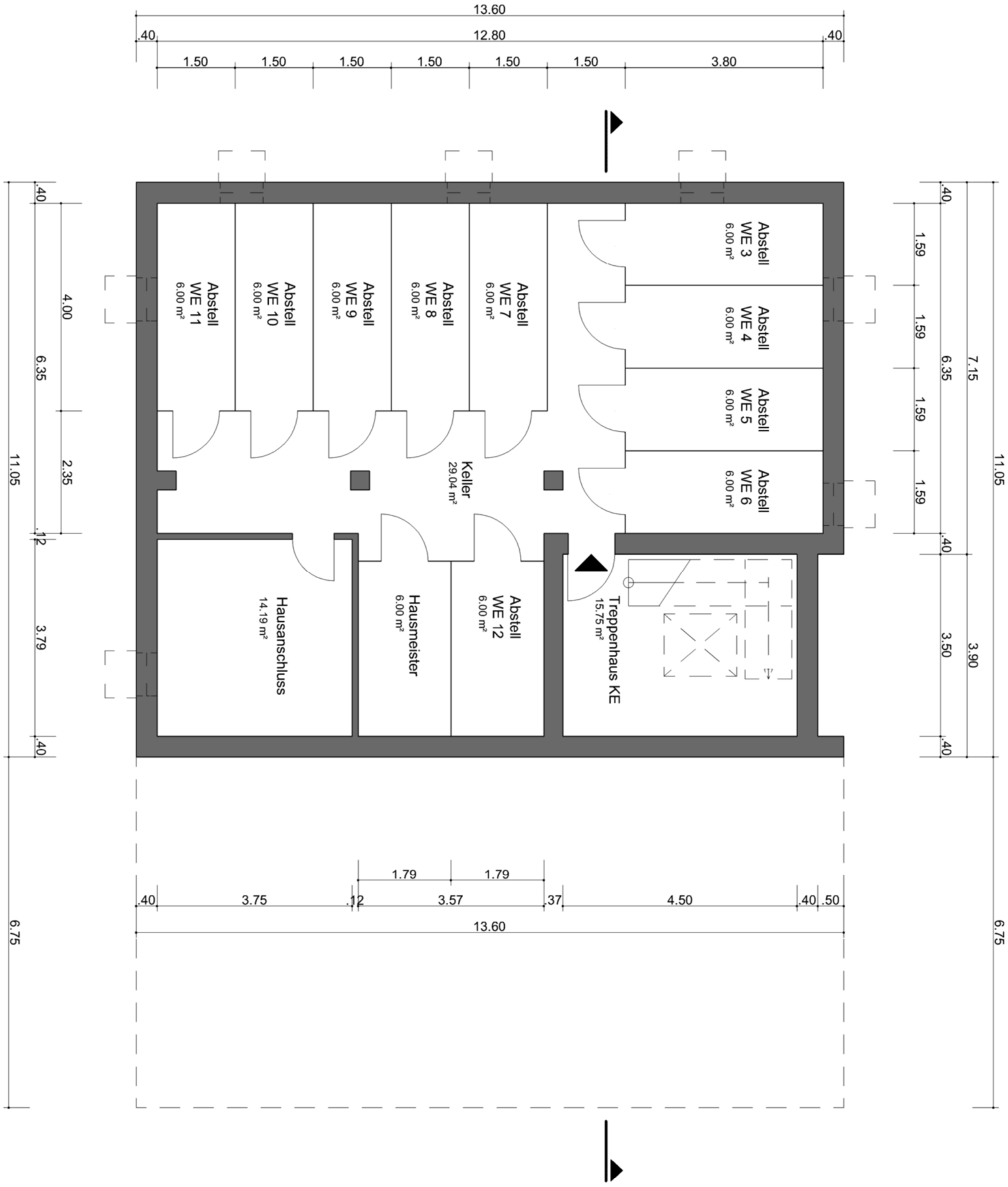
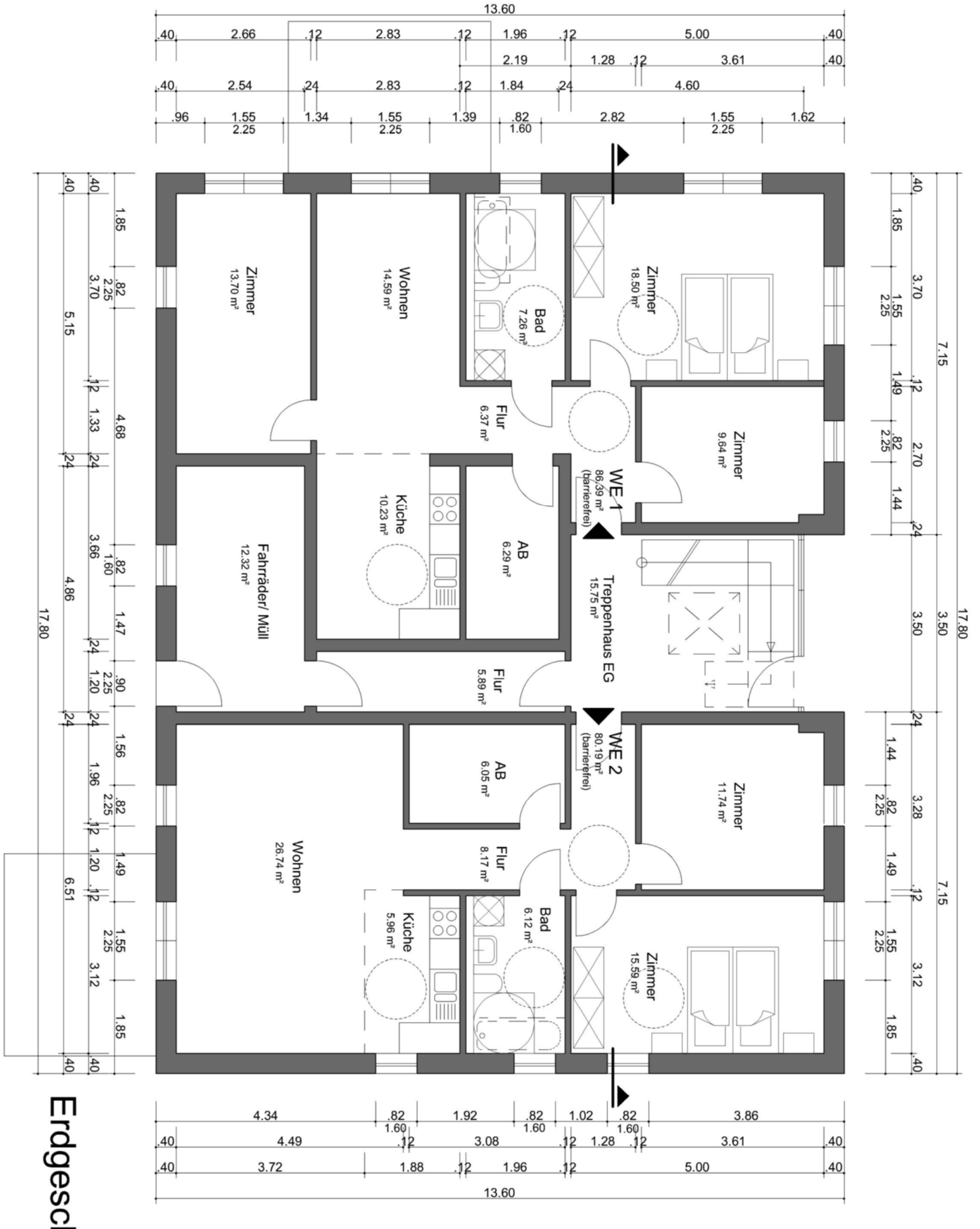


Kellergeschoss



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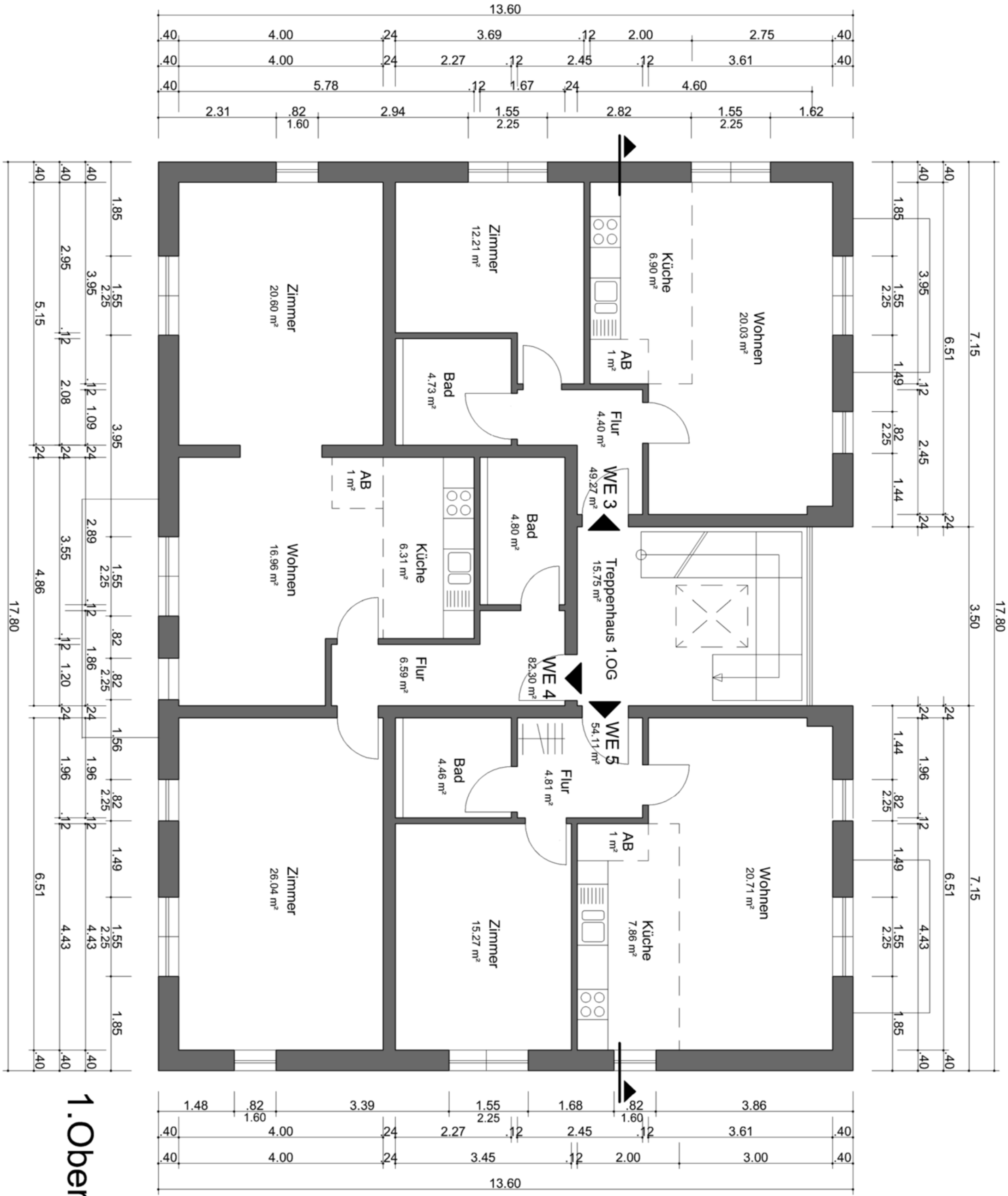
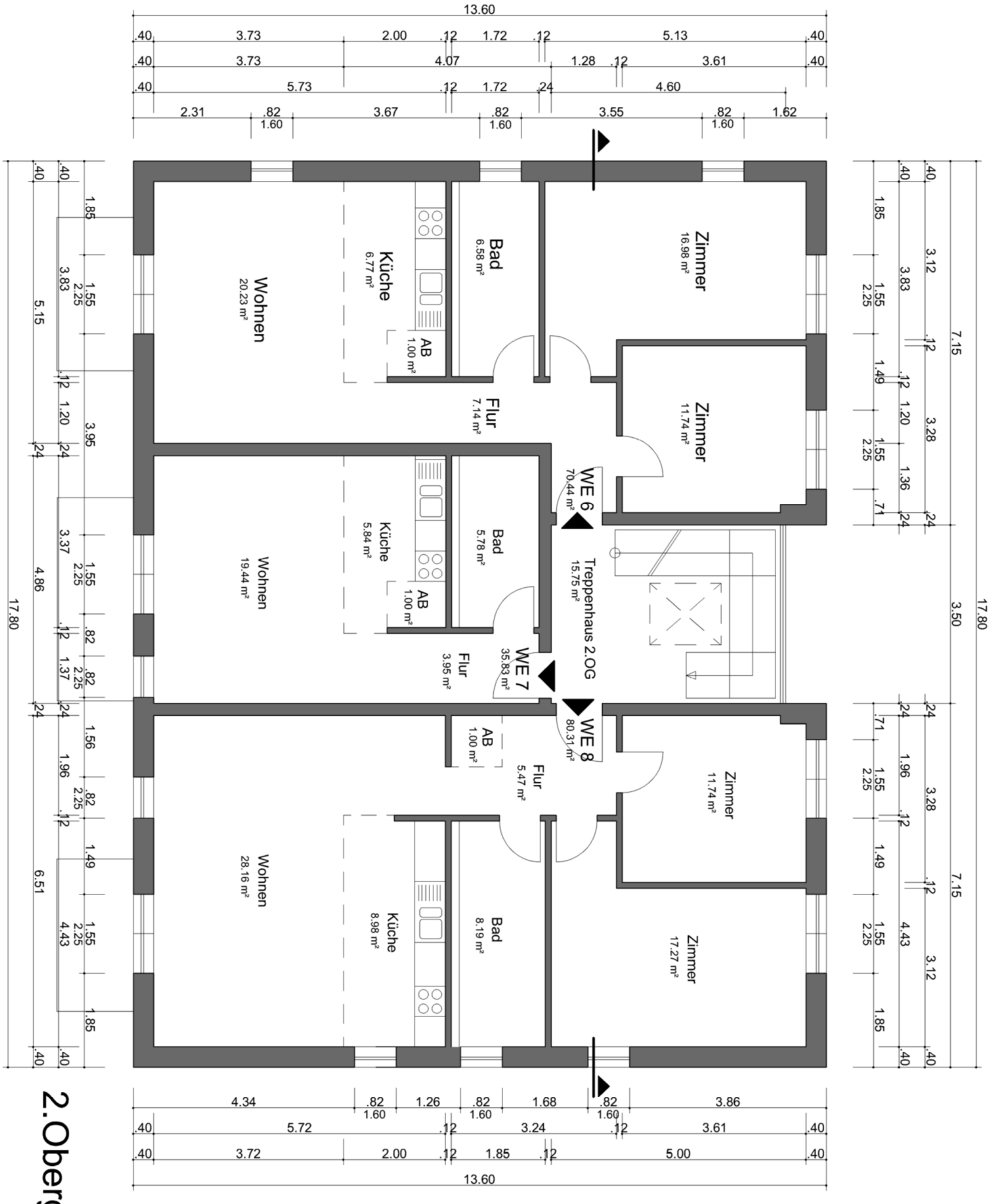


1.Obergeschoss



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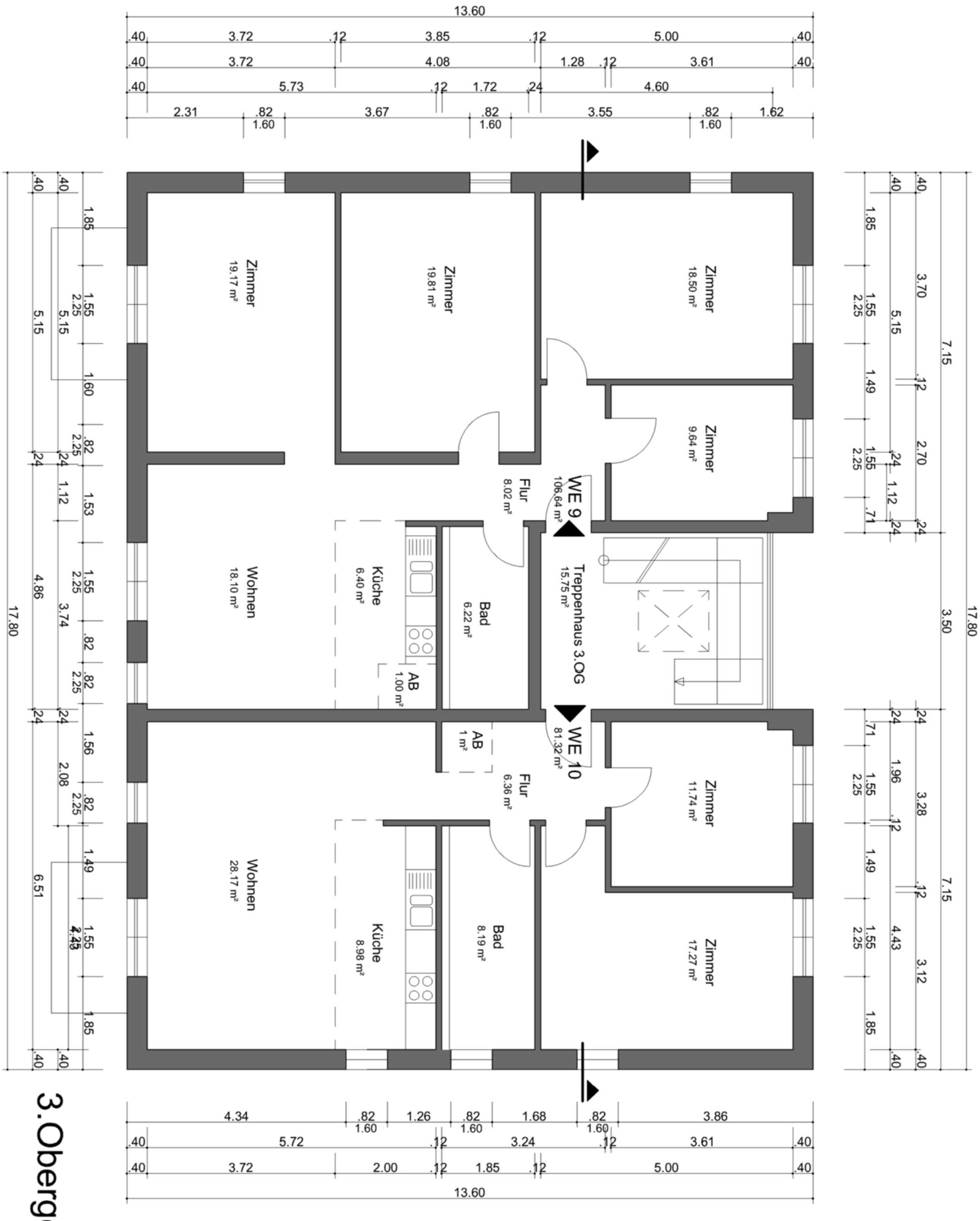

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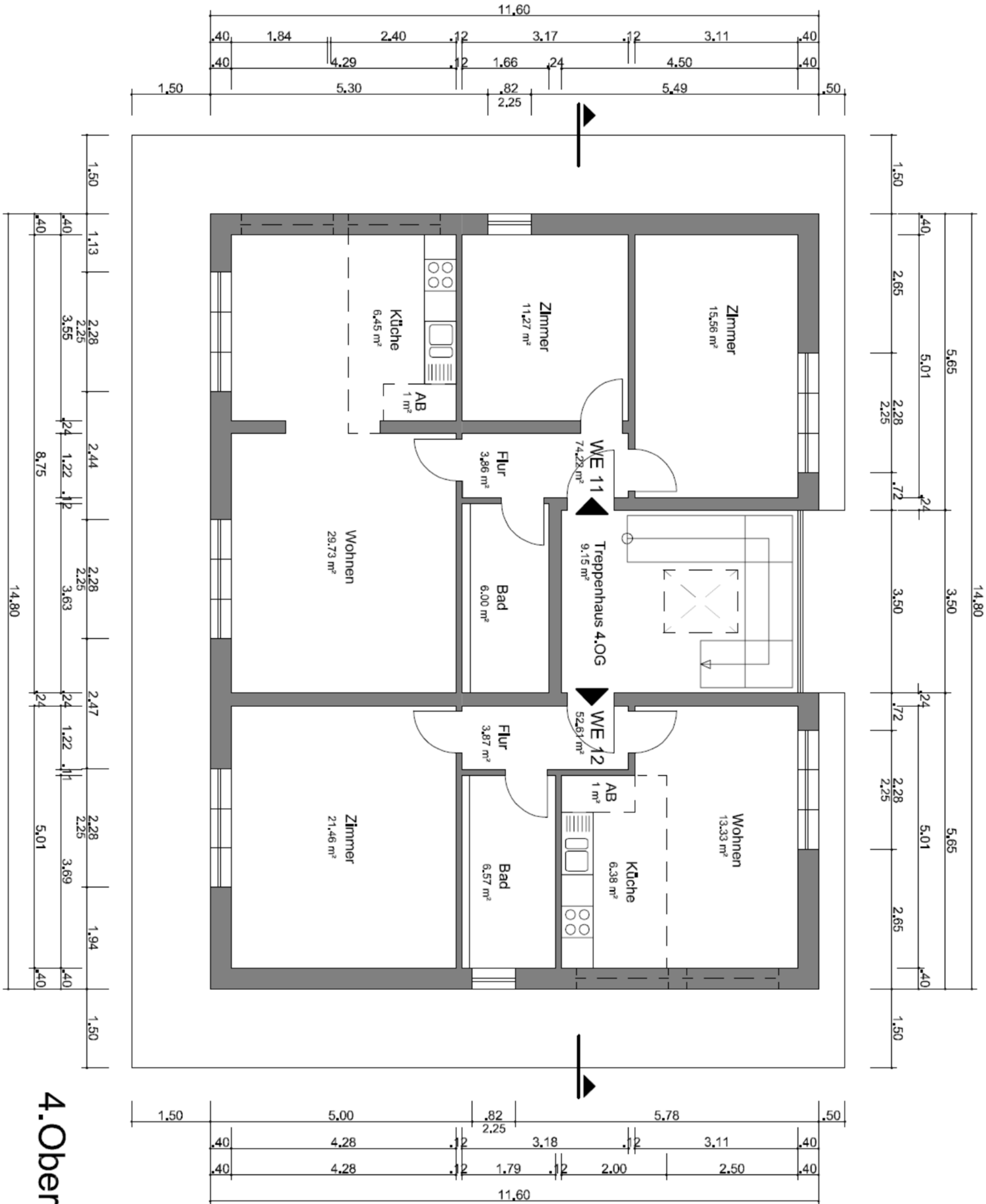

4.Obergeschoss

Appendix E

Construction information and eLCA data

Reinforced concrete wall (U=0.27 W/m²K) (SB)

Layer	**Thickness [m]**	**Material**	**λ [W/(mK)]**	**Exchange**	**GWP / m²**	**PERT / m²**	**PENRT / m²**	**PE total / m²**	**Funct. unit**	**Dataset**	**Comment**
Interior plaster	0.015	Lime plaster	1.00	1	6.12	7.47	33.07	40.55	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Reinforced concrete	0.2	Concrete	2.300	0	36.03	39.30	194.01	233.31	m³	Beton der Druckfestigkeits-klasse C 20/25	Thermal conductivity 1.15-1.65 W/(mK)
		Steel	-	0	22.35	123.89	287.80	411.69	kg	Bewehrungs-stahl	Assumption ratio: steel 50kg / concrete 1m³
Insulation	0.120	Mineral wool	0.035	1	17.36	32.66	210.11	242.77	m³	Mineralwolle (Fassaden-Dämmung)	Thermal conductivity not mentioned in the dataset
External plaster	0.010	Lime plaster	1.00	1	8.70	18.69	53.00	71.69	m³	Kalkputzmörtel	Thermal conductivity = 0.8 -0.9 W/(mK)
					90.57	**222.03**	**778.00**	**1000.03**			

Variants reinforced concrete wall

	Unit	**SB 1**	**SB 2**	**SB 3**	**SB 4**	**SB 5**	**SB 6**
U-value	W/m²K	0.31	0.27	0.23	0.21	0.19	0.17
GWP/m²	kgCO_2-eq/m²	90.57	90.57	96.36	96.36	102.15	102.15
PERT/m²	MJ/m²	222.03	222.03	232.91	232.91	243.80	243.80
PENRT/m²	MJ/m²	778.00	778.00	848.04	848.04	918.08	918.08
PE total/m²	MJ/m²	1,000.03	1,000.03	1,080.96	1,080.96	1,161.88	1,161.88

Brick wall (U=0.28 W/m²K) (ZI)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Interior plaster	0.015	Lime plaster	1	1	6.12	7.47	33.07	40.55	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
highly heat-insulating brick	0.365	vertically perforated bricks	0.11	0	46.92	96.11	484.61	580.72	m³	Mauerziegel	Thermal conductivity = 0.11 W/(mK), Density class = 0.65
External plaster	0.020	Light plaster	0.25	1	18.62	40.59	157.56	198.15	kg	Putzmörtel-Leichtputz	Thermal conductivity = 0.8 -0.9 W/(mK)
					71.67	**144.17**	**675.25**	**819.42**			

Variants brick wall

	Unit	ZI 1	ZI 2	ZI 3	ZI 4	ZI 5	ZI 6
U-value	W/m²K	0.302	0.279	0.242	0.201	0.175	0.156
GWP/m²	kgCO_2-eq/m²	71.67	71.67	79.38	79.38	87.74	87.75
PERT/m²	MJ/m²	144.17	144.17	159.97	159.97	177.09	177.09
PENRT/m²	MJ/m²	675.25	675.25	754.91	754.91	841.21	841.21
PE total/m²	MJ/m²	819.42	819.42	914.89	914.89	1018.30	1018.30

Sand lime brick wall (U=0.27 W/m²K) (KS)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Interior plaster	0.015	Lime plaster	1.00	1	6.1233	7.47	33.07	40.55	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Lime brick	0.175	Lime brick	1.900	0	55.92	75.81	402.57	478.38	m³	Kalksandstein Mix	Thermal conductivity = 1.9 W/(mK)
Insulation	0.120	Mineral wool	0.035	1	17.36	32.66	210.11	242.77	m³	Mineralwolle	Thermal conductivity not mentioned in the dataset
External plaster	0.010	Lime plaster	1.00	1	8.70	18.69	53.00	71.69	m³	Kalkputzmörtel	Thermal conductivity not mentioned in the dataset
					88.11	**134.64**	**698.76**	**833.40**			

Variants Sand lime brick wall

	Unit	KS 1	KS 2	KS 3	KS 4	KS 5	KS 6
U-value	W/m²K	0.304	0.269	0.233	0.206	0.189	0.167
GWP/m²	$kgCO_2$-eq/m²	88.11	88.11	93.90	93.90	99.69	99.69
PERT/m²	MJ/m²	134.64	134.64	145.52	145.52	156.41	156.41
PENRT/m²	MJ/m²	698.76	698.76	768.80	768.80	838.84	838.84
PE total/m²	MJ/m²	833.40	833.40	914.33	914.33	995.25	995.25

Aerated concrete wall (U=0.28 W/m²K) (PB)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Interior plaster	0.015	Lime plaster	1	1	6.12	7.47	33.07	40.55	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Aerated concrete	0.300	Aerated concrete	0.09	0	55.48	86.57	355.93	442.50	m³	Porenbeton P2 04 unbewehrt	Thermal conductivity = 0.09 W/(mK)
External plaster	0.020	Light plaster	0.25	1	0.014	0.031	0.12	0.15	m³	Putzmörtel-Leichtputz	Thermal conductivity = 0.8 -0.9 W/(mK)
					61.62	**94.07**	**778.26**	**483.20**			

Variants Aerated concrete wall

	Unit	PB 1	PB 2	PB 3	PB 4	PB 5
U-value	W/m²K	0.306	0.278	0.231	0.173	0.141
GWP/m²	kgCO_2-eq/m²	61.62	61.62	73.64	79.26	91.58
PERT/m²	MJ/m²	94.07	94.07	112.83	164.67	202.34
PENRT/m²	MJ/m²	389.13	778.26	1244.51	703.33	868.50
PE total/m²	MJ/m²	483.20	483.20	579.08	868.01	1070.85

Light concrete brick wall (U=0.28 W/m²K) (LB)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Interior plaster	0.015	Lime plaster	1.00	1	6.12	7.47	30.12	37.59	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Light concrete	0.365	Light concrete brick	0.110	0	24.44	13.87	131.70	145.58	m³	Mauersteine aus Leichtbeton aus natürlichen Zuschlägen - Hohlblock -	The bricks have a share of 60% empty space. This is filled with mineral wool.
		Mineral wool filled	-	0	15.84	29.80	23.41	53.21	m³	Mineralwolle (Fassaden-Dämmung)	Mineral wool from the dataset can be used for filling.
External plaster	0.02	Light plaster	0.25	1	18.62	40.59	157.56	198.15	kg	Putzmörtel-Leichtputz	Thermal conductivity = 0.8 -0.9 W/(mK)
					65.03	**91.74**	**342.79**	**434.54**			

Variants Light concrete brick wall

	Unit	LB 1	LB 2	LB 3	LB 4	LB 5	LB 6
U-value	W/m²K	0.306	0.279	0.255	0.220	0.183	0.145
GWP/m²	kgCO_2-eq/m²	57.86	65.03	69.04	57.86	65.03	84.78
PERT/m²	MJ/m²	83.96	91.74	67.05	83.96	91.74	221.29
PENRT/m²	MJ/m²	315.17	342.79	415.38	315.17	342.79	1197.96
PE total/m²	MJ/m²	399.14	434.54	482.43	399.14	434.54	1419.25

Solid wood wall (U=0.27 W/m²K) (HM)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Interior plaster	0.015	Lime plaster	1.00	1	6.12	7.47	30.12	37.59	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Building board	0.0125	Plasterboard	0.32	1	8.34	0.07	12.8	12.87	m²	Gipsfaserplatte	The environmental impact of the 12.5 mm plasterboard behaves linear to the dataset.
Insulation	0.050	Mineral wool	0.04	1	7.23	13.60	87.54	101.15	m³	Mineralwolle (Fassaden-Dämmung)	Thermal conductivity not mentioned in the dataset
Wood	0.125	Cross laminated timber	0.130	0	20.93	247.37	265.31	512.68	m³	3- und 5-Schicht Massivholzplatte (Durchschnitt DE)	The average dataset is appropriate for an approximation
Insulation	0.050	Mineral wool	0.040	1	7.23	13.60	87.54	101.15	m³	Mineralwolle (Fassaden-Dämmung)	Thermal conductivity not mentioned in the dataset
External plaster	0.010	Lime plaster	1.00	1	9.31	20.29	78.78	99.07	kg	Putzmörtel-Leichtputz	Thermal conductivity = 0.8 -0.9 W/(mK)
					59.18	**302.44**	**562.10**	**864.54**			

Variants Solid wood wall

	Unit	HM 1	HM 2	HM 3	HM 4	HM 5	HM 6
U-value	W/m²K	0.271	0.225	0.184	0.155	0.143	0.123
GWP/m²	kgCO_2-eq/m²	59.18	63.52	69.31	75.10	75.10	80.89
PERT/m²	MJ/m²	302.44	310.60	321.49	332.38	332.38	343.26
PENRT/m²	MJ/m²	562.10	614.63	684.63	754.71	754.71	824.74
PE total/m²	MJ/m²	864.54	925.24	1006.16	1087.09	1087.09	1168.01

Roof (U=0.20 W/m²K)

Layer	**Thickness [m]**	**Material**	**λ [W/(mK)]**	**Exchange**	**GWP / m²**	**PERT / m²**	**PENRT / m²**	**PE total / m²**	**Funct. unit**	**Dataset**	**Comment**
Interior plaster	0.015	Lime plaster	1.00	1	6.12	7.47	30.12	37.59	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Reinforced concrete	0.250	concrete	2.300	0	45.04	49.12	242.51	291.64	m³	Beton der Druckfestigkeitsklasse C 20/25	Thermal conductivity 1.15-1.65 W/(mK)
		Steel	-	0	27.94	154.87	359.75	514.62	kg	Bewehrungsstahl	Assumption ratio: steel 50kg / concrete 1m³
Roof membrane	0.010	Bitumen roof sealing	0.170	1	9.74	18.75	767.30	786.05	m²	Bitumenbahnen V 60 (Dicke 0,005 m)	Several layers give the thickness of the resulting sealing
Insulation	0.120	Expanded Polystyrene	0.035	1	32.32	5.33	436.70	442.0	m³	EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035	The EPS is pressure-resistant
Gravel	0.050	Rolled gravel	0.70	1	7.51	5.09	122.89	127.98	kg	Kies 2/32 getrocknet	
					128.68	**240.65**	**1959.29**	**2199.94**			

Cellar wall (U=0.35 W/m²K)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Interior plaster	0.015	Lime plaster	1.00	1	6.12	7.47	30.12	37.59	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
Reinforced concrete	0.250	Concrete	2.300	0	36.03	39.30	194.01	233.31	m³	Beton der Druckfestigkeitsklasse C 20/25	Thermal conductivity 1.15-1.65 W/(mK)
		Steel	-	0	22.35	123.89	287.80	411.69	kg	Bewehrungsstahl	Assumption ratio: steel 50kg / concrete 1m³
Insulation	0.100	Extruded Polystyrene	0.035	1	42.90	36.48	571.35	607.84	m³	XPS-Dämmstoff	This insulation is prepared for earth-touched application.
					107.41	**207.16**	**1083.28**	**1290.45**			

Cellar ground plate (U=0.32 W/m²K)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
screed	0.050	Cement screed	1.4	1	47.66	71.48	342.72	414.20	kg	Zementestrich	
Ground plate	0.250	Concrete	2.300	0	45.04	49.12	242.51	291.64	m³	Beton der Druckfestigkeitsklasse C 20/25	Thermal conductivity 1.15-1.65 W/(mK)
		Steel	-	0	27.94	154.87	359.75	514.62	kg	Bewehrungsstahl	Assumption ratio: steel 50kg / concrete 1m³
Insulation	0.100	Extruded Polystyrene	0.035	1	42.90	36.48	571.35	607.84	m³	XPS-Dämmstoff	This insulation is prepared for earth-touched application.
					163.55	**311.97**	**1516.33**	**1828.31**			

Cellar ceiling (U=0.36 W/m²K)

Layer	Thickness [m]	Material	λ [W/(mK)]	Exchange	GWP / m²	PERT / m²	PENRT / m²	PE total / m²	Funct. unit	Dataset	Comment
Screed	0.050	Cement screed	1.40	1	47.66	71.48	342.72	414.20	kg	Zementestrich	
Ceiling plate	0.25	Concrete	2.300	0	45.04	49.12	242.51	291.64	m³	Beton der Druckfestigkeitsklasse C 20/25	Thermal conductivity 1.15-1.65 W/(mK)
		Steel		0	27.94	154.87	359.75	514.62	kg	Bewehrungsstahl	Assumption ratio: steel 50kg / concrete 1m³
Insulation	0.080	Mineral wool	0.035	1	11.57	21.77	140.07	161.85	m³	Mineralwolle (Fassaden-Dämmung)	Thermal conductivity not mentioned in the dataset
Interior plaster	0.015	Lime plaster	1.00	1	6.12	7.47	30.12	37.59	m³	Kalk-Innenputz	Thermal conductivity not mentioned in the dataset
					138.35	**304.73**	**1115.18**	**1419.91**			

Appendix F

Building variants with characteristic

	variant 1	variant 2	variant 3	variant 4	variant 5	variant 6	variant 7	variant 8
	standard	personal living space	energy demand	low-tech	combi-nation	efficiency	renewable resource	lifetime
Wall type	LB	LB	LB	HM	HM	LB	LB	LB
Wall area south [m²]	179.05	107.4	179.05	179.05	107.4	179.05	179.05	179.05
Wall area east [m²]	167.65	100.6	167.65	167.65	100.6	167.65	167.65	167.65
Wall area north [m²]	200.07	120	200.07	200.07	120	200.07	200.07	200.07
Wall area west [m²]	157.63	94.6	157.63	157.63	94.6	157.63	157.63	157.63
Wall to Cellar [m²]	26.8	26.8	26.8	26.8	26.8	26.8	26.8	26.8
Wall to Soil [m²]	26.8	26.8	26.8	26.8	26.8	26.8	26.8	26.8
Area Roof [m²]	239.32	239.32	239.32	239.32	239.32	239.32	239.32	239.32
Area Floor Cellar [m²]	129.42	129.42	129.42	129.42	129.42	129.42	129.42	129.42
Area Floor Soil [m²]	110.91	110.91	110.91	110.91	110.91	110.91	110.91	110.91
Area Window south [m²]	66.34	39.8	66.34	66.34	39.8	66.34	66.34	66.34
Area Window east [m²]	22.21	13.3	22.21	22.21	13.3	22.21	22.21	22.21
Area Window north [m²]	64.39	38.6	64.39	64.39	38.6	64.39	64.39	64.39
Area Window west [m²]	32.23	19.3	32.23	32.23	19.3	32.23	32.23	32.23
Area Door south [m²]	2.09	2.09	2.09	2.09	2.09	2.09	2.09	2.09
Area Door east [m²]	0	0	0	0	0	0	0	0
Area Door north [m²]	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
Area Door west [m²]	0	0	0	0	0	0	0	0
Volume [m²]	3285.56	1929.9	3285.56	3285.56	1929.9	3285.56	3285.56	3285.56
Interior Temperature [°C]	19	19	18	19	18	19	19	19
Transmission heat loss [W/m²*K]	0.43	0.40	0.43	0.43	0.39	0.37	0.43	0.43
Persons in the Building []	19	19	19	19	19	19	19	19
Lifetime [years]	50	50	50	50	50	50	50	80

Appendix G

Building variants with results per year

per year and building		variant 1	variant 2	variant 3	variant 4	variant 5	variant 6	variant 7	variant 8
		standard	personal living space	energy demand	low-tech	combi-nation	efficiency	renewable resource	lifetime
GWP [kg CO_2-eq./year]	building envelope	2,367.99	2,001.65	2,367.99	2,286.28	1,952.63	2,646.93	2,367.99	1,479.99
	use	13,967.71	9,685.60	12,499.98	13,880.09	8,615.19	12,509.18	0	13,967.71
	total	16,335.70	11,687.25	14,867.98	16,166.37	10,567.82	15,156.11	2,367.99	15,447.70
PE [MJ/year]	PERT building envelope	941.28	797.56	941.28	1,765.43	1,292.00	1,448.05	941.28	588.30
	PENRT building envelope	6,005.05	5,468.37	6,005.05	6,863.24	5,983.24	9,351.73	6,005.05	3,753.15
	total building envelope	53,069.15	45,346.57	53,069.15	95,134.74	70,583.54	81,754.66	53,069.15	50,817.25
	use	60,145.79	39,732.06	53,501.44	59,746.77	35,089.32	53,542.79	0	60,145.79
	total	113,214.94	85,078.64	106,570.60	154,881.51	105,672.87	135,297.46	60,015.48	110,963.05
Costs [€]	building envelope	276,192.34	208,446.73	276,192.34	375,090.10	267,779.77	323,457.58	276,192.34	276,192.34

per year and person		variant 1	variant 2	variant 3	variant 4	variant 5	variant 6	variant 7	variant 8
		standard	personal living space	energy demand	low-tech	combi-nation	efficiency	renewable resource	lifetime
GWP [kg CO_2-eq./year]	building envelope	124.63	105.35	124.63	120.33	102.77	139.31	124.63	77.89
	use	735.14	509.76	657.89	730.53	453.43	658.37	0	735.14
	total	859.77	615.11	782.52	850.86	556.20	797.69	124.63	813.03
PE [MJ/year]	PERT building envelope	49.54	41.97	49.54	92.91	68.00	76.21	49.54	30.96
	PENRT building envelope	316.05	287.80	316.05	361.22	314.90	492.19	316.05	197.53
	total building envelope	2,793.11	2,386.66	2,793.11	5,007.09	3,714.92	4,302.87	2,793.11	2,674.59
	use	3,165.56	2,091.16	2,815.86	3,144.56	1,846.80	2,818.04	0	3,165.56
	total	5,958.68	4,477.82	5,608.97	8,151.65	5,561.73	7,120.91	3,158.70	5,840.16
Costs [€]	building envelope	14,536.43	10,970.88	14,536.43	19,741.58	14,093.67	17,024.08	14,536.43	14,536.43