Ingenieurfakultät Bau Geo Umwelt

Value-Based Decision Making Within the Complexity of Building Construction –

Development of a System Model of Building Construction for the Derivation of a Holistic Value-Based Decision Making Approach

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PROLOGUE

This thesis is the result of my work at the chair of Timber Structures and Building Construction at the TU Munich as a research and teaching associate. During this time, the challenge to learn and deliver in many different aspects of building construction, starting from teaching and communicating to researching and investigating, was a unique opportunity to grow personally.

I want to thank Professor Stefan Winter as head of the chair for all his advice and support and especially his trust to allow for space to develop and implement one's own ideas in teaching and research. Many thanks also to Professor Annette Hafner for all the in-depth discussions and joint research as well as her personal advice. Thanks also to Professor Matti Kuittinen for his thorough review and an inspirational discussion.

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Munich, June 2020

Samuel Ebert

ABSTRACT

Value-Based Decision Making Within the Complexity of Building Construction

Development of a System Model of Building Construction for the Derivation of a Holistic Value-Based Decision Making Approach

Problem | Increasing complexity in all areas of modern life, from global political and environmental challenges, to national and even personal questions of sustainability and economics, is impeding the possibility to meet multiple and conflicting goals at the same time. The field of building construction is no less confronted with these challenges of making effective and balanced decisions, especially since solutions increasingly require interdisciplinary approaches.

Goal | The goal of this thesis is to derive an universal, value-based approach for making sustainable decisions in the field of building construction that successfully manages the inherent complexity of the issue on an interdisciplinary level.

Methods | To derive this holistic, value-based decision-making approach, two main methods are used:

The first is to define goals and indicators in the context of the construction industry in a top-down approach by tracing the underlying values of technical action that inform these goal systems. This analysis serves as a groundwork for a new structuring of goals. Subsequently, four different goals are examined in detail and indicator systems developed to describe these goals: the goal of structural safety, the goal of minimising environmental impacts, the goal of resource efficiency and the goal of minimal life cycle costs.

General system theory serves as the second method that describes and combines systems of different disciplines. To develop a system model for specific goals and their indicators, a bottom-up approach is used that combines smaller indicator models into a bigger system model of building construction. The potential of this method to eventually arrive at a holistic system model of buildings is shown when even previously non-existent indicators for the goals of resource efficiency and recyclability can be integrated into the system model, together with a determination method for these indicators. Merging these two tools in the application of the system model for specific goals and their indicators illustrates the adaptability and suitability of these methods for the goal of the thesis.

Results | A parameter variation of 1472 versions of building components delivers a comprehensive basis for a multitude of indicator results. A sensitivity analysis illustrates the impact of different options in the study design. Based on the results of exterior wall components, the indicators are interpreted and two approaches are derived: an approach to effective decision-making for each indicator individually, and an approach to decision-making based on evaluation. The evaluation approach and the possibilities of comparing, weighting and narrowing down the results to one final decision are illustrated by three exemplary exterior wall components.

Conclusion | This thesis illustrates a value-based approach to making effective and well-balanced decisions within the interdisciplinary complexity of building construction. It is the aim of this thesis to trigger a shift in the discussion about sustainable decision making in building construction, away from individual solutions and towards recognizing and incorporating the underlying values that lead to these solutions. On the basis of the goal of resource efficiency, the thesis illustrates how, starting from a specific value, its objectives and corresponding indicators can be derived, in order to integrate them into the debate and ultimately implement them in practice.

Keywords: complexity, building construction, values, interdisciplinarity, sustainable building, decision making, system theory, life cycle assessment, recycling, material flows, life cycle costs, efficiency.

KURZFASSUNG

Werteorientierte Entscheidungsfindung innerhalb der Komplexität der Baukonstruktion

Entwicklung eines Systemmodells der Baukonstruktion zur Herleitung eines ganzheitlichen, wertebasierten Entscheidungsprozesses

Problem | In allen Bereichen modernen Lebens, von politischen und ökologischen Herausforderungen zu nationalen und selbst individuellen Fragen nach nachhaltigen und trotzdem ökonomischen Lösungen, wird der Versuch, eine Vielzahl an oft gegensätzlichen Zielen gleichzeitig zu erreichen, von stetig zunehmender Komplexität erschwert. Auch das Bauwesen ist nicht von der Herausforderung ausgenommen, effektive und ausgewogene Entscheidungen zu treffen, welche die Ansprüche der heutigen interdisziplinären Forschungslandschaft erfüllen.

Ziel | Das Ziel dieser Arbeit ist, einen wertebasierten, interdisziplinären und universal anwendbaren Ansatz zu entwickeln, um nachhaltige Entscheidungen im Bauwesen treffen zu können, die erfolgreich die bestehende Komplexität des Themas bewältigen.

Methoden | Um einen solchen ganzheitlichen, wertebasierten Ansatz zur Entscheidungsfindung zu entwickeln, werden zwei Methoden eingesetzt:

Zuerst werden Ziele und deren Indikatoren im Kontext des Bauwesens analysiert, um zu den ihnen zugrundeliegenden Werte des technischen Handelns vorzudringen, von denen aus eine neue Struktur der angestrebten Ziele entwickelt wird. Anschließend werden vier unterschiedliche Ziele untersucht und Indikatorensysteme entwickelt, welche diese Ziele abbilden: Das Ziel der Tragsicherheit, das Ziel der Minimierung der Umweltwirkungen, das Ziel der Ressourceneffizienz und das Ziel geringer Lebenszykluskosten.

Als zweite Methode dient die Allgemeine Systemtheorie der Beschreibung und Zusammenführung unterschiedlicher und interdisziplinärer Teilbereiche. Ein Systemmodell für spezifische Ziele und deren Indikatoren wird mittels eines Bottom-Up-Ansatzes entwickelt, welcher kleinere Indikatorenmodelle zu einem größeren Systemmodell der Baukonstruktion zusammenführt. Das Potenzial dieses Modells, langfristig tatsächlich ein ganzheitliches Systemmodell für Gebäude zu entwickeln, wird an der erfolgreichen Integration zuvor nichtexistierender Indikatoren für die Ziele der Ressourceneffizienz und Recyclingfähigkeit in das Systemmodell als auch der Entwicklung eines Nachweisverfahrens für diese Indikatoren sichtbar. Die Kombination beider Methoden während der Anwendung des Systemmodells für spezifische Ziele und ihrer Indikatoren bestätigt, wie gut sie sich für die Absicht dieser Arbeit eignen.

Ergebnisse | Eine Parametervariation von 1472 Bauteilversionen bildet eine umfangreiche Grundlage für eine Vielzahl an Indikatorenergebnissen. Eine Sensitivitätsanalyse verdeutlicht den Einfluss verschiedener Optionen im Studiendesign. Basierend auf den Ergebnissen für Außenwandbauteile werden die Indikatoren interpretiert und zwei mögliche Ansätze entwickelt: ein Ansatz für die effektive Entscheidungsfindung für einzelne Indikatoren, sowie ein Ansatz für eine evaluationsbasierte Entscheidungsfindung. Der Bewertungsansatz sowie die Möglichkeiten des Vergleichs, der Gewichtung und der Eingrenzung der Ergebnisse hin zu einer finalen Entscheidung werden am Beispiel dreier Außenwandkomponenten illustriert.

Fazit | Die Arbeit eröffnet die Möglichkeit eines wertebasierten Ansatzes für eine effektive und ausgewogene Entscheidungsfindung im interdisziplinären Kontext des Bauwesens. Die Arbeit zielt darauf ab, einen Wandel in der Debatte um nachhaltige Entscheidungsfindungen im Bauwesen anzustoßen, weg von Einzellösungen und hin zu einem Bewusstsein für und eine Einbindung der zugrundeliegenden Wertestrukturen. Die Arbeit zeigt u.a. anhand der Frage der Ressourceneffizienz auf, wie dessen Ziele und entsprechende Indikatoren von einem zugrundeliegenden Wertesystem abgeleitet werden können, bevor diese in die Debatte eingebracht und praktisch umgesetzt werden.

Stichwörter: Komplexität, Baukonstruktion, Werte, Interdisziplinarität, nachhaltiges Bauen, Entscheidungsfindung, Systemtheorie, Ökobilanzierung, Recycling, Stoffströme, Lebenszykluskosten, Effizienz.

Table of Contents

Glossary, Abbreviations and Symbols

Glossary and Abbreviations

λ-value	Thermal Conductivity
AC	Aerated Concrete
ADPe	Abiotic Resource Depletion Potential of elements
ADPf	Abiotic Resource Depletion Potential of fossil fuels
AP	Acidification Potential
b	Bituminous Sheeting
BauGB	German Federal Building Code (German: “Baugesetzbuch”)
BauPG	German Building Products Act (German: “Bauproduktegesetz”)
BBodSchG	German Federal Soil Protection Act (German: „Bundes-Bodenschutzgesetz“)
BBSR	Federal Institute for Research on Building, Urban Affairs and Spatial Development (German: “Bundesinstitut für Bau-, Stadt- und Raumforschung”)
BKI	German Information Centre for Building Costs (German: “Baukosteninformationszentrum”)
BM	Brick Masonry
BMI	German Federal Ministry of Interior, Building and Community (German: “Bundesministerium des Inneren, für Bau und Heimat”)
BMU	Federal Minister for the Environment, Nature Conservation, and Nuclear Safety (German: “Bundesminister für Umwelt, Naturschutz und nukleare Sicherheit“)
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (German: “Bundesminister für Umwelt, Naturschutz, Bau und Reaktorsicherheit“)
BNB	Rating System Sustainable Buildings (German:“ Bewertungssystem Nachhaltiges Bauen“)
ca	Carpet Flooring
CC	Construction Costs
CE	Cellulose
cf.	Confer (German: “vgl.”)
CG	Cellular Glass
CLT	Cross Laminated Timber
CO2	Carbon Dioxide
CPD	Construction Products Directive
CPR	Construction Products Regulation
CRU	Components for Reuse
CS	Calcium Silicate
DECT	Digital Enhanced Cordless Telecommunications
DF	Decision Factor
DGNB	German Sustainable Building Council (German: „Deutsche Gesellschaft für Nachhaltiges Bauen“)
DS	Deconstruction Site Waste

DW	Demolition Waste
e.g.	For example (Latin: „exempli gratia”; German: “z.B.”)
EEWärmeG	Renewable Energies Heat Act (German: „Erneuerbare-Energien-Wärmegesetz“)
ELC	End of Life Costs
EnEG	Energy Conservation Act (German: „Energieeinsparungsgesetz“)
EnEV	Renewable Energies Heat Act (German: „Energieeinsparverordnung“)
EP	Eutrophication Potential
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene (PS)
ER	Essential Requirement (see CPD or CPR)
EW	Exterior Wall
EWIS	Exterior Wall Insulation System (German: “WDVS”)
f	Facing Layer
ff	Facing Framework
FO	Foundation
FR	Flat Roof
FS	Floor Slab
g	Green Roof
GaBi	LCA Database (German: “Ganzheitliche Bilanzierung”)
GDA	The Joint German Occupational Safety and Health Strategy (German: “Gemeinsame Deutsche Arbeitsschutzstrategie”)
GEG	Building Energy Act (German: “Gebäudeenergiengesetz”)
GHG	Green House Gases (German: “THG – Treibhausgase”)
GI	Goal Indicator
GLT	Glue Laminated Timber
GWP	Global Warming Potential
HeizAnlV	Heating System Ordinance (German: „Heizungsanlagenverordnung“)
HLz	Vertical Corning Brick (German: “Hochlochziegel”)
HOAI	Fee regulations for architects and engineers (German: “Honorarordnung für Architekten und Ingenieure“)
HS	Hollow Space
HY	Hybrid Structure
i	Internal Insulation
i.e.	That is (Latin: „id est”)
IEEE	Institute of Electrical and Electronics Engineers
in	Installation Level
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile Range
IW	Interior Wall

KG	Cost Group (CG); (German: “Kostengruppe”)
KrWG	Waste Management Act (German: “Kreislaufwirtschaftsgesetz”)
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
li	Linoleum Flooring
LVL	Laminated Veneer Lumber
m	Metal Roof
MBO	German Model Building Regulations (German: “Musterbauordnung”)
MER	Materials for Energy Recovery
MERf	Material for Final Energy Recovery
MFR	Materials for Recycling
MMR	Material for Material Recovery
MMRf	Material for Final Material Recovery
MRU	Material or Components for Reuse
MSM	Material for Secondary Material Use
MW	Mineral Wool
MWD	Material Waste for Disposal
NRG	National Reduction Goals
OC	Operational Costs
ODP	Ozone Depletion Potential
OSB	Oriented Strand Board
p	Plaster Layer
pa	Parquet Flooring
pc	PVC Floor Coating
PE	Polyethylene
PEET	Primary Energy Energy Use Total
PEMT	Primary Energy Material Use Total
PENRE	Primary Energy Renewable Energy Use
PENRM	Primary Energy Renewable Material Use
PENRT	Primary Energy Renewable Total
PERE	Primary Energy Renewable Energy Use
PERM	Primary Energy Renewable Material Use
PERT	Primary Energy Renewable Total
pl	Plaster/Planking
POCP	Photochemical Ozone Creation Potential
POCP	Photochemical Oxidation Creation Potential
pp	Double Planking
PR	Pitched Roof
PU	Polyurethane
PVC	Polyvinyl Chloride

r	Roofing Tiles
RC	(Steel-) Reinforced Concrete
RDK	Bulk Density Class of Masonry (German: “Rohdichteklasse”)
RSL	Respected Service Life
RSP	Reference Study Period
rs-PEET	Renewable share of PEET
rs-PEMT	Renewable share of PEMT
R-value	Heat Transfer Resistance
s	Synthetic Sheeting
sc	Suspended Ceiling
SDO	Study Design Options
SFK	Strength Grade of Stones (German: “Steinfestigkeitsklasse”)
SI	Sub-Indicator
SPH	Service Phases (German: Leistungsphasen LPH)
ST	Solid Timber
t	Timber Cladding
TE	Timber Elements
TGA	Technical Building Equipment (German: “Technische Gebäudeausrüstung“)
tl	Tile Flooring
UF	Utilisation Factor
UNFCCC	United Nations Framework Convention on Climate Change
U-value	Heat Transfer Coefficient
VDI	Association of German Engineers (German: “Verein Deutscher Ingenieure”)
VOC	Volatile Organic Compounds
vs	Visible Surface
WF	Wood Fibre
WHO	World Health Organization
WSVO	Ordinance on Thermal Insulation (German: „Wärmeschutzverordnung“)
x	Perimeter Insulation
XPS	Extruded Polystyrene

Symbols

Γ	*Environment*
Ω	*Superset*
$\sum$	*System*
$\sum^{+}$	*Supersystem*
$\sum'$	*Subsystem*
$\sum S$	*Structural System*

$\sum F$	*Functional System*
$\sum H$	*Hierarchical System*
E	*The set of general elements e*
R	*The set of general interactions r*
α	*Set of attributes a*
φ	*Set of functions f*
κ	*Set of parts k*
π	*Set of relations p*

E_d	*Design value of effect of actions*
R_d	*Design value of the resistance*
γ_m	*Partial factor for material properties*
η	*Conversion factor*
G_k	*Characteristic value of a permanent action of all relevant components*
Q_k	*Characteristic value of a single variable action*
S_k	*Characteristic value of the variable action of snow*
a	*Load centre referred to the wall axis*
A_{eff}	*Effective contact area*
b	*Total width of the cross section*
d	*Total thickness of the cross section*
e	*Centre distance of the studs/posts*
W	*Effective area moment of inertia*
$f_{c,0,d}$	*Design value of compressive strength along the fibre*
$f_{c,90,d}$	*Design value of compressive strength perpendicular to the fibre*
$f_{cd,pl}$	*Design value of pressure strength*
$f_{m,d}$	*Design value of bending strength*
Φ	*Reduction coefficient*
$k_{c,90}$	*Coefficient to take into account the type of action, the risk of splitting and the degree of compression deformation*
$k_{c,y}$	*Buckling coefficient for buckling around the y-axis*

r	*(Pearson) Product-moment correlation*
R^2	*Coefficient of determination*
s	*Significance*

1 Introduction

1.1 Motivation and Background

„That it goes "so on" is the catastrophe." – W. Benjamin[1]

Motivation

Our present times are exciting times. While it is likely that every generation experiences their present times as special or extraordinary, our current era of global digitalisation provides a truly distinguishing factor, making it almost impossible not to be confronted with contemporary issues on a daily basis. These are, to only name a few of the most recent: the aftermath of the 2015 "refugee crisis" in Europe with all its consequences, mass protests demanding the mitigation of climate change (the "Fridays for Future" movement, starting in 2019), the global COVID-19 pandemic of 2020, or the "Black lives matter" movement that sparked worldwide protests calling for social and racial justice. These major challenges all have to be addressed at the same time. Our society is facing profound, worldwide challenges, which are increasing ever more rapidly (WEF, 2020). Being confronted with these challenges in an often overwhelming intensity, due to a constant availability of information, leads not only to a feeling of urgency, but also a call for responsibility down to the level of daily decisions: What to eat? What to buy? What to wear? Where and how to live? How to travel? – and many more. As humans, we face the responsibility to address the conflicts arising from multiple global and exponential developments. At its core, meeting this responsibility means giving a response to someone – whoever that turns out to be – for what we are or are not doing (Lenk, 1993, p.115).

This thesis of course neither can nor will confront all of these challenges. Yet it aims to respond to a single characteristic all of them have in common: There is a complexity inherent in these challenges, owing to the fact that each problem stretches over multiple disciplines and includes many different dynamics, to the effect of overwhelming the individual's capability of giving an adequate response. The problems in question cannot be tackled individually because they interrelate with each other. For example, the climate crisis is leading to extreme weather events, which will destroy the livelihoods of many people, leading them to leave their country and seek refuge in other countries, sparking social tensions… and so on.

Finding a solution for any of the very specific problems we are faced with while simultaneously keeping an integrating perspective in mind already is and will continue to be one of the main challenges of our times. No field of science, academia or politics currently offers a unified solution to this, including the field of construction. This thesis therefore aims at developing a

[1] German Source: „Dass es »so weiter« geht, ist die Katastrophe." – Walter Benjamin: "Charles Baudelaire. Ein Lyriker im Zeitalter des Hochkapitalismus"; Zentralpark, 1937, in: Gesammelte Schriften. 1. Band. Herausgegeben von Rolf Tiedemann und Hermann Schweppenhäuser. Suhrkamp, Frankfurt am Main: 1991, S. 683

basic, but workable approach of sustainable decision-making in the context of technical systems – like buildings – to solve the challenge of meeting multiple and conflicting goals in various disciplines of building construction.

Background – Global Development

The challenge of rapid change of our times is probably most spectacularly seen in the rapidly increasing number of our world population. Since reaching the milestone of one billion people living on this planet in the year 1804, this number has grown exponentially to about 7.791 billion inhabitants today (Worldometers, 2020), with ~87% of the total increase taking place in the last one hundred years alone (1920-2020). The collateral consequences of this development can be observed on almost every level and have been highlighted in many studies. As early as 1972, the Club of Rome manifested in its book, "Limits to Growth", that the ever-increasing consumption of the world population cannot be satisfied in the long run (Meadows et al., 1972). Since then, humanity witnessed the consequences of their actions having serious effects on their ecosystem, beginning with a change in the earth's ozone layer around 1980, continuing with large losses of forest areas due to acid rain, the consequences of over-fertilization of large agricultural areas, an increasing shortage of resources and water, decreasing biodiversity, the loss of countless species, right up to life-threatening effects of toxic components on the earth's ecosystem and the human organism – a necessarily uncomplete list. Many of these global risks and challenges were formally addressed by the sustainable development goals (SDG) proclaimed by the United Nations in the year 2015.

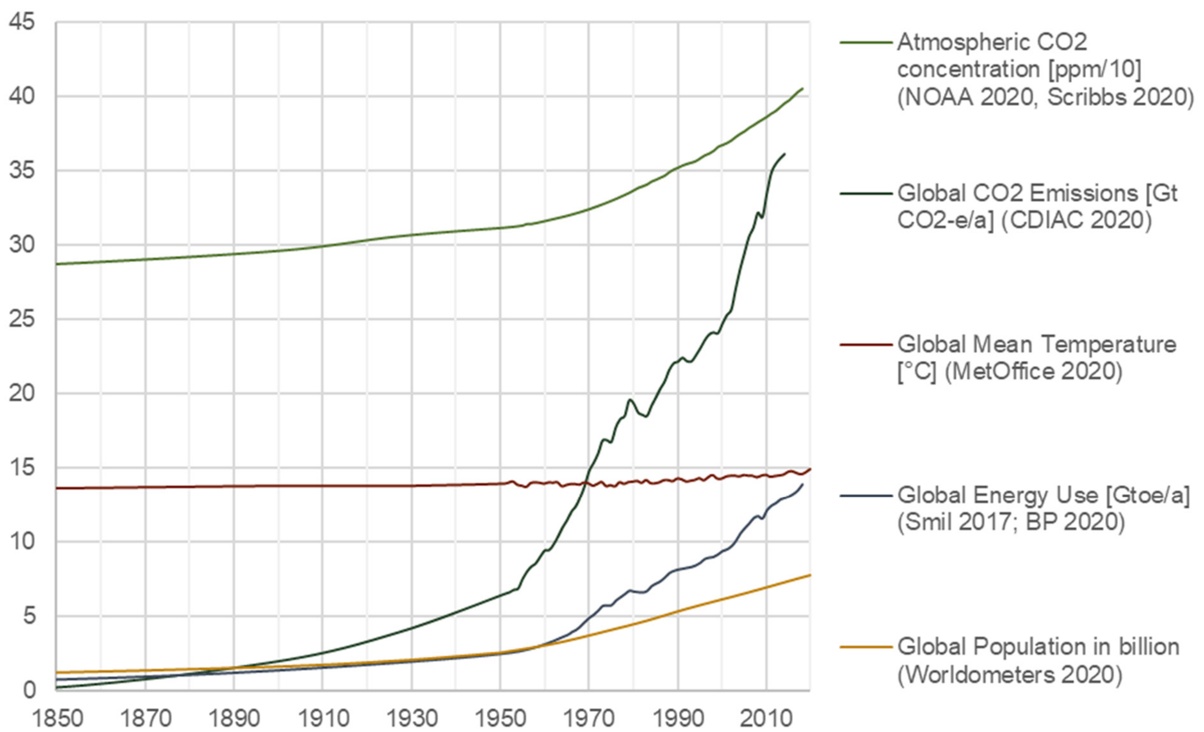

Figure 1-1: Global Development between 1850 and 2020 showing the increase of global population, primary energy use, mean temperature, CO_2 emissions and CO_2 concentration in the atmosphere (with data provided by (Worldometers, 2020; Smil, 2017; BP, 2020; Met Office, 2020; Boden et al., 2017) – illustrated by the author

Accompanying population growth is a similar growth in energy consumption. Until the year 1850, the yearly energy consumption of humanity was less than one billion ton of oil equivalent per year. This rose to a total of almost 14 billion tons of oil equivalent per year today (Smil, 2017; BP, 2020). This constant consumption of fossil energy sources, together with the deforestation of large amounts of biogenic carbon in global forest areas, is the main cause of the significant increase in humanity's emission of greenhouse gases (Boden et al., 2017). As early as 1896, the Swedish physicist and chemist Svante Arrhenius described the greenhouse gas principle as a natural principle which, due to carbon dioxide in the atmosphere, keeps the average global temperature warm enough to allow life to flourish (Arrhenius, 1896). A certain degree of climate change has since been found out to be normal. Yet, due to the increasing emissions of fossil based carbon dioxide and other greenhouse gases, the concentration of anthropogenic greenhouse gases in the atmosphere has intensified significantly and artificially (Meinshausen et al., 2017)[2]. As a result, the higher concentration of GHG in the atmosphere is leading to an amplification of the greenhouse effect. The consequences are seen in an additional increase in global temperature of about 1°C since 1850, with 2015, 2016, 2017 and 2018 all being the hottest years ever recorded (Met Office, 2020). Global warming of this kind is predicted to cause many additional changes in the planet's general climate.

The problem of climate change receives a particular focus in current science and politics as well as in the public eye. The manifold consequences of this problem are interlinked with the other problems facing humanity to a high degree and have been extensively investigated and the findings presented by an Intergovernmental Panel on Climate Change (IPCC) on a scientific basis (Pachauri and Mayer, 2015). The global risks outlined by the IPCC contain extreme weather events like extreme temperatures, extreme precipitation, cyclones, flooding and storms – an increase of which can be observed already (Munich RE, 2020) –, as well as sea level rise, ocean acidification, ocean carbon dioxide fertilisation and others (Ripple et al., 2017). With the severity of climate change as one of if not the most urgent global challenge in mind, this thesis necessarily puts specific emphasis on the issue.

The global community even today struggles to adequately address the challenge of climate change. After the foundation of the United Nations Environment Programme (UNEP) at the first environmental conference in Stockholm 1972, the UNEP, together with the World Meteorological Organization (WMO), jointly established the IPCC in 1988. The following "Earth Summit" in Rio de Janeiro in 1992 directly addressed the challenge of climate change for the first time in politics by ratifying the United Nations Framework Convention on Climate Change (UNFCCC), accompanied by an environmental action programme called "Agenda 21". Based on this framework, the world's nations agreed at the UN Climate Change Conference in Kyoto in 1997 on legally binding targets and deadlines to reduce global, anthropogenic CO2 emissions. The "Kyoto Protocol" went down as a milestone in world political history, as it was the first agreement of its kind addressing man-made climate change. However, the agreement only came into force in 2005, when it was signed by at least 55 countries responsible for more than 55% of global emissions. Further climate conferences followed in 2012 in Qatar, in which the

[2] This source illustrates the discussion of historic and anthropogenic changes in GHG concentration quite impressivly.

Kyoto Protocol was extended and prolonged (Kyoto II) and various other global challenges were discussed. However, some states, such as the USA or China, withdrew their signatures and commitment or, like Canada or Japan, withdrew during the commitment period. At the Climate Change Conference in Paris at the end of 2015 no new binding reduction targets could be set. Still, the global agreement of all participating countries to reduce GHG emissions and to mitigate global warming to less than 2°C – and only 1.5°C if possible –, represents an absolute novelty and a major diplomatic achievement (United Nations FCCC, 2015). Yet the agreement neither answer the question of how the participating countries intend to achieve these goals nor which concrete reduction targets are set in the respective NRGs ("National Reduction Goals") of each country.

The European Union wants to be seen as global leader in climate change mitigation, which is why it has made the statement to be climate neutral by 2050. As part of this role, the European Commission launched the “European Green Deal”, outlining specific goals for its member states. Having already reached a decrease of GHG emissions by -23% between 1990 and 2018, the new reduction targets are:

- A reduction of **50-55%** by **2030** compared to 1990 levels
- **Climate neutrality** by **2050**
- Achieving a **climate neutral, circular economy**

(European Commission, 2019)

The German government, as a response to the global objective of the Paris Agreement and the European targets, adopted the Federal Climate Change Act (KSG), aiming to meet the following reduction targets on a national level:

- A reduction of **55%** of GHG by **2030** compared with 1990 levels
- A (rather vague) confession to aim for carbon neutrality by 2050

(KSG, 2019)

These reduction targets align with the “German Sustainable Development Strategy”, adopted in 2002 and consistently extended with broader objectives (last update in 2018). The national goals are oriented after the global SDGs and currently include 67 indicators of 38 focus areas, listing some as:

- SDG13 / 13.1.a | Reduction of **GHG emissions**
  (with a current reduction of 28.5% in the year 2017)
  - by at least 40% by the year 2020 (compared to 1990)
  - by 55% by 2030 (compared to 1990)
  - by at least 70% by 2040 (compared to 1990)
  - by 80-95% by 2050 (compared to 1990)
- SDG7 / 7.1.b | Reduction of **primary energy consumption**
  - by at least 20% by the year 2020 (compared to 2008)
  - by at least 50% by the year 2050 (compared to 2008)

- SDG7 / 7.2.a | Increase in the **share of renewable energies** in total gross energy end-use consumption to 18 % by the year 2020, to 30% by 2030 and to 60 % by 2050
- SDG11 / 11.1.a | Limiting the **use of new land** for human settlements and transport to an average of 30 hectares (ha) per day by 2030

(Deutsche Bundesregierung, 2018)

These developments illustrate the slow and oftentimes cumbersome adaption and implementation of goals concerning global challenges. Setting global and national goals, while being a necessary declaration of intention, is little more than stage-setting for actual change. The decisive part will be seen in the measures taken as well as the monitoring, adapting and implementing of these measures. In the end, every sector and every part of society has to exercise their own responsibility and find individual, specific and workable solutions to these problems.

Background – Development in the Construction Industry

The construction industry is caught in the middle of all these developments. Given the construction industry's high share of global consumption of resources (40%), primary energy (30-40%) and GHG emissions (30%), the sector offers profound potential for sustainable change (UNEP, 2007).

With the EU Building Directive on the energy performance of buildings (EPBD 2002/91/EG, 2002) and its revision in 2010 (EPBD 2010/31/EU, 2010), Europe has already taken the first step to make the respective governments responsible for ensuring that from 2019, all new public buildings and from 2021, all new private buildings will be low-energy buildings (i.e. buildings with a very high overall energy efficiency, meaning nearly zero energy demand, which is largely covered by renewable energy sources). In addition, the directive concerning building products (CPD 89/106/EEC, 1988) sets a standard on multiple essential requirements (ER) for buildings and building components. It was replaced in 2011 by the regulation (CPR 305/2011, 2011), which extends the requirements by additional aspects of sustainability (cf. chapter 3.1.4).

On a national level, Germany’s primary energy heating consumption was already limited by the first thermal insulation regulation (WSVO) from 1977. In 2002, the German Energy Saving Ordinance (EnEV) consolidated the WSVO and the pre-existing heating system ordinance (HeizAnlV) and was revised over the following years (2004, 2007, 2009 and 2014) to lower the primary heating energy demand of buildings (~340 kWh/m²a in 1977). The above-mentioned EU guidelines were successively implemented in national law with the building product act (BauPG) in 1992 and the EnEV in 2002. The building energy act (GEG), which is currently in process and expected to pass in 2020, will consolidate the EnEV, the energy conservation act (EnEG), and the renewable energies heat act (EEWärmeG). The integration of the regulation and depiction of GHG emissions as well as the consideration of embodied energy is part of the discussion of the new building energy act (GEG, 2019).

In addition to the political focus on the primary energy consumption for heating, a variety of instruments of sustainable building certification like BREAM (1990), LEED (198) or the DGNB system (2007) were developed to cover many additional aspects. The first approach, with its focus on energy demand, has now matured into a holistic approach to the sustainability assessment of buildings. The various systems compare a large number of different indicators (DGNB, with more than 60 criteria) in terms of ecological, socio-cultural, economic and technical quality as well as process quality and site characteristics (see also chapter 3.1.4).

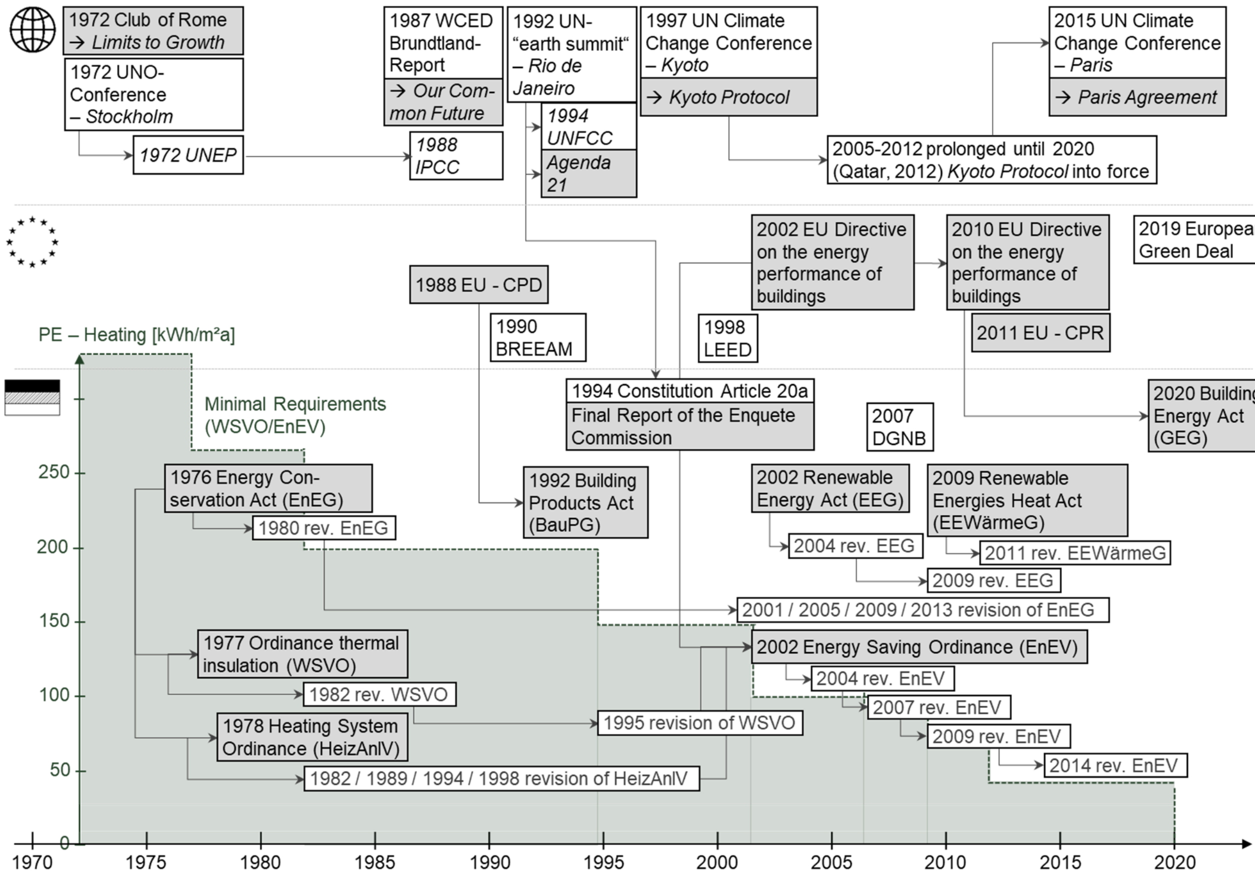

Figure 1-2: Historic development of sustainability standards and requirements on a global, european and national level – own work based on (Ebert et al., 2011, p.18)

As a consequence, the requirements for building construction have become ever higher: stricter regulations, higher customer expectations, increasingly complex construction mechanisms. The current building industry is confronted not only with a demand for shelter and structral safety, but is expected to satisfy more and more expectations simultaneously, many of which are techically feasible and justified (see chapter 3.1.5). This mirrors the increasing complexity in bulding construction. The design process seeks to resolve the complex set of requirements and boundary conditions in finding a concrete solution of construction (see chapter 3.1.3).

Therfore, the planning process reflects this increasing **complexity**:

> *"Planning, designing and constructing [...] are in principle extremely complex processes, because they are not linear but cyclical / concentric. They take place on shrinking circles or loops, on the circumference of which the boundary conditions that have to be fulfilled are queried anew with each cycle: function, stability, shape and integration into the environment, heat, sound and fire protection, durability, production, assembly, economy, etc. In this way they finally arrive at 'the point', i.e. at one of the many possible subjectively satisfying solutions, from which 'the solution' then emerges in further iteration steps, back and forth."* [3]
> – Jörg Schlaich (Moro, 2019b, foreword)

Arriving at "one of the many possible subjectively satisfying solutions", as Jörg Schlaich puts it, is a vivid description of the outcome of the planning process. Since there are many different such possible solutions, the question about which one is better suited is open for discussion. Observing this discussion and the different opinions contributed gave rise to the question if, rather than providing one specific solution, the underlying goal leading to this solution, or even the value behind a specific set of goals, should be the true focus of discussion. This thesis therefore pursues the question if a more value-based discussion is possible and how it can be achieved.

1.2 Goal, Method and Structure

Challenges and Goals

It is complexity in all its forms which makes keeping an overview of any problem and its agreed-upon goals difficult. Furthermore, the interdisciplinary nature of building construction and its changing requirements make it hard to balance which measures need to be adopted to achieve every requirement. What is needed therefore is a method that is able to display different disciplines with the same level of detail in order to achieve a holistic basis for decision-making.

Being confronted with complexity often leads to one of two responses: either ignoring and short-cutting it, or avoiding an adequate response altogether. In regard to actual decision-making, the difficulty lies in finding a balance between a holistic approach that does not neglect or ignore any aspects, and a specific management of individual aspects in order to achieve objectives within the given set of problems. The challenge therefore lies in developing an approach that effectively achieves individual goals and at the same time provide a tool that renders the interconnections and interdependencies between all relevant factors visible and con-

[3] German: „Das Planen, Entwerfen und Konstruieren […] sind im Prinzip äußerst komplexe Vorgänge, weil sie nicht linear sondern zyklisch / konzentrisch ablaufen. Sie verlaufen auf schrumpfenden Kreisen oder Schleifen, an deren Umfang bei jedem Umlauf erneut die Randbedingungen abgefragt werden, die es zu erfüllen gilt: Funktion, Standfestigkeit, Gestalt und Einfügung in das Umfeld, Wärme-, Schall- und Brandschutz, Dauerhaftigkeit, Fertigung, Montage, Wirtschaftlichkeit etc. So kommen sie schließlich auf „den Punkt", also zu einer der vielen möglichen subjektiv befriedigenden Lösungen, aus denen dann in weiteren Iterationsschritten, vor und zurück, „die Lösung" hervorgeht."

trollable so that balance can be reached. The tool has to be able to deliver concrete, measurable results and solutions while being generally valuable as well as applicable in individual situations.

The goal of this thesis is therefore to develop a systematic approach and procedure for value-based decision-making in building construction which overcomes the paralysing effect of systemic complexity. For this, instead of copying the existing definitions and sets of indicators, a **value-centred derivation of individual goals and indicators** is looked for. The complexity of different requirements and indicators in the construction industry, which exist in huge varieties, needs to be transparently structured and illustrated. This implies the development of a general approach to a **holistic decision-making basis,** using the method of **general system theory** for technical systems to develop an **integral system model for building construction**. This system model will then be analysed in order to find an approach for decision-making that is both **effective** and able to **balance multiple goals** simultaneously. Part of this analysis is an examination of the topic of evaluation in general, as well as personal weighting and the emphasis on individual goals.

Methodical Approach and Structural Overview

Unlike system theory, the topic of sustainability in the construction industry is a frequent topic in academic papers and theses. Regarding sustainability, however, the focus either lies on issues like benchmarks or simplification strategies in life cycle assessment (Braune, 2014; John, 2012), or on specific topics like building products or cities (Wittstock, 2012; Anders, 2015). The work of J. Göpfert and N. Krönert assisted in the comprehension of goals and requirements and how to effectively achieve them (Göpfert, 1998; Krönert, 2010). The work of A. Hermelink (Hermelink, 2007) was an inspiration in regard to the reference of G. Ropohl's conclusive derivation of a general system theory in the context of technical systems, which was used in this thesis as well. Furthermore, the application of this systematic approach in a very specific context of bridge engineering by H.G. Stempfle (Stempfle, 2007) confirmed the intention to work with Ropohl's method. One out of many catalysts for this thesis was the conclusion in A. Hafner's work regarding the pending challenge to raise awareness of the complexity of the processes in the construction industry (Hafner, 2012, p.144). Since there is no explicit pre-existing literature to this topic, all links to the works and literature used in this thesis can be found in their specific chapters.

The structure of the work is divided into the following three blocks:

A. Theory and introduction to the state of research
B. Development of an indicator and control model for buildings
C. Feasibility analysis using relevant indicators in example projects

Part A comprises the introduction (chapter 1), beginning with the author's personal motivation and sketching the global and national background and leading to the challenges in the context of construction industry in particular. Having illustrated the challenges and the resulting research questions, the relevant goals and methodological approach is portrayed. Additionally, the second chapter (chapter 2) explains two major issues considering the goal of deriving a value-based decision-making approach. The first section (chapter 2.1) starts at the beginning and tackles the questions behind the term “value-based” and their connection to the idea of sustainability, and derives a general approach for indicators, requirements, goals and underlying values. This clarifying structure will later be used with and translated into the context of building construction (cf. chapter 3.1). The second section (chapter 2.2) examines the method of system theory and especially the general system theory for technical system by G. Ropohl. System theory serves a unifying tool to combine different disciplines of building construction that speak the same methodological “language”.

Part B is focused on developing a system model for building construction (chapter 3) and the subsequent application and testing of this model (chapter 4). Chapter 3 takes a recourse to the two previously described tools of the structure of objectives and system theory addressed in chapter 2. Supplementing this toolbox is the categorization and structure of building construction (chapter 3.1), differentiating between the product and its parts and the processes and their functions, which serves as a kind of sorting system before being assembled into a system model. The next section (chapter 3.2) gives an overview of the general approach on how to develop a system model and then develops four exemplary indicator models step by step, before summarizing them into a draft for a system model for building construction, using the method of system theory. At this point it is important to mention that the scope of this thesis cannot and will not be a complete model – comprising all different goals –, but rather comprises an integral and exemplary approach that can be reiterated accordingly and indefinitely. The choice of exemplary indicators is focused on covering different underlying values as well as different characteristics and goals of current importance. The second part of Part B (chapter 4) then transfers this system model into an application in order to test its applicability and explanatory power, providing feedback to the development of the system model in return. This application is done using a parameter variation on the level of building components. For this, a thorough definition and selection of the scope of the parameter variation is necessary (chapter 4.1). Every goal and indicator requires a different focus on which parameters to consider and vary. In addition, the method used to determine the indicator results is portrayed in detail, further adding information to the development of the indicator models. After this in-depth compilation of 55 basic versions of building components with 1472 versions of building components in total, the results for every indicator are determined. Subsequently, the outcomes are illustrated and explained for every goal and its respective indicator(s) individually (chapter 4.2). The outcomes deliver valuable information regarding the definition and adaptation of the scope of the model for building construction.

The final **Part C** analyses the outcomes of the application of the system model (chapter 5). The analysis can be separated into two parts: interpretation of individual outcomes (chapter 5.1) and evaluation of multiple outcomes (chapter 5.2). The interpretation of individual indicator results tries to answer the question of how sensitive in regard to change each outcome is, how a goal can be achieved effectively and at which points correlation between indicators exists. This represents the effective side of the decision-making approach. The evaluation (chapter 5.2) tackles the challenge of balancing different goals by defining valuation standards for each indicator and introducing the idea of weighting according to the priority of values or goals. In total, a value-based decision-making process is described and discussed. Finally, the thesis ends with a summary, depiction and critical discussion of the essential conclusions as well as the prospect of a future need for action (chapter 6).

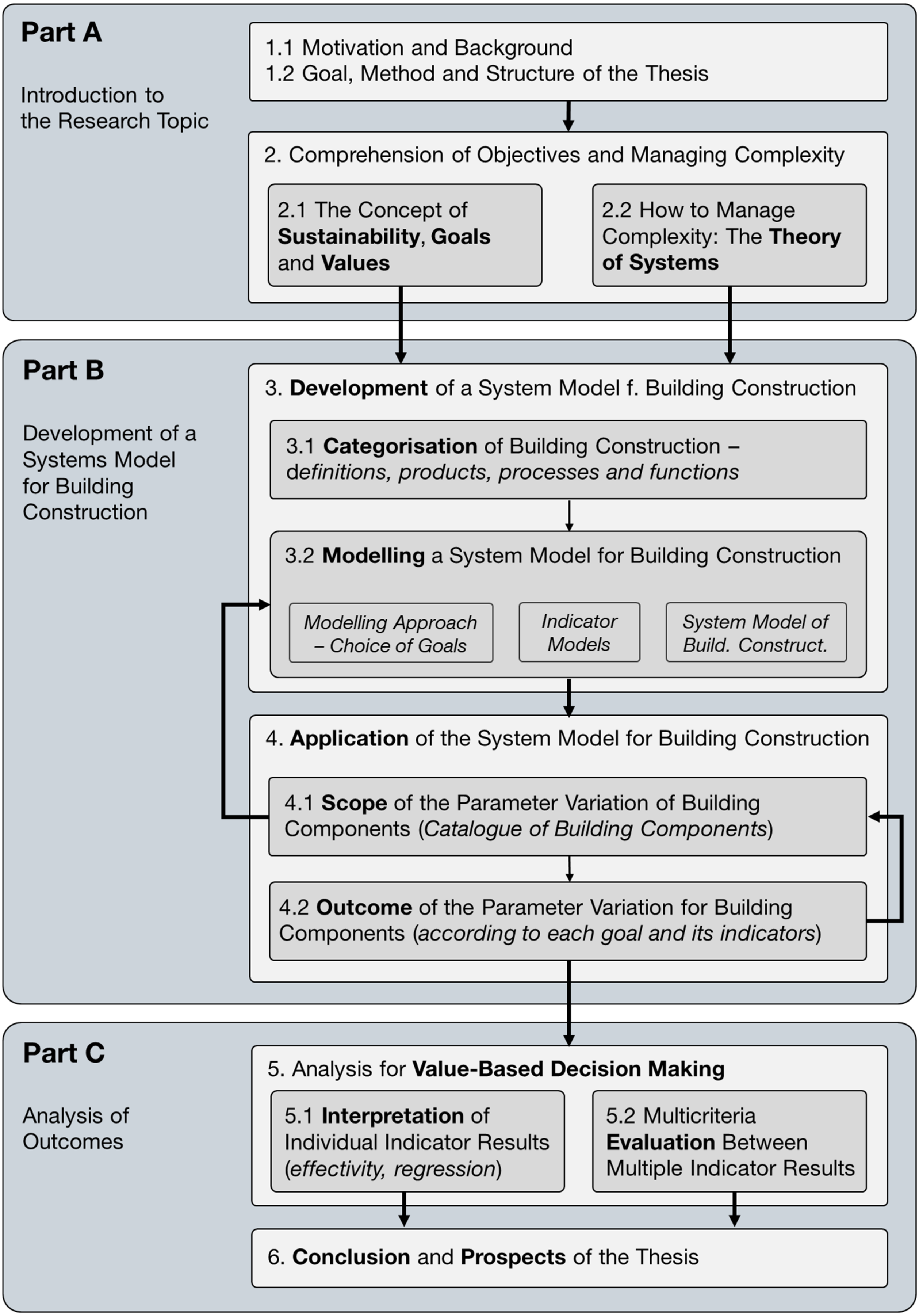

Figure 1-3: Structural overview of the thesis and individual chapters

2 Comprehension of Objectives and Managing Complexity

2.1 The Concept of Sustainability, Goals and Values

> *“Trivially, sustainability is a complex issue” – Ott/Döring [4]*

2.1.1 The Origins and Current State of ‘Sustainability’

Sustainability is an ambivalent term. On the one hand, it carries the basic vision for the solution of numerous problems that we as humanity are facing (see chapter 1). On the other hand – or perhaps precisely because of this –, the term is becoming an increasingly meaningless placeholder used for a variety of purposes. Any work that dares to address the issue of sustainable construction must therefore deal with the complexity and scope of the term 'sustainability'.

The Origin of the Term ‘Sustainability’

The definition of sustainable development currently used the most can be traced back to Gro Harlem Brundtland, who defined it in the Brundtland Report as follows:

> *"Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future.” (Brundtland, 1987, p.33)*

This definition describes an understanding of sustainability which central aspects are global **generational justice** and **equality** in relation to the dependency on resources due to elementary needs, as well as a long term perspective that comprises both present and future.

Humanity has only limited regenerable resources available to satisfy its needs, and it can use these resources only in a temporal horizon. The theory of justice therefore demands fair distribution of these resources between generations on a long-term basis as well as within a generation. Generations however, one shouldn’t forget, aren’t just abstract concepts. They always consist of individual persons (Ott and Döring, 2008, p.45). Being "sustainable" requires these resources to be used with appropriate foresight to avoid uncontrollable or sudden collapse. At the same, the basic needs of all people must be satisfied, as Ulrich Grober (Grober, 2010) describes in his summary of the conceptual development of sustainability.

Similarly, in their book 'The Limits to Growth', Meadows et al (1972) define a system as "sustainable" when it is in a "state of global equilibrium" (Meadows et al., 1972, p.180) and "without sudden and uncontrollable collapse" (Meadows et al., 1972, p.158). The early definition by the WWF and IUCN in the “World Conservation Strategy” describes the concept of sustainability as the use of a **regenerable natural system** in such a way that the essential properties of the system are preserved and its stock can grow back naturally. More precisely and positively, (Wiggering and Müller, 2004, p.90) define the concept of sustainability as "maintaining the

[4] Gemran Source: „Trivialerweise ist Nachhaltigkeit eine komplexe Angelegenheit“ Ott and Döring (2008, p.41).

functionality of the overall system". (Wiggering and Müller, 2004, p.90). In this way the term sustainability also describes the basic human need for **security**.

The Three Pillar Model of Sustainability

In the historical context of developing a definition of the term for a German strategy of national sustainability, the Enquete Commission of the German Bundestag formulated sustainability as follows:

> *“The main goal of the sustainability concern is to ensure and improve ecological, economic and social performance. These are interdependent and cannot be partially optimised without compromising development processes as a whole.”*
> *(Deutscher Bundestag 13. Wahlperiode, 1998, p.18)*[5]

The strength of this definition lies in its concretization around the three dimensions of **ecological**, **economic** and **social** aspects of social action. This however comes at the cost of weakening the systemic approach and the idea of balance. Nonetheless, and despite warnings of partial optimization, the **Three-Pillar Model** was developed based on this definition. It describes three essential systems in which a future-compatible approach should be taken into account:

- **Ecology**: Ecological sustainability describes a future-compatible handling and protection of the ecosystem of Planet Earth, its resources and smaller ecological sub-systems and cycles (climate, species, water, air, nutrients, etc.).
- **Economy**: Economic sustainability comprises the responsible use and protection of economic resources and the construction of an economic system that is sustainable in the future in order to maintain acquisition and social prosperity.
- **Social & Cultural**: Social sustainability refers to a balanced and sustainable social system that protects social and cultural values and the human organism.

There have been repeated calls for a hierarchy of the three dimensions, since economic systems are part of our society and the ecosystem earth is the basis of all life and action (Umweltbundesamt, 2002), which would effectively create a one-dimensional model. Internationally however, different views based on different value standards are debated as to which dimension should be given preference. Sometimes this leads to the social or economic dimension being preferred (Heinrichs and Michelsen, 2014). According to the Enquete Commission, although a comprehensive case could be made to put preference on the ecological pillar, this wouldn’t serve the original intention of following a practically realistic approach (Deutscher Bundestag 14. Wahlperiode, 2002).

The first problem with this model is that it considers these individual pillars separately while neglecting their interdependence, especially since they are able to dynamically interact with each other. For example, it might be more important to temporarily put more focus on one pillar

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[5] German: „Zentrales Ziel des Nachhaltigkeitsanliegens ist die Sicherstellung und Verbesserung ökologischer, ökonomischer und sozialer Leistungsfähigkeiten. Diese bedingen einander und können nicht teiloptimiert werden, ohne Entwicklungsprozesse als Ganzes in Frage zu stellen.“

in order to create an equilibrium between all three of them, which can only be done with an interconnected approach. The definition is also subject to criticism from professional circles, who demand its extension by a cultural dimension (Kreißig et al., 2009, p.9). Consequently, the social dimension is nowadays often described as a socio-cultural dimension (see above). The last objection is that this definition establishes an anthropocentric standpoint in which ecology serves as a means to an end. Sustainability is needed only to ensure the future of the human species. This is contrasted with a physiocentric standpoint, where nature has an intrinsic value (VDI 3780, 2000, p.19f) separate from its usefulness to human society.

The three-pillar model has systematic deficits, as it pretends the pillars to be of equal rank without explaining how this equality can be achieved. As said before, the need to protect each pillar individually poses the danger to neglect the dynamic interdependence of the whole. Because of this, the pillars have already occasionally been pitted against each other by using them as a platform for pre-existing demands of various industries and interest groups. They were successful insofar as they fleshed out three essential areas of sustainability, but the model lacks in terms of comprehensiveness and effectiveness (Ott and Döring, 2008, p.37ff).

Strong and Weak Sustainability

A similar approach to the Three-Pillar Model is taken by the concepts of **strong** and **weak sustainability**, which were significantly influenced by Herman Daly (Döring, 2004). The basic assumption of the idea of 'weak sustainability' is that capital can be substituted. Physical, human, natural, knowledge and social capital all contributes first and foremost to the total capital of humanity (Ott and Döring, 2008, p.103ff). Mankind is therefore put at the centre. In contrast, the idea of 'strong sustainability' attributes an intrinsic value to nature, making it impossible or at least limiting the chance to substitute natural capital, which has a limited capacity. This difference can also be described as pure growth of man-made *and* natural capital as opposed to taking into account the capacity limits of natural capital when looking at man-made growth (Radermacher and Beyers, 2011). In terms of strong sustainability, Yeong Heui Lee formulates the term sustainability as follows:

> *"Sustainable development is the maintenance of growth within the carrying capacity of the ecosystem to meet the material and immaterial needs of present and future generations in such a way that lasting harmony and symbiotic coexistence between human society and nature is achieved. Sustainable development aims at a lasting, prosperous, harmonious and thus sustainable development of environment, economy and society. An essential foundation is the respect and esteem of human beings for and towards nature and its laws." (Lee, 2001, p.4)*[6]

[6] German: "Nachhaltige Entwicklung ist die Aufrechterhaltung des Wachstums innerhalb der Tragfähigkeitsgrenzen des Ökosystems, um die materiellen und immateriellen Bedürfnisse gegenwärtiger und zukünftiger Generationen in einer Art und Weise zu befriedigen, dass eine dauerhafte Harmonie und ein symbiotisches Zusammenleben zwischen der menschlichen Gesellschaft und der Natur erreicht wird. Nachhaltige Entwicklung zielt auf eine dauerhafte, gedeihliche, harmonische und damit zukunftsfähige Entwicklung von Umwelt, Wirtschaft und Gesellschaft ab. Eine wesentliche Grundlage ist die Achtung und der Respekt der Menschen gegenüber und vor der Natur und ihren Gesetzmäßigkeiten."

How This Thesis Defines the Concept of Sustainability

From the author's point of view, a comprehensive definition of sustainability requires a combination and extension of the existing definitions due to their described disadvantages and deficits. Sustainability as a basic vision needs a **guiding** and **dynamic** character rather than a closed, rigid definition that has to ignore or exclude essential aspects. For further use of the term, therefore, the following basic definition is used.

> *The guiding principle of sustainability describes the appreciation of ecological, economic and socio-cultural systems as well as a responsible striving for the permanent preservation of the state of equilibrium of the complex and dynamic system of Earth.*

According to this definition, the guiding principle of sustainability is neither static nor trying to achieve a singular state. Instead, it describes a dynamic process (striving) whose goals and contents can change, but whose core values remain constant.

Those **values**, which are essential for permanently maintaining the described state of equilibrium, are:

- A lasting protection and security of human beings (as individuals as well as a society) and their existential needs, in addition to
- Equality for all people and generations
- Fair treatment (justice) of humanity, nature and the future
- A balance of all of the above

For the purpose of this definition (and in addition to the systemic approach of this thesis), “the protection of human beings and their needs” includes the total capital of natural and technical systems. Ecological, economic and social systems are considered elementary systems for the maintenance and development of human life.

A *guiding principle* is a vision for the future and the basis for action. To explain the scope of this guiding principle as well as the means to its realization, the following chapters will explain, define and link together these terms:

- To achieve a guiding principle, *goals* are to be set and pursued.
- *Means* serve to achieve a goal.
- *Values* are the criteria for selecting, evaluating and weighing goals.
- *Needs* are basic values necessary for the preservation and development of human life.
- *Quality* corresponds to an agreed set of goals.
- *Indicators* serve to measure and portray the quality of a goal.

2.1.2 Goals and Underlying Values

Having established a concept of sustainability as a value-based guiding principle, a few fundamental clarifications are in order to avoid misinterpretations. The first of those terms in need of a precise understanding are goals and a basic understanding of the values behind them. A sustainable change of conditions and actions in the sense of the definition of this work requires both a concretization of the desired condition and a roadmap on how to achieve it.

What is a goal? In the sense of a state description a **goal** stands as:

> *"A goal is a state of affairs imagined to be possible and whose realisation is pursued; a goal is set by means of a decision. " (VDI 3780, 2000, p.4)*

Facts can be states, objects, actions, processes or relationships. In his work, Nils Krönert reduces the concept of a goal to even more abstract terms: "A goal is a desirable state which can be achieved" (Krönert, 2010, p.20). These very abstract and general definitions are usually concretized by interrelating a large number of goals and giving them a hierarchy of overall and subordinate objectives. These clusters of goals are summarized as a **goal system**. The nature of their relationships can be either **concurrent**, i.e. competing or interfering with each other in the pursuit of the objectives, **indifferent**, i.e. without interfering with each other in the pursuit of the objectives, or **positively correlating**, i.e. mutually reinforcing.

In order to achieve a goal, different **means** are needed. A selection or preference of appropriate means is made on the basis of criteria that are primarily measured by the extent to which they contribute to achieving the goal (VDI 3780, 2000, p.4 ff).

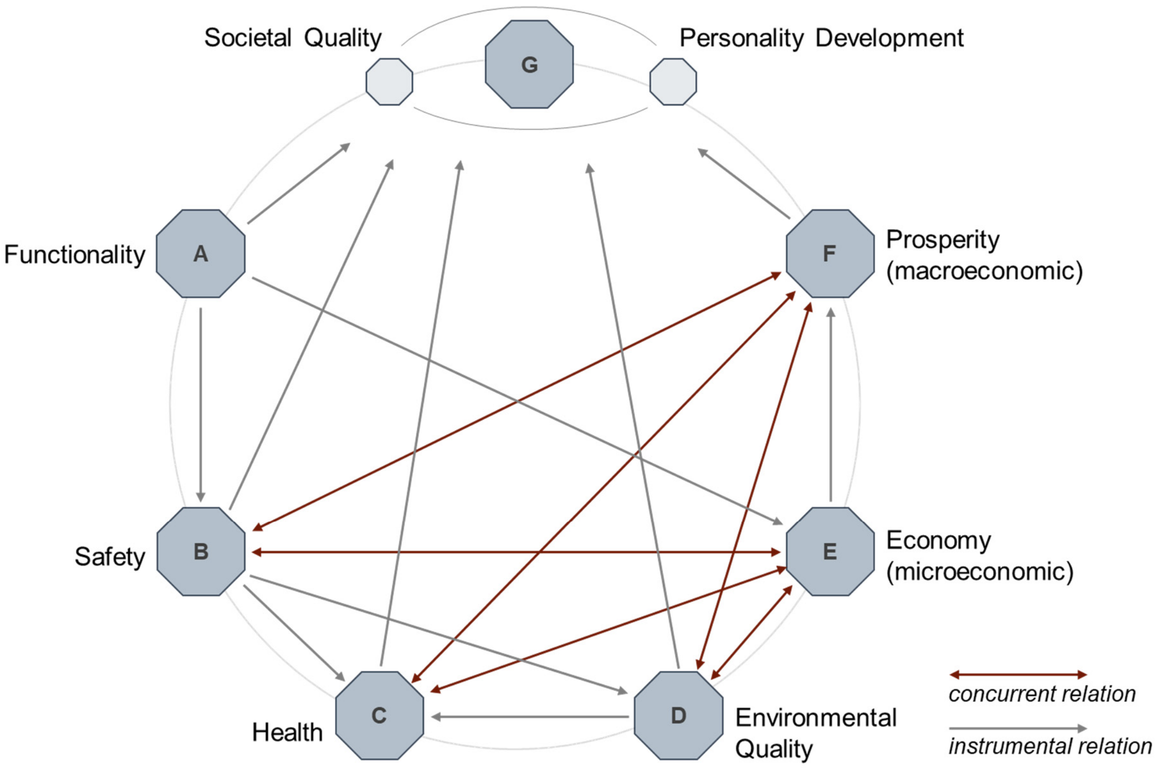

Figure 2-1: Relationships of the essential values of technical action – depiction by the author according to (VDI 3780, 2000, p.23)

The question of which goals are to be chosen in the first place is decisively influenced by the **Values** of the entity setting the goal.

> *„Values are expressed in evaluations; they are characteristic of something being recognised, prized, admired, or sought after." (VDI 3780, 2000, p.6)*

Values determine how certain goals are weighed against each other, which ones are considered more important. They are used to justify, evaluate or approve decisions, strategies and the choice of means. Like goals can be integrated into goal systems, values, too, are usually not isolated, but are in a competitive, indifferent or correlating relation to each other within a **value system**.

Values can be further differentiated into **needs**, **interests** and **norms**.

- **Needs** (as in human needs) differ from other values in that they are not arbitrary but necessary for the preservation and development of human life.
- **Interests**, on the other hand, refer to the values and needs of specific individuals or groups. As a natural result, conflicts of interest arise, which can also lead to conflicts.
- Lastly, social consensus, social obligations or standardizations with regard to certain values are considered as **norms** (VDI 3780, 2000, p.6).

Table 2-1: Comparison of human needs according to Maslow and Max-Neef, based on (Hermelink, 2007, p.195)

<table>
<tr><th></th><th>Basic Needs according to Maslow (1943, 1954 and 1970)[a]</th><th>Needs according to Max-Neef (1991)[b]</th></tr>
<tr><td>Existence</td><td>Basic physiological and existential needs</td><td>Subsistence</td></tr>
<tr><td>Safety</td><td>Need for security</td><td>Protection</td></tr>
<tr><td rowspan="2">Relationship</td><td rowspan="2">Need for affection and love</td><td>Affection</td></tr>
<tr><td rowspan="2">Participation</td></tr>
<tr><td rowspan="2">Effectiveness</td><td rowspan="2">Need for approval and appreciation</td></tr>
<tr><td>Understanding</td></tr>
<tr><td>Recreation</td><td rowspan="4">Need for individual fulfilment</td><td>Idleness</td></tr>
<tr><td rowspan="2">Development</td><td>Creation</td></tr>
<tr><td>Identity</td></tr>
<tr><td>Autonomy</td><td>Freedom</td></tr>
<tr><td>Completeness</td><td>Need for transcendence</td><td>-</td></tr>
<tr><td colspan="3">Notes and Sources:
a. (Koltko-Rivera, 2006, p.2)
b. (Max-Neef, 1991, p.32ff)</td></tr>
</table>

Max-Neef[7] describes human needs on four existential levels: human 'being', 'having', 'doing' and ‘interacting’ (Max-Neef, 1991, p.32 ff). Values can therefore be understood as a background system of objectives, decisions and human actions. According to Maslow and Max-Neef, basic human needs can be described as shown in Table 2-1.

2.1.3 Quality – How Goals Can Be Achieved

To achieve goals effectively in the sense of the defined guiding principle of sustainability requires a description of the state of these goals that must be critically examined repeatedly. From this description, corresponding requirements can be derived depending on the system or object under consideration. The term used to describe the state of an objectives is **Quality**.

Quality can be understood in different ways. In general the term quality (from the Latin qualitas; characteristic, state, condition) describes the sum of all properties of an object. From an evaluative point of view, quality is also colloquially associated with the concept of goodness (i.e. good or bad quality). Often, however, subjectively desirable characteristics are also implied, which cause an evaluative understanding of quality (Helmus and Offergeld, 2012, p.15 ff). According to DIN EN ISO 9000, the term quality is defined as the

> *“degree to which a set of inherent characteristics of an object fulfils requirements”*
> *(DIN EN ISO 9000, 2015, p.39).*

The inherent characteristics of an object, described as characteristic features, can be both quantitative and qualitative and can be assigned to one of the following classes: physical, sensory, behavioural, time-related, ergonomic or functional (DIN EN ISO 9000, 2015, p.52 ff).

However, this definition describes a rather static understanding of quality, since it primarily refers to products, services and processes. An integral approach is the Total Quality Management TQM method, which was defined in DIN ISO 8402 (1995) as a management method for organisations that puts quality at the centre. It is based on the participation of all its members and aims at long-term business success through customer satisfaction and benefits for the members of the organisation and for society.

This definition shifts the focus of attention away from a technically sophisticated product as a fulfilment of quality requirements to a complete implementation of established demands. This leads to the conclusion that product quality is a result of process quality (Weeber and Bosch, 2001).

Quality of sustainability meanwhile describes the condition of an object or system that corresponds to the model of sustainability and fulfils its requirements. Due to the dynamic component of the guiding principle, this condition can change and transform.

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[7] Manfred A. Max-Neef - Chilean economist and development economist of German origin, born 1932 in Valparaíso, member of the Club of Rome, the European Academy of Sciences and Arts, the New York Academy of Sciences and Humanities and the World Future Council, among others.

The **requirements** which need to be fulfilled in order to achieve the desired quality differ from the **goals** said quality is trying to measure in the limitations of their possibilities. While goals can be idealized and can refer to any conceivable situation, requirements describe the desired situation that is possible within the boundary conditions and prerequisites of the systems under consideration. In this context, requirements describe and reflect the system properties or the system behaviour (Mavin et al., 2017, p.1). Accordingly, requirements represent demands or expectations which are "specified, usually presupposed or obligatory" (DIN EN ISO 9000, 2015, p.39). The Institute of Electrical and Electronics Engineers (IEEE) defines requirements in the field of information technology as follows:

> *“(1) A condition or capability needed by a user to solve a problem or achieve an objective.*
> *(2) A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed documents.*
> *(3) A documented representation of a condition or capability as in (1) or (2).”*
> *(American National Standard, 1990, p.65)*

According to the definition of point (1), requirements can also be seen as a **means** to solve problems or achieve goals and can therefore be derived from goals. If different requirements are derived from the objectives and depending on the system, different ways to achieve the objectives or approaches to solutions are created (Krönert, 2010, p.21).

Furthermore, goals can be competing with each other, whereas requirements cannot be in conflict with each other because of the system properties and the system behaviour. For this reason, a careful differentiation between goals and requirements as well as a basic understanding of the system is necessary to create optimal requirements. In this work, requirements are understood according to Nils Krönert or to IEEE point (2):

> *“A requirement is the state or capability that a system or system component must have in order to fulfil a contract, a standard, a performance specification or other formal documents (goals).”* [8] *(Krönert, 2010, p.22)*

2.1.4 ‘Indicators’ – Measuring Quality and Reflecting Goals

In order to describe different goals and requirements and to measure quality, **indicators** are needed in order to be able to map the change of the (system) state. An indicator (Latin ‘indicandum’ meaning ‘marker’) is generally understood to be a "circumstance or characteristic that serves as a [conclusive] sign or indication of something else.” (Duden, 1992). As quantitative and qualitative parameters, indicators provide information about the current state of a system

[8] German Source: „Eine Anforderung ist Beschaffenheit oder Fähigkeit eines Systems oder einer Systemkomponente, die erfüllt werden muss, damit ein Vertrag, eine Norm, eine Beschreibung oder andere formelle Dokumente (Ziele) erfüllt werden können.“

and enable a comparison with the target state in order to adjust the system and to enact appropriate measures in the event of deviations. That way indicators describe the extent to which goals have been achieved (Wiggering and Müller, 2004, p.32). As a systematic reduction of complexity, indicators specify and convey overarching goals and underlying guiding principles (Birkmann, 1999, p.121).

Indicators **describe different issues** and can be classified accordingly. They can describe both individually measured values and characteristics (usually at the micro level) as well as an aggregation of multiple aspects (at a macro level).

Over the course of the development of indicators, various approaches to the description of indicators have emerged. A differentiation with regard to an extended cause-and-effect relationship described by an indicator is offered by the Pressure-State-Response (PSR) approach (e.g. by the OECD), which distinguishes possible driving and reaction factors as well as measure indicators (Bückmann, 2015, p.18). This approach can be extended by two further dimensions (Drivers and Impact). The resulting DPSIR model (Drivers-Pressure-State-Impact-Response) is sorted into the following structure (Müller and Burkhard, 2012, p.2 ff; EEA - European Environment Agency, 2014, p.19):

- **Drivers** | Driver indicators describe the correlation behind the effects that cause a change (direct/indirect; natural/anthropogenic).
- **Pressures** | Pressure indicators describe a concrete influence on a system as a result of one or more causes (drivers).
- **State** | State indicators describe the state of a system as a result of one or more influencing pressures.
- **Impact** | Impact indicators describe the effects on and consequences for a system by changing the state of the system.
- **Response** | Response indicators provide information about state, inputs and effects (natural/anthropogenic; legislative/planned/) and describe a reaction. Often reactions also represent new causes.

Depending on context and circumstances, different classifications of indicators are possible. In his dissertation, Bastian Wittstock (2012) defines *independent* (not relevant), *descriptive* (without evaluation), *singular-prescriptive* (describing one requirement), *multiple-prescriptive* (describing several requirements), and *performance indicators* (describing quality levels) (Wittstock, 2012, p.70 ff). Peter Mösle (2009) classifies three different types of indicators according to their different characteristics: *computable or physically measurable indicators*, *descriptive or multiple indicators* and *process-oriented indicators (Mösle, 2009)*. These two definitions already clarify essential characteristics such as goal orientation, measurability, meaningfulness or a time reference.

The SMART method (Specific, Measurable, Appealing, Reasonable, and Time Bound), first developed by Peter Drucker, is a very general description of the requirements for objectives and indicators. However, the requirements for developing suitable indicators of sustainability can be supplemented and specified by further characteristics (Bardt, 2011, p.14; Birkmann, 1999, p.125; Andler, 2015, p.245 ff; Wiggering and Müller, 2004, p.15/p.52/p.130 ff/p.215 ff; OECD, 1993, p.7):

Requirements for *indicators*:

- **Goal Orientation** | Indicators should adequately reflect goals and guiding principles.
- **Operationalisation** | Indicators should be relevant for action and concretely implementable.
- **Holistic Approach** | Indicators should be able to, in a manner appropriate to the problem, fully depict interdisciplinary interactions and an integral system view.
- **Validity** | Indicators should, if possible, make a precise, comprehensible and unambiguous statement.
- **Time & Location Reference** | Indicators should describe a temporal development and cover a spatial coverage.
- **Measurability** | Indicators should be describable in a qualitatively concrete way or be quantitative, calculable or physically measurable.

Requirements for *indicator sets* and background data:

- **Data Quality** | Indicators should be developed on a scientific basis with sufficient quality and sensitivity to changes.
- **Data Availability** | Necessary data should be available in sufficient quality and should be collectable with reasonable effort.
- **Consensus** | The selection of indicators should be undisputed in terms of argumentation, recognised and developed in a participatory manner.
- **Clarity** | The indicator set should be sufficiently simple and clear.
- **Regularity** | Data and indicators should be updated regularly.

In the previous section, indicators were differentiated according to 'what' parameter or quantity they describe (cause, effect, condition, impact, reaction). In the following, the indicators are differentiated according to **'how'** goals – and indicators and their characteristics accordingly – can be described. In concrete terms, the above-mentioned requirements for indicators result in the following essential characteristics:

Table 2-2: Essential characteristics of indicators

	Characteristics
Goal Orientation[1]	*How is the goal described or represented?* ➢ Descriptive (description of the goal's current state) ➢ Prescriptive/Normative (determination of a target state)
Operationalisation[2]	*How is measurability or implementation achieved?* ➢ Qualitative (descriptive representation) ➢ Quantitative (measurable representation)
Holistic Approach[3]	*How many aspects and correlations are described?* ➢ Singular (one single aspect) ➢ Multiple/Aggregated (several aspects)

Validity	*What kind of statement do the indicators give?* ➢ Concrete (direct and precise reference) ➢ Abstract (indirect and imprecise reference)
Reference of Time and Location	*What is the goal's correlation between time and location?* ➢ Dynamic (the goal varies over time/location) ➢ Constant (the goal is constant over time/location)
Measurability[4]	*How can the goal be measured by the indicator?* ➢ Nominal (representing the ‚identity', respective category) ➢ Ordinal (representing direction, rank, and order) ➢ Interval (differentiating of the ranking order)

Notes and Sources:
1. Based on (Statistisches Bundesamt, 1999)
2. Based on (Andler, 2015, p.244)
3. Based on (Statistisches Bundesamt, 1999)
4. Based on (Zangemeister, 1973, p.149 ff; Kosfeld et al., 2016, p.6 ff)

The behaviour of many indicators can be described by a large number of possible combinations of these different characteristics, whereby certain characteristics frequently occur in combination.

Excursion 1: Measurability

Measurability is relevant for illustrating and describing the differences between indicator results. The possibility to scale indicator values differently allows making comparative statements. There are distinctions between (Zangemeister, 1973, p.6 ff):

- **Nominal** scale (qualitative representation)
- **Ordinal** scale (comparative/intensity representation)
- **Interval** scale (quantitative representation)
- **Ratio** scale (quantitative representation with a fixing point)

An example: The indicator "colour" is used to describe the actual state of an object. Accordingly, there are different colours, whose equality and inequality can be described qualitatively using a **nominal** scale, e.g. in the form of an allocation matrix.

Figure 2-2: Nominal scaling option for the example indicator 'colour'

This nominal scale can be transformed into an **ordinal** scale by means of a ranking and sequence, e.g. the rainbow colour spectrum. In this way, statements can be made as to which colour is at the beginning or end of the spectrum (order).

Figure 2-3: Ordinal scaling option for the example indicator 'colour'

By using the unit wavelength to describe the colour, a transformation into an **interval** scale is carried out, which, in addition to the order of priority, makes it possible to make a statement about the intervals between the individual colours, since the interval of a wavelength unit (nanometre) is always the same.

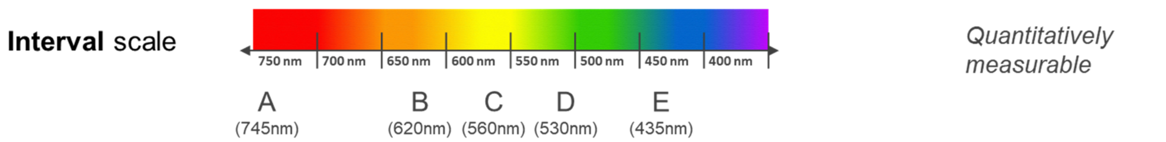

Figure 2-4: Interval scaling option for the example indicator 'colour'

With an additional origin (0 nanometre) the interval scale gets a reference point and becomes a **ratio** scale.

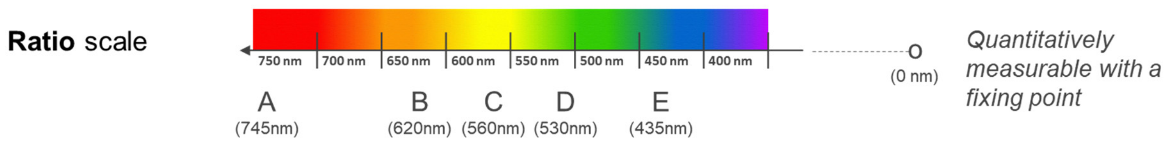

Figure 2-5: Ratio scaling option for the example indicator 'colour'

Excursion 2: Operationalisation

One last item of table 2-2 needs to be addressed. **Operationalisation** describes two categories of how measurability of indicators can be achieved. Generally, **nominal** scales serve the measurability of qualitative indicators, which can only describe and categorize facts in a very basic way. **Ordinal** scales are able to order qualitative as well as quantitative indicators into categories, which in turn can be evaluated. **Interval** scales are often used to describe an order or direction (towards a goal or an optimum) of quantitative indicators in a more differentiated way. Combining these characteristics, the following **categorisation** of indicators can be established, taking into account the characteristics of the objective, their informative value and the possibility of operationalisation:

- Type 1 | Qualitative-Descriptive Indicators (describing various abstract categories with non-judgmental allocation, e.g. beauty or taste)
- Type 2 | Qualitative-Normative Indicators (describing the direction of concrete category options, e.g. grading tables, good-bad, agreement-rejection)
- Type 3 | Quantitative-Descriptive Indicators (describing a distinctly measurable abstract target value, e.g. "as little as possible" costs/emissions)
- Type 4 | Quantitative-Normative Indicators (describing a distinctly measurable concrete target value, e.g. limit values or comfort spectrums)

The additional characteristics of holistic and place/time reference complement the description of the indicators and can be applied equally to all four categories. All in all, the characteristic types can be linked to the DPSIR classification (Drivers-Pressure-State-Impact-Response, see above), resulting in a multitude of possible combinations.

2.1.5 'Evaluation' – The Explanatory Power of Indicators

Indicators visualize the extent to which an objective is achieved. Evaluating these indicators serves the decision-making process, which is situated between the poles of objective observation and subjective emphasis.

Indicator evaluation is based on a scale with maximum and minimum evaluation variables that describes the ratio of indicator result to evaluation result. For example, an interval scale from 0 to 100 for the evaluation scale indicates an easily comprehensible classification in percent as a degree of fulfilment, whereas a grade scale from 1 to 5 or 6 indicates the relationship to school evaluation systems (in Germany). Both the indicator values and the evaluation scale can be described using different scales. The nature of an evaluation (ranking, preference) cannot be described using a nominal scale, which is why this form of scaling is neglected in the following examination of evaluation scales.

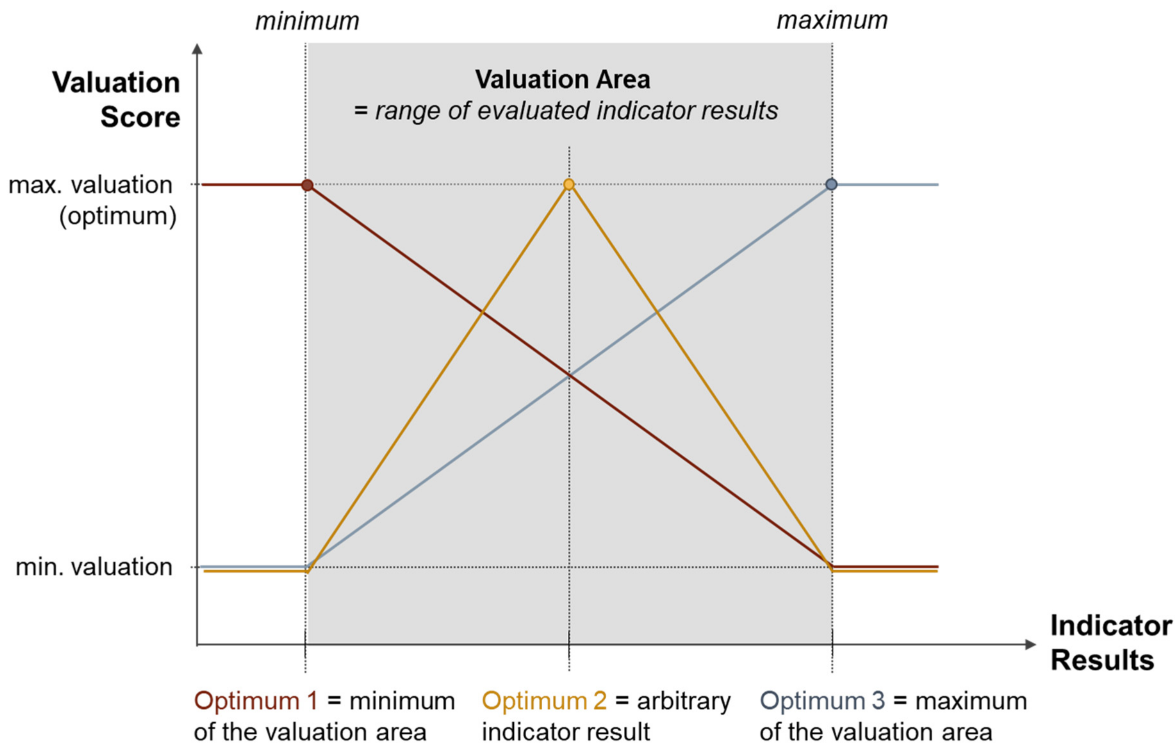

Figure 2-6: Relation (linear) between evaluation score and indicator results with different definitions of an optimum based on the illustration by (Wittstock, 2012, p.41)

Depending on the expected indicator results, a valuation area is defined as a limitation of the indicator results by a lower and an upper limit (maximum and minimum). The limits of the valuation area can be chosen according to the ideal results (possibly outside the indicator results) or based on the real results (worst and best indicator results). Which range of possible indicator values the valuation area covers and represents is up to the discretion of the evaluator.

For the purpose of goal orientation, an indicator value must be defined as an optimum, i.e. as the best value of the evaluation scale (e.g. goal 100%, zero or a specific indicator value). Often the upper or lower limit value of the valuation area also represents the optimum, but this can vary. Accordingly, values outside the valuation area receive no valuation at all or the corresponding valuation of the limit values.

For a complete description of evaluation scores, each indicator result x of the valuation area must be represented on the valuation scale y. The relationship between the indicator result and the evaluation score can be described using a merit function y(x) depending on the indicator results x. The course of these functions is usually linear, but can be defined differently. Depending on the goal definition and evaluation approach, the evaluation function can be continuously differentiated or with individual discontinuities (step function) (cf. Figure 2-7 and Figure 2-8) and can also be different in different areas (sections) (cf. Figure 2-9).

The following definitions apply:

- Y_{max} … **maximum valuation** (optimum)
- Y_{min} … **minimum valuation**
- X_{max} … **maximum** of **indicator results** in the valuation area
- X_{min} … **minimum** of **indicator results** in the valuation area

A common example for evaluation is the grading scale in school. By this example a variety of the possibilities for evaluation can be explained vividly.

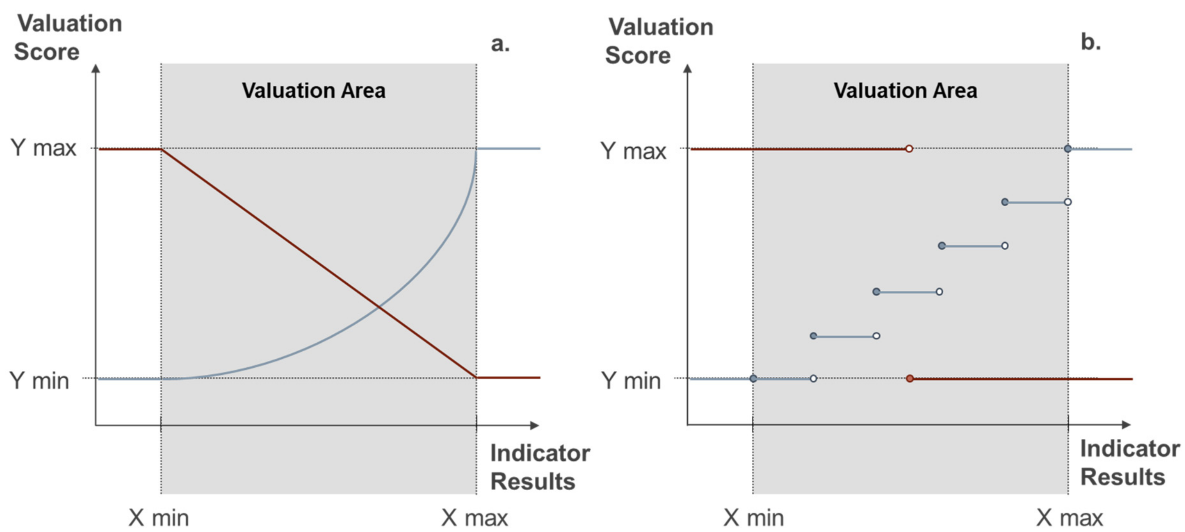

Figure 2-7: Examples of continuously differentiated merit functions (a.) and merit function with discontinuities (b.).

The traditional valuation standard for an exam with metric point system for the correct answers (ratio scale with e.g. 0-60 points) is reflected by a valuation standard with a continuously differentiated linear merit function (a.) with the valuation score expressed in percentage (ratio scale with 0-100%). A translation of the points as indicator results into a valuation score with an ordinal scale like school grades (grade 1-5, A-F, or other grading systems) leads to a valuation standard described by a merit function with discontinuities (b.), e.g. all points between ≥54 are represented by the grade A, points between ≥48 and <54 are represented by the grade B, etc.

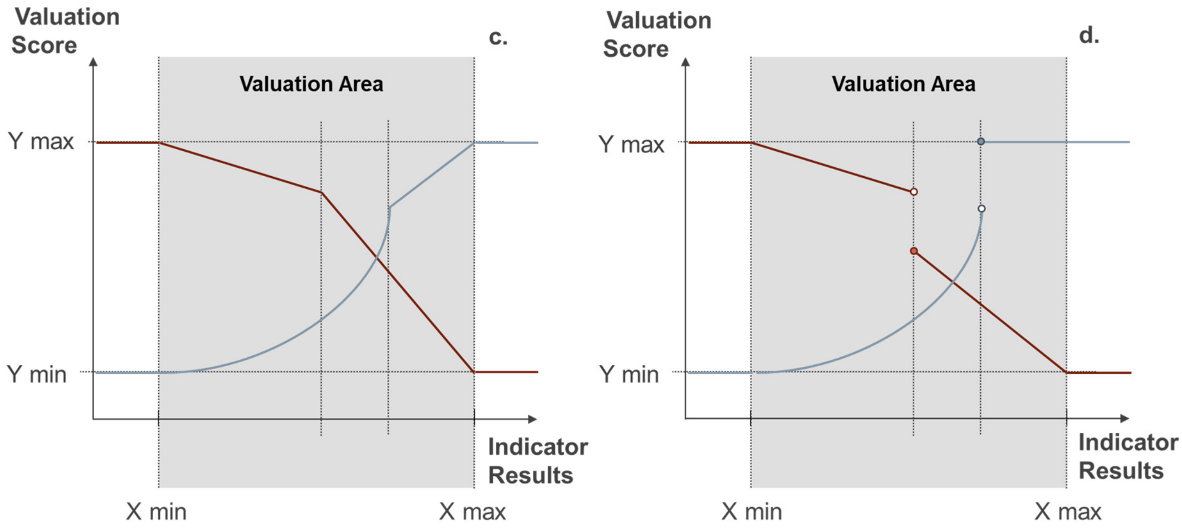

Figure 2-8: Examples of piecewise continuously differentiated merit functions (c.) and piecewise defined merit functions with discontinuities (d.).

Piecewise merit functions for valuation standards reflect a differentiation of the evaluation function between different corridors (c.), e.g. beneath the barrier of passing an exam (e.g. at 50% of possible points) there is a different continuously differentiated merit functions then after this barrier (e.g. 50-100% of the points). A continuous merit function can only be defined for indicators that are described using an interval or ratio scale. However, it is also possible to describe qualitative and comparative indicators that are represented by a nominal or ordinal scale.

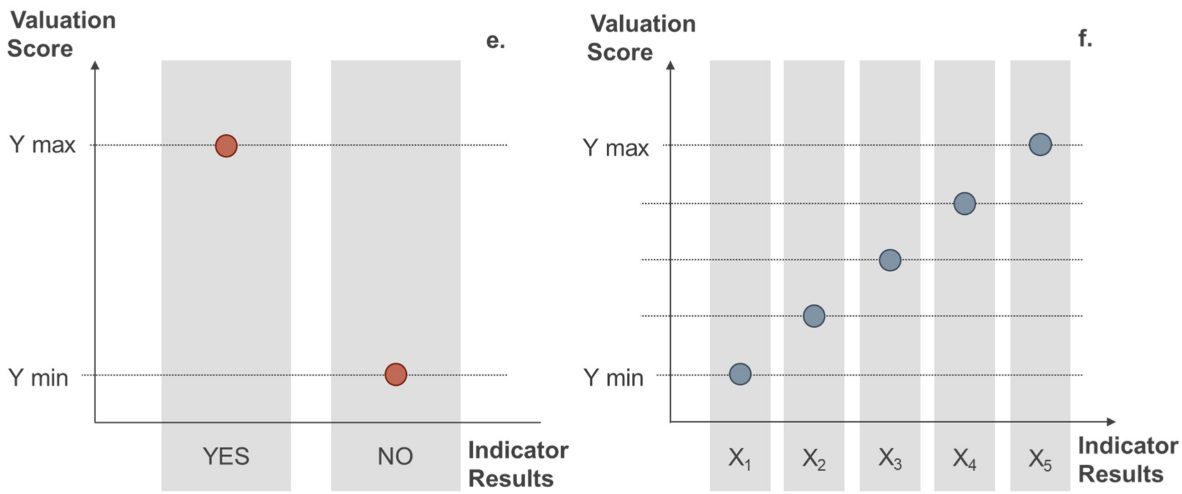

Figure 2-9: Examples for an evaluation of binary indicator results of a nominal scale (e.) and the evaluation of indicator results of a directional ordinal scale (f.).

The simplest evaluation in school is ‘passed’ and ‘not passed’ which indicates a binary nominal scale for the valuation score (a.) and defines a benchmark criterion for the indicator defined be the teacher or lecturer, e.g. submission of a homework, paper, etc. If there are more options for the valuation score, e.g. ‘passed with excellence’, ‘passed’, and ‘not passed’ which are defined by a crucial criteria to achieve this score the binary valuation standard is transformed to a directional valuation standard (f.).

Further examples and the application of the principles of evaluation in this thesis are presented in chapter 5.2.

2.2 How to Manage Complexity: The Theory of Systems

"The whole is more than the sum of its parts." – Aristoteles[9]

2.2.1 'Holism' – The Complexity of Reality

This early quotation, which is attributed to Aristoteles, can be used to describe the holistic law of general systems theory, which states that *"constitutive characteristics are not explainable from the characteristics of isolated parts"* (Bertalanffy, 1968, p.55). The quote captures the impression we get when we take a closer look at the reality that surrounds us, trying to understand its complexity. At a very early stage in life, we learn to explain the world to ourselves and to act accordingly, by means of the rationality of 'Actio' and 'Reactio' – action and reaction, deed and consequence.

This causality of cause and effect however quickly reaches its limits when it comes to understanding reality. For a more appropriate description, a deeper understanding, and for the analysis of complex, interdisciplinary interrelationships of reality (Ropohl, 2012, p.25) – and in the context of this work also for the analysis of building – it becomes necessary to think in systems. Thinking in systems offers a powerful tool with which to connect vastly disparate disciplines and inputs.

Human actions and behaviour can be motivated in different ways. In general, they can be divided into:

- accidental – non-oriented actions
- inconsistent – contradictory actions
- traditional – habitual actions
- emotional – actions based on emotion
- rational – rational action

(Zangemeister, 1973, p.48)

Evaluating and assessing these decision-making methods is usually situational and subjective, and none of them can be considered a priori as "right" or "better". However, in the context of the analysis of technical systems (buildings) a rational way of acting (i.e. the exclusion of random, inconsistent, traditional and emotional actions) seems optimal and appropriate (Zangemeister, 1973, p.47 ff). Rationality describes a logical and consistent occurrence of the above mentioned 'Actio' and 'Reactio'.

Rational human action however is frequently impeded by the absence of a direct causality between the initial cause and the resulting effect of events. This is also called **ambiguity**, which arises out of the following (Göpfert, 1998, p.39 ff):

[9] Aristoteles and Lasson (1907, p.129); Thanks to research and clarification to G. Ropohl and O. Geudtner, see also Ropohl (2012, p.25).

- **Complexity**: The number and nature of elements and relationships is too diverse to be cognitively grasped and surveyed.
- **Ambiguity of goals**: The goals behind a given behaviour are unclear.
- **Novelty**: The knowledge to explain a behaviour or to achieve a goal is missing.
- **Dynamics**: Elements, relationships and the design goals pursued change over time, making permanent solution knowledge obsolete.

Ambiguity results from the limitation of our human rationality, which is constrained by three essential limitations (Göpfert, 1998, p.50):

1. The limits of *physiological capacity* | restricted perception, absorption and limited speed of information processing
2. The limits of *knowledge* | limited storage capacity, retention time, retrieval and application of relevant information
3. The limits of *objectivity* | dependence on individual wishes, values and thought patterns

Systems theory advances our basic cause-and-effect thinking, which serves as an everyday explanatory approach, by defining a structured, integral approach. Systems theory is universally applicable in various fields of science (biology, mathematics, technology, chemistry, sociology, etc.) in cases where the cause of an effect is not obviously causally derivable (Rosner, 2015). In addition, systems theory sees itself as a mediator between these various disciplines and aims to counteract the ever increasing fragmentation of knowledge in the scientific disciplines with all its consequences (Ropohl, 2012, p.181). As a contrast to the analytic approach, systems theory pursues the paradigm of a synthetic, integral approach including the definition of problems, language and terminology, models of thought, methods and quality criteria (Ropohl, 2005). The structural differences between the two approaches can be seen in table 2-3.

Table 2-3: Comparison of the systemic and analytic approach (Ropohl, 2005, 2012)

	Systemic Approach	Analytic Approach
Scope	Holistic – concentrating on the interdependencies of a system	Specific – concentrating on specific aspects of a system
Evaluation	Evaluating by comparing the system model with reality	Evaluating by delivering empiric proof of a theory
Concept	Multi-dimensional net models	Linear models of derivation
Methods	Integrative methods aiming for better decision-making and synthesis	Specialized methods aiming for better knowledge and understanding
Discipline	Focus on interdisciplinarity	Focus on special disciplines
Outcome	Imprecise knowledge of minor details with better understanding of larger goals	Precise knowledge of minor details with poor understanding of larger goals

Because of ambiguity and limitations, different systems can be modelled based on the different nature and combination of the causes of the ambiguity.

Simple systems describe the connection between impact and effect with a few, directly causal system variables or parameters. A trivial example for a simple system is the traditional, cultural value system of a society, which makes the connection for certain behaviour patterns retrospectively or in advance accessible to an outsider: e.g. that in many cultures a clear "No" is perceived as impolite and thus an affirmative promise that has not been kept becomes understandable.

Complicated systems refer primarily to an increased quantity of system parameters required to causally link and describe input and output variables (cause and effect). This means that the control of these systems depends primarily on the limitation of physiological capacity (Vieweg, 2015). Classical examples can be found in technical systems such as the functioning of a car engine, where the variety of different physical principles and the interaction of the multitude of individual parts complicate the system. With appropriate expertise, effort and perseverance, the complications can be countered and reduced.

Complex systems are characterized not only by the fact that both input and output variables have non-linear and dynamic properties, but that they can also be disproportionate to each other. In addition, there are usually a large number of interactions and dependencies among the system parameters, which make the system behaviour difficult to predict. Complexity implies an integral and holistic approach (Vieweg, 2015). Classical examples of complex systems are our human brain, the Internet or financial markets.

Chaotic systems finally, in contrast to the three previous system types, cannot be rationally explained and are therefore completely unpredictable. An essential characteristic in chaotic systems is the randomness and arbitrariness with regard to the quantity and quality of the influences and effects. Chaotic systems are described as non-linear and dynamic. Weather phenomena, insect populations, the three-body problem or turbulence are typical examples of chaotic systems (Bossel, 2004).

2.2.2 Basic Approaches to and Definition of System Theory

Ropohl (2012, p.56 ff) distinguishes three basic concepts of system and thus uncovers how differently complexity and the structure of systems can be dealt with:

- **Functional concept** | The system is understood as a kind of black box and is separated from its environment with which it is related by effects and impacts. This concept describes the behaviour as functions without knowing the inner causal relationships. Thus the effect as a function, or 'what the system does', contrasts with the observation of the nature of the system.

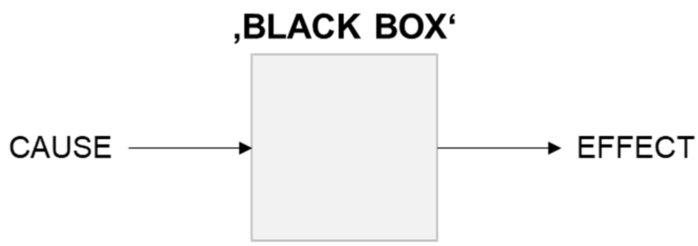

Figure 2-10: Illustration of the concept of a functional system

- **Structural concept |** The structural concept focuses on the system structure by considering a multitude of interrelated elements. The nature of the system, its elements, functions and effects are also considered. Taking integration, interdependencies and context into account – as opposed to an isolated consideration of the elements – this concept is usually described as having integral quality.

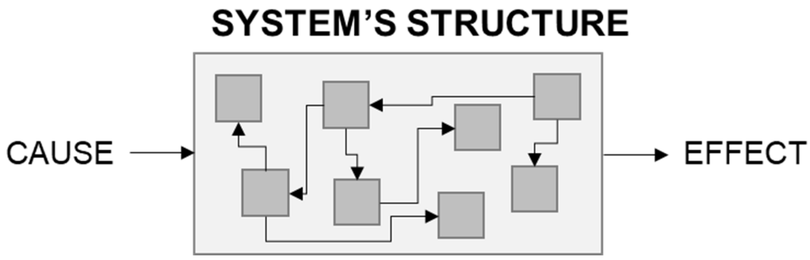

Figure 2-11: Illustration of the concept of a structural system

- **Hierarchical concept** | The hierarchical concept emphasizes the environment and the context of systems and places the system in a hierarchical order of superordinate systems (supersystems) and subordinate systems (subsystems). Often the micro, meso and macro levels are used. In general, an in-depth view down the hierarchy provides a more detailed explanation and a view up the hierarchy provides a broader understanding of the meaning.

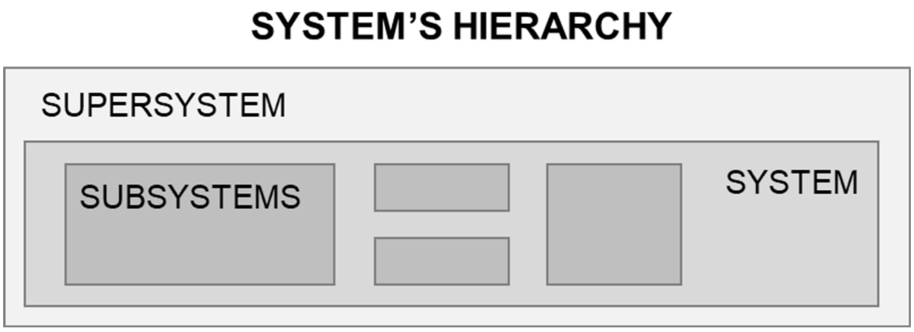

Figure 2-12: Illustration of the concept of a hierarchical system

These system approaches do not differ in their content, but form variants that are more appropriate for one or the other content and purpose. Although these approaches often compete with each other at the beginning, competition is actually not necessary as they can be combined with each other (Ropohl, 2012, p.56 ff).

The following explanations focus on the structural concept and the understanding of structural interrelationships in buildings and, as a result, the identification of decisive control parameters to achieve objectives in building. The following questions are prioritized:

- How can a systems-theoretical approach help to better understand the complexity of construction and identify interrelationships?
- How can interdisciplinary systems of construction be defined and linked?

2.2.3 Main Components of General Systems

> *"Man lives and works within social systems. His scientific interest is exposing the structure of nature's systems. His technology has produced complex physical systems." (Forrester, 1968, p.1-1)*

Systems, as Jay Forrester illustrates in this quote, were not invented by humans. They are part of our reality and the everyday context in which we move, live and work. However, the observation, investigation and the transformation of a real system into a fictitious model offers a high potential to understand and control this reality.

The term 'system' or 'systemic' has always been used in different disciplines and with different meanings.[10] As one of the decisive co-founders of the General Systems Theory, Ludwig von Bertalanffy defines the generalized term "system" as *"parts standing in interaction"* or *"a complex of interacting elements"* (Bertalanffy, 1968, p.19; p.55). These **system elements** differ in three elementary aspects: the number 'n' of elements, the species 'p' of elements and the relation 'R' between the elements (Bertalanffy, 1968, p.54). Ropohl (2012, p.62 ff) defines these system elements as attributes and functions and thus a system as the sum of these attributes.

The ***linkage of effects*** (their structure and relation) or interactions between elements are defined by different behaviours of the relations of elements. This means that no interaction exists if a different behaviour or change cannot be observed in regard to another relation (Bertalanffy, 1968, p.54-55). This change of behaviour can also be described as a *function*.

Systems according to Bertalanffy are not a trivial reformulation of the familiar (e.g. buildings as a system for protection from the environment), but rather the striving for knowledge and insight into the behaviour and interaction within the set up systems. This search is reflected in the observation of the *stimulation*, i.e. **input** and **output** of the system, its external functions and relations with the environment, investigating the communication between elements (effects) and observing the coordination of the system by analysing the experiences the system draws on (feedback) (Zeeuw, 2016, p.60 ff).

Similarly, Jay W. Forrester defines systems as *"a grouping of parts that operate together for a common purpose. [...] A system may include people as well as physical parts"* (Forrester, 1968, p.1-1). Forrester specifies Bertalanffy's generalized definition and assigns a **system purpose** to the system and an expanded definition of the nature of the individual elements. Moreover, systems are not divisible, which means that **system identity** – the fundamental property of a system – is lost when **system integrity** – the totality of the system – is divided or violated (Bossel, 2004).

To investigate a system, it is necessary to clearly distinguish it from the **system environment** by a specific **system boundary** in order to obtain maximum autonomy of the system (Ropohl, 2012, p.59 ff). The system boundary is usually found where the coupling to the environment is

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[10] Compare the differentiated explanations of the word and concept as well as historical and modern usage and approaches in Ropohl (2012, p.21 ff).

the least significant or not relevant for the system function and the effects are not determined by the system itself or are independent of it. The purpose of the system can also have a strong influence on the system boundary (Bossel, 2004).

Ropohl unites all three system concepts (see passage 2.2.2) by defining a system as *"a whole which has relationships between certain attributes, which consists of interrelated parts or subsystems and which is delimited from its environment or excluded from a subsystem at a certain level"* (Lenk and Ropohl, 1978, p.31).

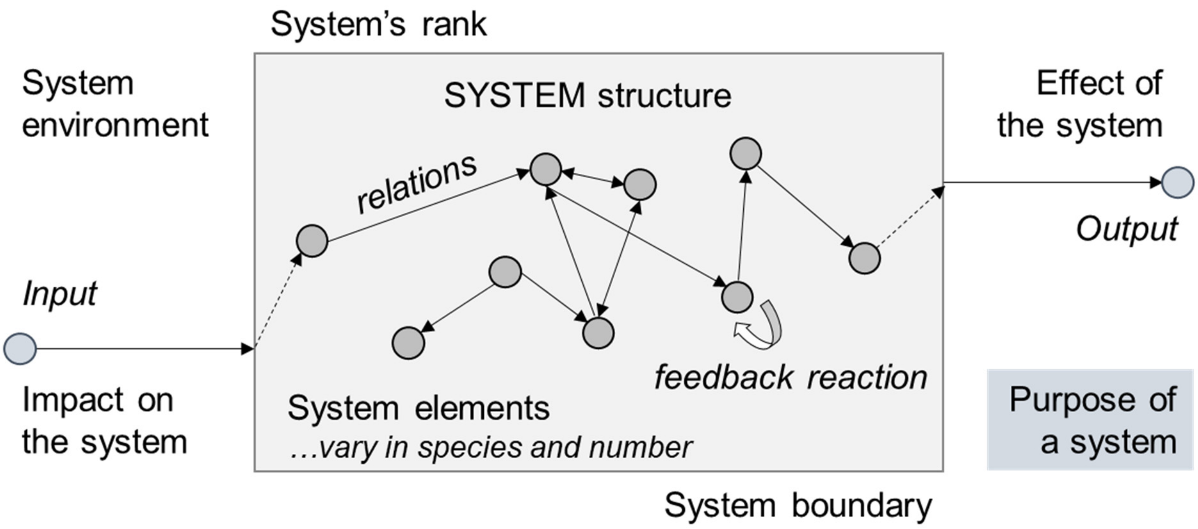

Figure 2-13: Illustration of the basic concept of general systems referring to Bossel (2004)

In systems theory, it is necessary to find principles that allow an accurate description and investigation and that can be applied to specific cases. In the context of this work the term system is used as follows:

The term "system" is understood as a thought model of reality that comprises a whole of different, multiple elements that have an observable structure, relation, change, effects or functions due to their interactions. Systems pursue a system purpose and delimit themselves with the system boundary and by a certain rank from their environment, but are related to it by input and output variables.

2.2.4 Main Characteristics of General Systems

An elementary component of system analysis is observing and describing the behaviour and changes of the system, whereby the decisive components which influence the behaviour can be defined. In a first step, Ropohl, in his work on general systems theory, distinguishes systems from the "rest of the world" (Ω) and describes systems using the mathematical language of set theory. For a clear definition of the system $\sum$ in relation to the 'whole', here expressed by the superset Ω, the environment Γ of the system is defined as (Ropohl, 2012, p.59 ff):

$$\Gamma = \Omega \setminus \Sigma \tag{2-1}$$

Γ	Environment
Ω	Superset
∑	System

Since the environment cannot be defined exhaustively, this definition is of a primarily formal nature and describes the 'rest' outside of the defined system from which a system delimits itself.

Based on the merging of the existing system concepts – in the sense of the previous definition as a **functional system**, a **structural system** and a **hierarchical system** –, Ropohl (2012) develops a general system approach. This general approach defines the essential components of systems as relational structures comprising the quantity of elements (attributes, sizes, parts, etc.) and the quantity of interactions (relations, functions, etc.).

$$S = (E, R) \tag{2-2}$$

$E = \{e_i\}$	The set of general elements e
$R = \{r_i\}$	The set of general interactions r

The different elements can be categorized according to *matter, energy and information*, each of which is related to *space* and *time*. *Matter* is understood to be everything that expands spatially (form), is inert and has mass. *Energy* is the force that performs work in the physical sense. For a better understanding and to emphasize the predominant meaning, the actual equivalence between energy and mass and the fact that *information* really consists of material or energetic signals are neglected in this case (Ropohl, 2012, p.151 ff).

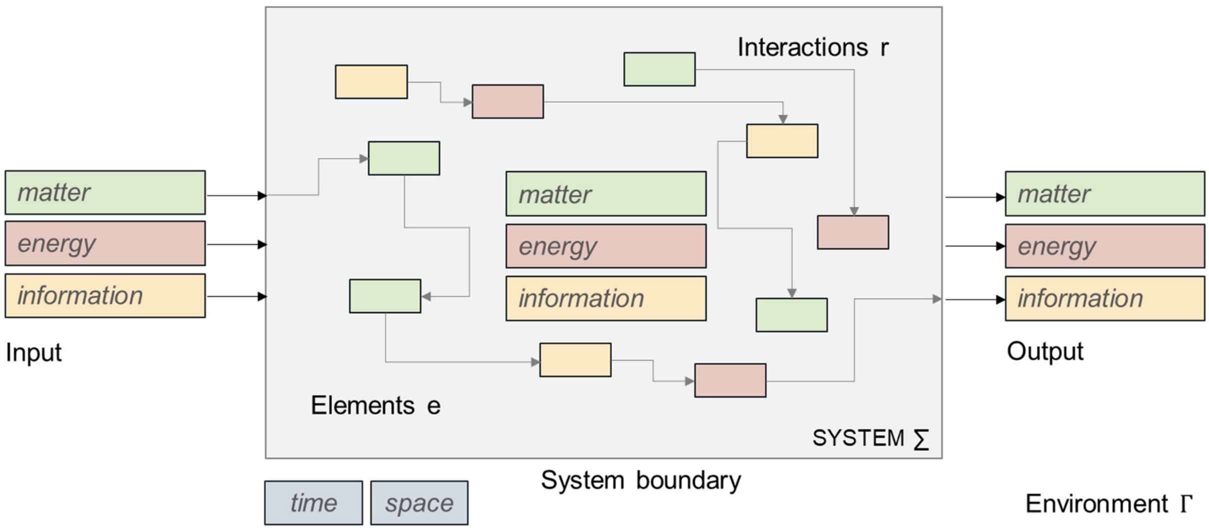

Figure 2-14: Illustration of the basic concept of general systems referring to Ropohl (2012)

The Functional System

The **functional system** ∑F is described in the form of a set of *attributes 'a'* and a set of *functions 'f'* as an ordered pair:

$$\sum F = (\alpha, \varphi) \tag{2-3}$$

α	= {a_i}	Set of attributes a
φ	= {f_i}	Set of functions f

Attributes are the subset of related elements that can be described through functions. These system properties describe changes within and by the system and are described by the effect of the system elements or different system variables:

- *Input variables*, influences or inputs that describe effects from the environment on the system: X_j
- *State variables* that define the state and condition within the system structure (memory variables): Z_j
- *Output variables*, effects or outputs that represent the effects of the system on its environment: Y_j

Accordingly, an input variable as a downstream element ($X \Leftrightarrow (\gamma, X)$) is delimited from any element of the environment ($\gamma \in \Gamma$) and an output variable as an upstream element ($Y \Leftrightarrow (Y, \gamma)$). State attributes describe the system itself. The set of all attributes can be defined as:

$$\alpha = \{X_j, Z_j, Y_j\} \tag{2-4}$$

The sum of all individual state variables is necessary for a complete description of the system (see also *structural system*). Due to the temporal dimension, state variables are always as well storage variables that cause a change of state via entries and exits. The number of state variables is called the *dimensionality* of the system (Bossel, 2004). Relationships between attributes are described by functions. A *function* is defined as the relation between the attributes a_j of the attribute set α:

$$f_q \subset \boldsymbol{X}\, a_j \tag{2-5}$$

Attributes can have different values. The correlation of these values is called the Cartesian product X. In this way, functions between attributes can be represented and described both as a qualitative assignment of the attribute value xi to an attribute value yi (for example, with multiple assignments), and in the 'classical' mathematical sense using a curve y(x). Accordingly, the following functions can be classified using the respective attributes that are in relation to each other (Ropohl, 2012, p.62 ff):

- *Input function*: Describes exclusively the relationship between input attributes, usually over time T:

$$f_x \subset X_j\, \boldsymbol{X}\, T \tag{2-6}$$

- *Output function*: Defines exclusively relations between output attributes, also over the time T:

$$f_y \subset Y_j \boldsymbol{X} \, T \qquad (2\text{-}7)$$

- *State function*: Describes exclusively relations between state attributes, usually over the time T

$$f_z \subset Z_j \boldsymbol{X} \, T \qquad (2\text{-}8)$$

- *Result function*: Describes the relations between input and output and vice versa in combination with the time T

$$f_e \subset X_j \boldsymbol{X} \, Y_j \boldsymbol{X} \, T \rightarrow \Delta X_j \qquad (2\text{-}9)$$

- *Transfer function*: Describes the extent to which input attributes affect and change states in combination with the time T

$$f_{\mathrm{t}} \subset X_j \boldsymbol{X} \, Z_j \boldsymbol{X} \, T \rightarrow \Delta Z_j \qquad (2\text{-}10)$$

- *Marker function*: Describes the dependence and relation of the output attributes on the state, taking into account the time T:

$$f_m \subset Z_j \boldsymbol{X} \, Y_j \boldsymbol{X} \, T \qquad (2\text{-}11)$$

The entire set of all functions f is accordingly defined as:

$$f = \{ f_x, f_y, f_z, f_e, f_{ü}, f_m \} \qquad (2\text{-}12)$$

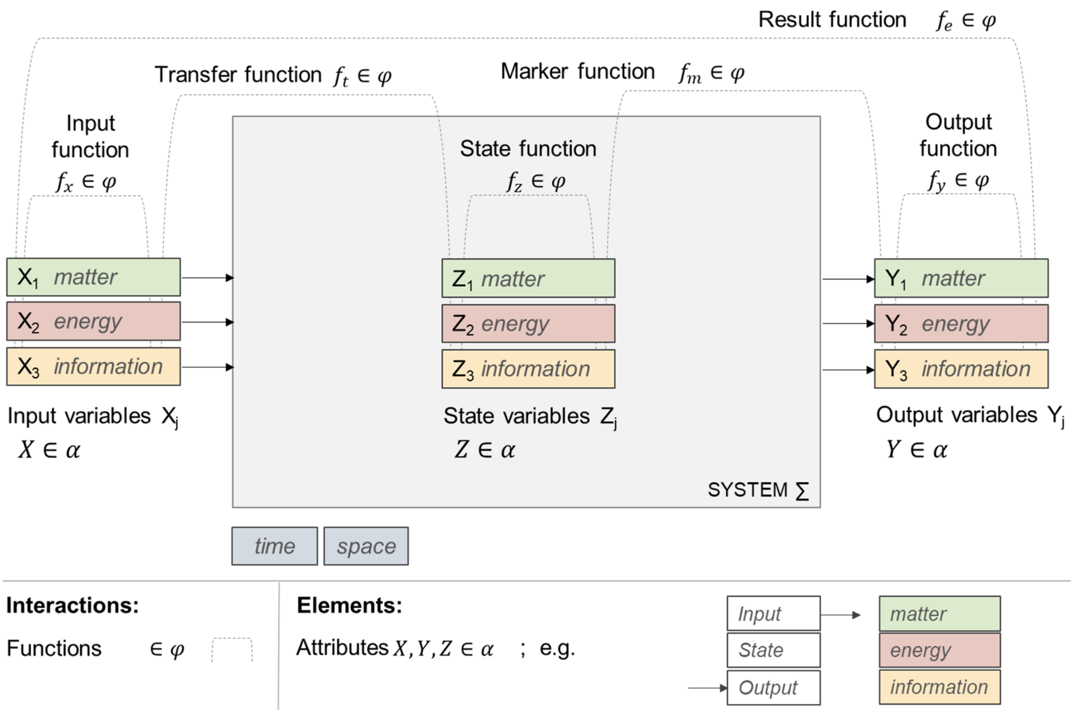

Figure 2-15: Illustration of the basic concept of the functional system

Functions that define relationships between attributes over time T are called function-dynamic and are found largely in dynamic systems, which also include result functions in the form of feedback, with an effect of output on input variables.

The Structural System

According to the opening quotation, the structural system describes the 'more' the whole is than the sum of its parts. The structural system ∑S comprises the set of all parts and the set of all relations:

$$\sum S = (\kappa, \pi) \qquad (2\text{-}13)$$

κ	$= \{k_i\}$	Set of parts k
π	$= \{p_i\}$	Set of relations p

Parts can be unspecified but clearly distinguishable "elements" (parameters, attributes, quantities, processes) within a system and can include other subsystems, too. A *relation* describes a relationship between individual parts and is defined as a subset of the Cartesian product over the parts k_j of the part set κ:

$$p_n \subset \boldsymbol{X}\, k_m \qquad (2\text{-}14)$$

A *linkage* represents a special relation in the case where the output of one part becomes the input of another part. If the output of a downstream part additionally becomes the input of the upstream part, this is called *feedback*. These interactions influence individual parts as well as the entire behaviour of a system. Systems with parts changing over time or time-dependent mutual couplings are also called *control systems* or *dynamic systems*.

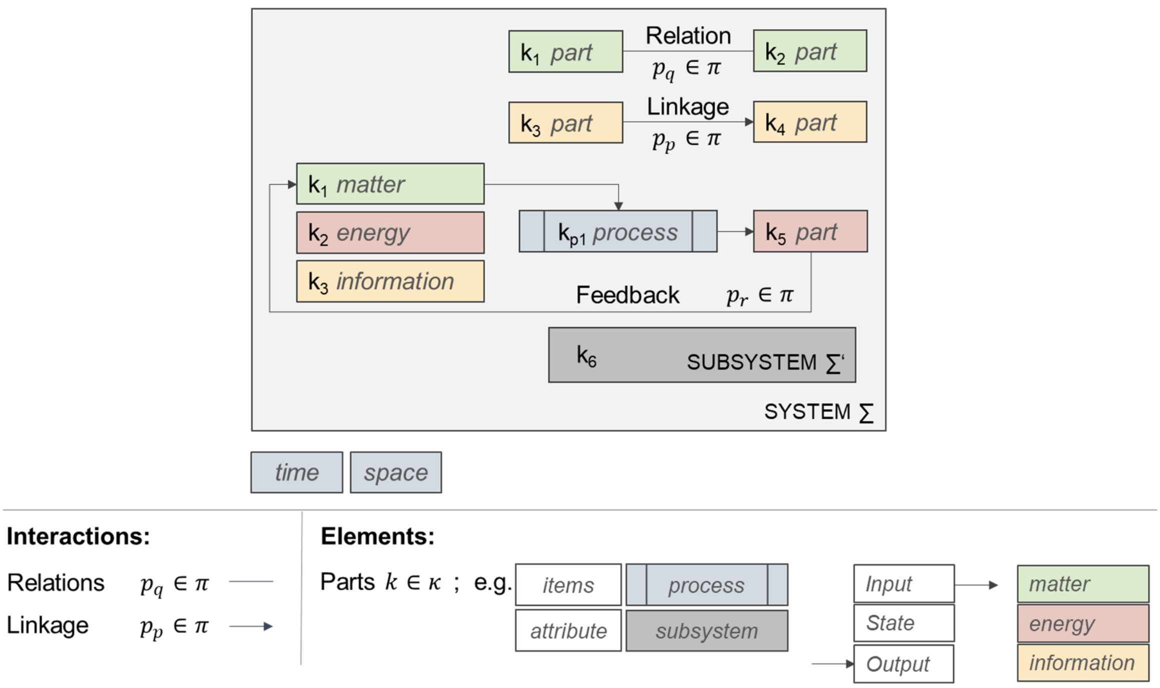

Figure 2-16: Illustration of the basic concept of the structural system

The Hierarchical System

Systems also differ in their modularity, i.e. systems can consist of several delimitable subsystems, or subsystems which also have a specific partial behaviour, making them individual entities of another system. If the behaviour of the subsystems is known, the behaviour of the overall system can be derived from the interaction of the subsystems, a process called linearity. In a case where the usually autonomous behaviour of a subsystem is influenced by the intervention of a superordinate subsystem, a hierarchy H within the system structure ∑ in the form of superordinate supersystems ∑+ and subordinate subsystems ∑' is assigned:

$$\sum H = (\ldots, \Sigma^{++}, \Sigma^{+}, \Sigma, \Sigma', \Sigma'', \ldots) \qquad (2\text{-}15)$$

Hierarchy is understood in this context as a purely formal ranking and has no reference to power or value relations.

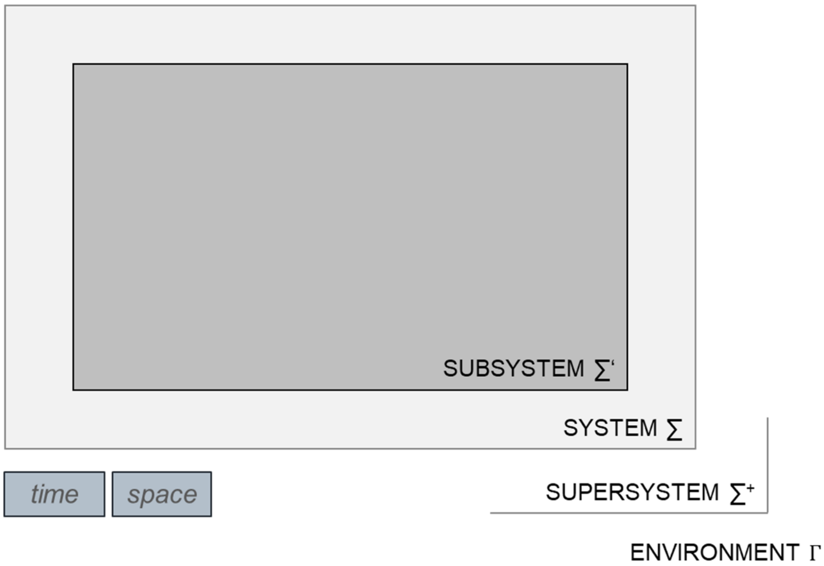

Figure 2-17: Illustration of the basic concept of the hierarchical system

Synthesis: General Systems

Functional systems in the form of *attributes 'a'* and *functions 'f',* as well as structural systems in the form of *parts 'k'* and their *relations 'p'* define a system ∑, comprised – in the context of a system hierarchy – of *subsystems* $\sum'$ and *supersystems* $\sum^{+}$, as following (Ropohl, 2012, p.62 ff; p.77 ff):

$$\sum^{+} = (\alpha^{+}, \varphi^{+}, \kappa^{+}, \pi^{+}) \text{ mit } \sum \in \kappa^{+} \subset \sum^{+} \qquad (2\text{-}16)$$

$$\sum = (\alpha, \varphi, \kappa, \pi) \qquad (2\text{-}17)$$

$$\sum' = (\alpha', \varphi', \kappa', \pi') \text{ mit } \sum' \in \kappa \subset \sum \qquad (2\text{-}18)$$

α	$= \{a_i\}$	Set of attributes a
φ	$= \{f_i\}$	Set of functions f
κ	$= \{k_i\}$	Set of parts k
π	$= \{p_i\}$	Set of relations p

Oftentimes, the number of individual parts of a system is described as the *variety*, the number of state variables as the *dimensionality* and the number of relations as the *complexity* of a system (Ropohl, 2012, p.71).

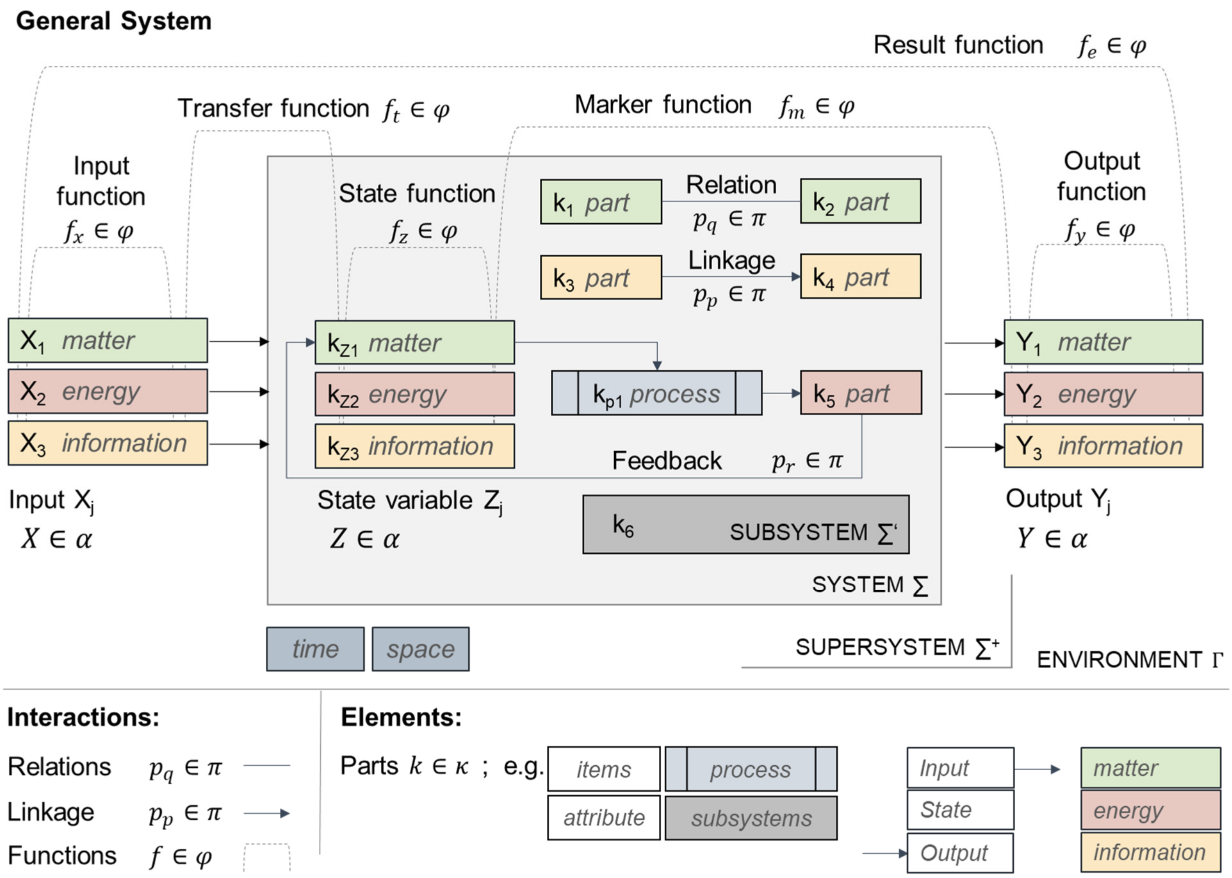

Figure 2-18: Illustration of the detailed concept of a general system based on Ropohl (2012)

Systems have different properties and characteristics, which lead to a differentiation and classification of systems. According to the hierarchical understanding of the system, the different relationships of the systems to their environment can be distinguished as (Ropohl, 2012, p.91):

- **Closed Systems**
  Completely closed systems without reference to the environment do not occur in reality, but can be investigated as radically reduced system models.
- **Relatively isolated Systems**
  In general, relatively isolated system models with reduction of the relationships in relation to the purpose of the investigation are used.
- **Open Systems**
  Open system models describe a highly realistic assumption, but can mostly not be sustained in practical application.

With respect to the functional concept of systems, the attributes of the functions (inputs, outputs, state) can be numerical or non-numerical and different in their description, i.e. the signals can be measurable/numerical quantifiable or qualitative. The expression of the characteristics can be described in the form of antonymous word pairs as follows (Lenk and Ropohl, 1978, p.34; Ropohl, 2012, p.91; Bossel, 2004):

- **Linear | Non-linear**
  In linear systems, the degree of impact changes proportionally to the degree of effect, whereas in nonlinear systems the system response can be erratic, underproportional or overproportional.
- **Deterministic | Stochastic**
  Deterministic systems exclude random changes within the system, while stochastic systems explicitly take them into account.
- **Static | Dynamic**
  Dynamic systems show a dependence of the attribute values on time. Static systems are time-independent and do not show any relevant changes in attributes over time.
- **Discrete | Continuous**
  Continuous systems show a course of corresponding values with any number of intermediate values and can be measured and defined at any time and at any place. Discrete systems have unique time- or location-dependent properties and changes, i.e. without intermediate values.
- **Unstable | Stable**
  Stable systems always strive for a state of equilibrium, even if disturbances in the meantime lead to distractions of individual values. These can also be called self-organizing systems. In contrast, unstable or in-stable systems react to disturbances and deviations from attribute values with a violent system change (e.g. exponential growth).

The structure of systems in terms of the relations of their individual parts can be described in terms of number, form and time dependence as (Ropohl, 2012, p.91; Lenk and Ropohl, 1978, p.34):

- **Invariant | Variant**
  Systems are time-invariant if the same result and behaviour of a system is obtained at different starting times while maintaining the same initial conditions and actions. In contrast, "age" plays a role in time-variant systems. In addition to time, other displacements can also show a variance.
- **Autonomous | Controlled**
  Systems can be autonomous and self-sufficient, i.e. based on the principle of autopoiesis, the process of self-creation, regulation and maintenance, or they can be driven and controlled exogenously by relations that transcend system boundaries.
- **Numerical | Non-numerical**
  The state system can either be recorded numerically – if quantitative and measurable state variables can be determined –, or non-numerically and therefore primarily described qualitatively. Both methods are essential to describe different aspects of systems.

2.2.5 'Models' – Translating the Complexity of Systems

"All models are wrong, but some are useful" - George Box (1978)

How correct the British statistician George Box was with this statement depends primarily on the definition of the term 'model'. It does however very impressively reflect the fundamental fact that it is impossible for models to represent a complete version of reality correctly. Models primarily serve to represent and abstract reality, for example static systems as models of the real load-bearing behaviour of building components, or other hydraulic, mechanical or electrical models.

System models unfold their greatest potential in decision-making processes, in the assessment of future behaviour or in achieving objectives through the fictitious "playthrough" of so-called "thought models" (Bossel, 2004). Illustrating real connections and conditions with models (which were subsequently checked and tested) has accompanied human thinking since its earliest days, in the form of models of reality (buildings, bridges, ships, maps, etc.), or thought models (schedules, organization charts, physical equations, etc.). These models are often used to predict future behaviour in order to solve a problem or achieve a desired goal and to anticipate failure. The reasons for modelling are manifold (Stachowiak, 1973, p.139; Bossel, 2004):

- *Cost reduction or avoidance*: Replacement of the actual resources by less real (because small scale) or mental resources, e.g. computing power.
- *Simplification*: Clarification and concretization of unclear and complex events
- *Time advantage*: Models can deliver fast results and offer the possibility to run them repeatedly.
- *Risk minimization*: Model failure is subject to a known risk without putting the real system at risk.

Within the framework of general systems theory, the transition from systems to models is fluid and not always uniform in use. Models are understood as the less concrete representation of a concrete system. Systems therefore stand between the concrete reality and the abstract model (see definition in chapter 2.2.2). Ropohl and Stachowiak describe three essential characteristics of models (Ropohl, 2012, p.52 ff; Stachowiak, 1973, p.131 ff):

- **Representation Feature**
  Models 'of something' represent natural or artificial original systems (objects, processes or configurations) and are in this sense a 'representation of reality'.
- **Abbreviation Feature**
  In model development, the respective attributes are shortened to describe the model. Only the relevant attributes of the represented original are mapped.
- **Pragmatic Feature**
  In addition to the representation feature, models are not a complete representation of reality but always pursue and fulfil a model purpose. Models are therefore always limited to certain users (for whom), within a time frame (when) and for certain processes in terms of the model purpose (what for).

Not to be neglected is the fact that models only represent a limited, interested section of reality and can therefore make statements only for a specific model purpose. For this reason, the model purpose is of decisive importance. Take a birthday cake for example. The model – the cake recipe – serves only the purpose of baking the cake. It cannot even begin to describe the taste of the cake or its effect as a birthday present. Furthermore, there is always a certain uncertainty about the validity of the model. This can be counteracted with validation, but it means that models should be as simple as possible and as complex as necessary.

> *The term "model" is understood as a simplified representation of a fictitious or real system, which represents the system appropriately reduced and suitable in the sense of the model purpose.*

The development of models is called modelling and can be described by three basic concepts (Bossel, 2004, p.29 ff)[11]:

1. **System Delimitation** | Hierarchical concept
   The hierarchical concept is based on the defined model purpose and describes what belongs to the system and its environment. In this way, the system boundaries of the model are defined and the system is related to subsystems and supersystems.
2. **Imitation of the system's structure** – *Imitation Modelling (IM)* | Structural Concept
   Based on the purpose of the model, structural concepts try to reproduce the essential functional behaviour and effect structure of the original system in order to reproduce the same behaviour as the original. To build a so-called "Glass Box" model, real system parameters and processes are required.
3. **Simulation of the system's behaviour** – *Mirror Modelling (MM)* | Functional Concept
   The so-called "black box" concept aims to observe the behaviour and effects of the system and to describe them with the help of a mathematical function. The behaviour is usually observed in retrospect and the concrete functioning of the system is not considered. Therefore, behavioural observations are primarily relevant for modelling.

Usually a mixed form of all three concepts is used. This option is called "Opaque/Grey Box" model. In this case, care is taken to ensure that the system structure is represented qualitatively correctly and on the basis of the unknown model parameters. The system behaviour is numerically controlled to such an extent that the empirical behaviour corresponds as closely as possible to the observed behaviour. For this purpose, relevant observations of the behaviour are required as well as knowledge of the system interrelationships and parameters.

The development of a virtual model in the context of system theory can also be described by modelling and mapping the real system as well as the thought model and continuous adaptation. At the beginning of the modelling process, the purpose of the model and the problems

[11] See also the different system concepts by Ropohl (2012) in chapter 2.2.2

which are to be investigated are defined. Only then a model concept is developed according to the structure (structural concept) and the behaviour (functional concept) and separated from its environment (hierarchical concept) (Bossel, 2004, p.40 ff).

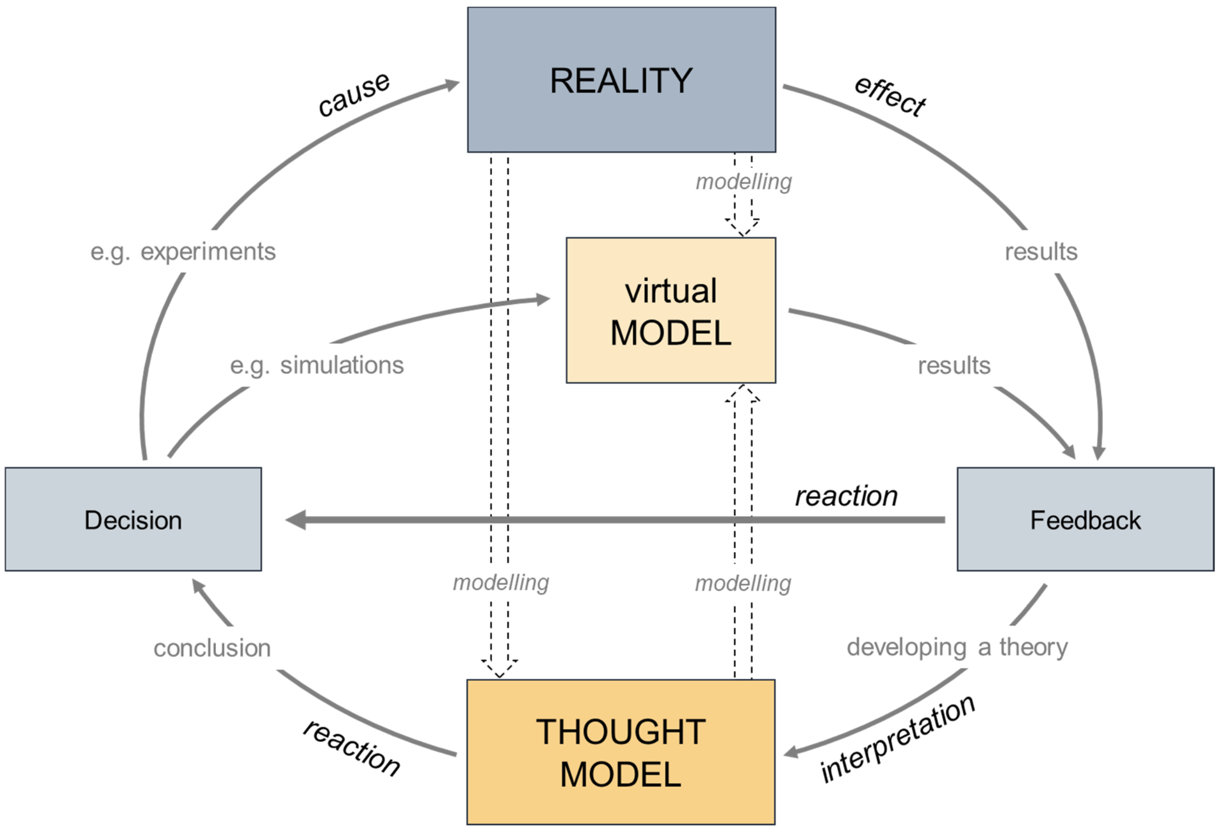

Figure 2-19: Problem-solving procedure by modelling and simulation

For a simulation-capable, virtual model that goes beyond purely qualitative effects ('There is an effect from A to B') to quantitative, computable interactions (specific values and logical operations), the virtual model must be transferred to a simulation model. The following steps, according to Bossel (2004, p.41 ff), are necessary for a simulation-capable model:

- *Dimensional analysis*
  The meaning and dimensions of the individual variables (input, state and output variables as well as other parameters) must be precisely defined and hierarchically delimited (subsystems, supersystems).
- Determination of the *functional relationships*
  The effect relationships (functions) between the variables must be clearly specified in their functional dependence (input, output, state, result, transfer, marking function).
- *Quantification*
  The impact relationships must be quantified using the parameter values.
- Development of the *simulation diagram (flow chart)*
  Development of an overall representation (diagram), e.g. by a graphical representation of the system structure.
- Simulation instructions and *computable model*
  Formalization of the individual functions into logical operations (simulation instructions).

- *Validation check* of the model structure
  The structure of the "real" system should be reproduced correctly by the model.
- Development of *alternative forms of representation*
  Increase of clarity and comprehensibility through modularization (e.g. based on the hierarchy of sub and super systems) without loss of validity.
- Attempt at *compact representation*
  Traceability to simpler, elementary structures to facilitate analysis and generalization.

Validity via the **validity of models** is more important than absolute correctness. This validity of models is defined by four essential aspects and their questions (Gnauck, 2002, p.50 ff; Bossel, 2004, p.36):

- **Behavioural validity**: Is the same model behaviour qualitatively generated in relation to the original system for the model purpose in question?
- **Structural validity**: Does the model structure for the model purpose under consideration correspond to the effect structure of the original in terms of the number of essential state variables and processes?
- **Empirical validity**: Do the numerical and logical results of the model agree with the empirical results of the original for the model purpose, or are they plausible and consistent?
- **Practical validity**: Do the model and simulation capabilities reflect the basic requirements of the model purpose and the user?

In the light of this context, George Box's statement that all models are wrong seems confirmed: All models only describe a part of reality. However, by corresponding working models it is possible to achieve essential progress in handling the complexity of reality.

3 Development of a Systems Model for Building Construction

3.1 Categorisation of Building Construction

> *„It is my experience that it is rather more difficult to recapture directness and simplicity than to advance in the direction of ever more sophistication and complexity.“ – E.F. Schumacher* (Schumacher, 1973)

3.1.1 Defining Terms and Goals of 'Building'

Having established the principles of general system theory as well as the definition and derivation of objectives and values, both concepts need to merge in order to develop a system model for building construction. However, prior to the step of modelling the system, it's necessary to categorize the different elements in the context of building construction in an applicable and holistic manner, especially in regard to the whole of the parts, processes and functions of a building. To do exactly that, the following chapter provides these categorizations as tools for the subsequent modelling process.

To reach the goal of a comprehensive and at the same time valid representation of building construction in the form of a model, a clear structure and breakdown of construction itself is essential. "What is the purpose of a building?" The answer to this fundamental question in combination with existing definitions will allow a definition of the term 'building' from which further classification and structuring steps for the modelling process can be derived.

In the German Model Building Regulations ("Musterbauordnung", MBO) the terms 'building structure' ('bauliche Anlage') and 'building' ('Gebäude') are defined as follows (MBO, 2016):

> *"Constructions are installations connected to the ground and made of construction products."* [MBO §2 (1)][12]
>
> *"Buildings are independently usable, covered structures that can be entered by people and are suitable or intended for the protection of people, animals or property."* [MBO §2 (2)][13]
>
> According to Section 3 (1) of the MBO, *"construction works are to be arranged, constructed, altered and maintained in such a way that public safety and order, in particular life, health and the natural foundations of life, are not endangered."* [MBO §3 (1)][14]

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[12] German Source: „Bauliche Anlagen sind mit dem Erdboden verbundene, aus Bauprodukten hergestellte Anlagen.“

[13] German Source: „Gebäude sind selbstständig benutzbare, überdeckte bauliche Anlagen, die von Menschen betreten werden können und geeignet oder bestimmt sind, dem Schutz von Menschen, Tieren oder Sachen zu dienen.“

[14] German Source: Bauliche Anlagen sind nach §3 Abs. 1 MBO „so anzuordnen, zu errichten, zu ändern und instand zu halten, dass die öffentliche Sicherheit und Ordnung, insbesondere Leben, Gesundheit und die natürlichen Lebensgrundlagen, nicht gefährdet werden.“

The essence of these definitions are:

- Buildings consist of the sum of their building products
- Buildings are made through processes like arrangement, construction and maintenance

The objective for buildings is found in the aspect of its **protective function** of life and health of humans, animals or objects as well as of safety and order. In his work on building construction, Moro et al. (2019, p.2-3) describe the term 'construction' (lat. 'constructio', layering) of a building as not only the structure of the building, but both the actual building **process** of planning, preparing and assembling of its individual parts (called constructing), which leads to the assembled final **product**, the structure of individual parts, called 'construction'. In a holistic sense, the building process as well as the building structure must also be considered in the **context** and interdependence of its global and local **environment** as well as in the context of **economic added value** as mentioned in the following explanation:

> *"Buildings and structural works as part of the built environment are complex systems designed to fulfil defined tasks and functions. Buildings and structures provide both living space and a work environment, and they affect their users' well-being, health and satisfaction as well as the quality of social life. They represent commercial and economic values, help to create and protect jobs and values, and they trigger energy and substance flows which affect the global and local environment.*" (BMUB, 2014, p.9)

This definition already describes building structures as a **complex system,** meeting functional requirements through several interdependencies with its environment. Its system character can be described by **input** and **output** flows (energy, materials, capital, and products) which are responsible for the resource consumption and environmental impact of the system 'building'. The scope of these input and output flows is shown in the following comment:

> *"(…) today's buildings and associated infrastructure cause approximately 30 % of the energy and material flows and effects on the environment. Therefore in implementing the principles of sustainable development great significance must be attached to construction in matters of resource conservation and environmental impact."* (König et al., 2010, p.6)

In conclusion, by combining these different perspectives, approaches and aspects, the term 'building structures' as used in this thesis is defined as follows:

> ***Building Structures*** *– through the process of construction – are technically manufactured products made of building components and materials, which are used by humans for living and economic purpose. Throughout their life cycle, they serve to satisfy the fundamental needs of man and society, should not limit or harm man or the environment in the long term and contribute to added economic value.*

With this definition three major possibilities for ordering the structure of building construction can serve as a starting point for the following categorization:

1. Construction as a **product**
2. Construction as a **process**
3. Construction with different **functions** and objectives

3.1.2 Categorising Construction as a Product

Looking at a building structure as the final product of the sum of its building elements, the following section will give an overview of different possibilities to structurally order the physical elements of construction.

Before differentiating building structure and its different elements and components, different types of buildings need to be distinguished. Structures can be subdivided in many ways, e.g. according to their function and purpose or according to their construction, building style, building material and the way they are created, so-called building methods. The following functional order structure for buildings is based on the HOAI (including an additional segmentation of protective structures according to their main functions) (HOAI, 2013):

- **Protective structures**, including buildings
  Protection against weather, forces of nature, attacks, examples according to different functions (use):
  - Residential buildings
  - Office and administration buildings
  - School and educational buildings
  - Accommodation and hotel buildings
  - Industrial buildings (laboratory, workshop and factory buildings)
  - Multi-storey car parks and storage buildings, halls
  - Cultural and assembly sites, sacred buildings
  - Sports halls and sports facilities
  - Health buildings
  - Structures for protection against the weather (umbrellas, roofs, etc.)
  - Structures for protection against attacks and forces of nature (protective walls, dams, rooms, dikes, etc.)
- **Infrastructures**
  Handling of passenger and goods traffic
- **Structures for supply and disposal**
  Supply of water, electricity, heat and other resources including the disposal of solid waste materials
- **Temporary structures**
  Mobile and movable structures

The physical structure of a building is often divided into three subsystems with specific tasks (Moro, 2019b, p.30 ff):

1. The supporting structure as that subsystem of a building which transfers loads between elements as well as to the ground
2. The (building) envelope as that subsystem of a building which envelops the structure and forms the enclosure
3. The supply and disposal as that subsystem of a building which supports the main system by means of additional technical measures and equipment

This subdivision however retains a mixture of product and function. For example, the building envelope usually also assumes load-bearing functions, making it difficult to clearly differentiate between both subsystems. Konrad Weller (1986) provides a cleaner and more consistent breakdown of a building structure and its individual parts with the following hierarchy (Weller, 1986, p.83-84):

- Building structure
- Main structure
- Substructure
- Group of Component
- Component
- Group of Parts
- Separate part
- Wrought or pre-product
- (Building) Material

This detailed list can be reduced to four essential **levels of perspective** which reflect a systematic classification of the entire building, including context and environment, the variety of individual rooms and their different usages and requirement profiles, the individual building components that create the room as well as the respective building materials each building element consists of:

1. **Building** level
2. **Room** level
3. Building **component** level
4. Building **material** level

Each Level describes different properties and aspects, and each level, starting upwards at the material level and ending in the building level, is integrated into its subsequent level, reflecting the functions of the building as a whole.

These Levels of perspective allow different delimitations and comparisons, offering a substantial differentiation of individual aspects. For example, insulating materials (building material level) have different values of thermal conductivity. By integrating them into an external wall (building component level), heat transfer can be calculated in relation to the thickness and the sum of all building materials. However, the comfort level and heat energy demand in the room

(room level) depends on the outside climate, room volume, window areas, use, detailed design and other aspects. The heat energy demand for the entire building (building level) can be determined by linking the individual rooms and other technical aspects of the system.

Table 3-1: Combination of the categorization of construction parts and levels of perspective

Parts of construction by Weller (1986)	**Level of perspective**	***Examples***
Building structure	**Building** Level	*e.g. buildings with grounds*
Main structure	**Room** Level	*e.g. stories and zones*
Substructure		*e.g. different rooms*
Group of components	**Building Component** Level	*e.g. wall element with windows*
Component		*e.g. outer wall*
Group of parts	**Building Material** Level	*e.g. EWIS*
Separate parts		*e.g. cellulose insulation material*
Wrought or pre-product		*e.g. sheet metal*
(Building) Material		*e.g. steel or timber*

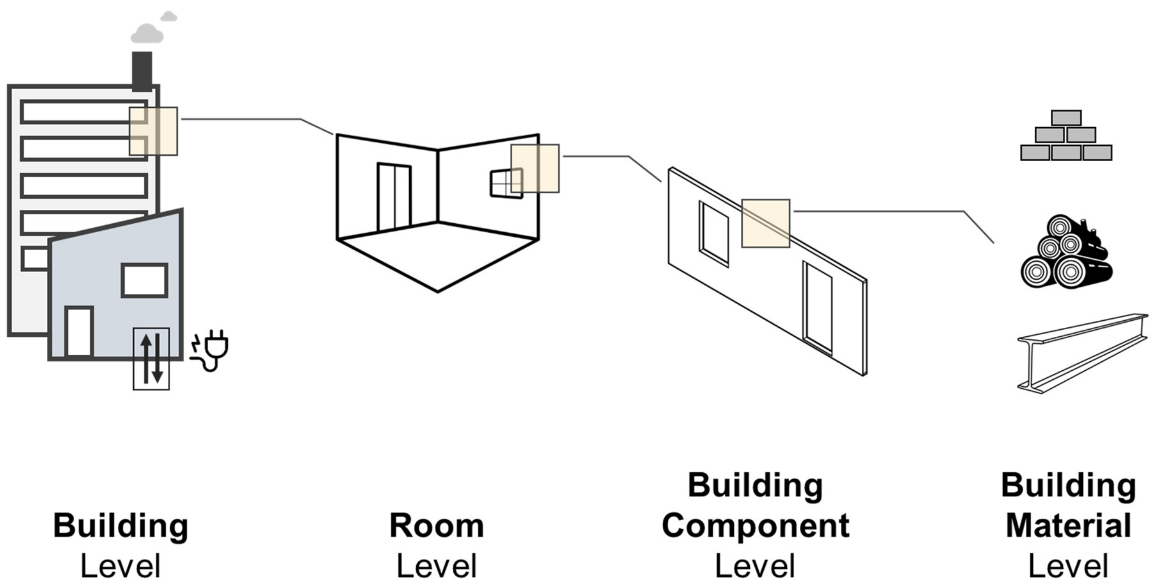


Figure 3-1: Illustration of the different levels of perspective[15]

The structure of DIN 276, which is the basis for determining the costs of services and technical products of a building, can be used to further differentiate the delimitation of **building components** of a building. Costs are structured in cost groups (CG; German: “Kostengruppe, KG”)

[15] Illustrations amongst own work is offered by The Noun Project and licensed by CC; artists: Batibull; Gan Koon Lay; mette galaxy

with CG 300 and CG 400 standing in for the building structure. Each CG can be further subdivided.

- CG 100 Property
- CG 200 Preparation and development
- CG 300 Building – Building construction
- CG 400 Building – Technical installations
- CG 500 Outdoor facilities
- CG 600 Equipment and works of art
- CG 700 Ancillary building costs
- CG 800 Financing

CG 300 includes the entire structural shell and finishing work of the building that is used in constructing the building. The structure of the various sub-products of the building is based on the position of its various components (inside and outside, roof, foundation) as well as the position of individual layers (cladding, covering, etc.) and takes into account fundamental functional differences (windows, doors, load transfer, sun protection, etc.).

With regard to materials science, building materials are classified as raw materials into abiotic (fossil, mineral and mineral ores) and biotic raw materials. Within this categorization fossil and biotic materials each offer the possibility for multipurpose-use. They can either be used as energy or as material (in the case of biotic raw materials also as foodstuffs) (BMUB, 2016, p.36).

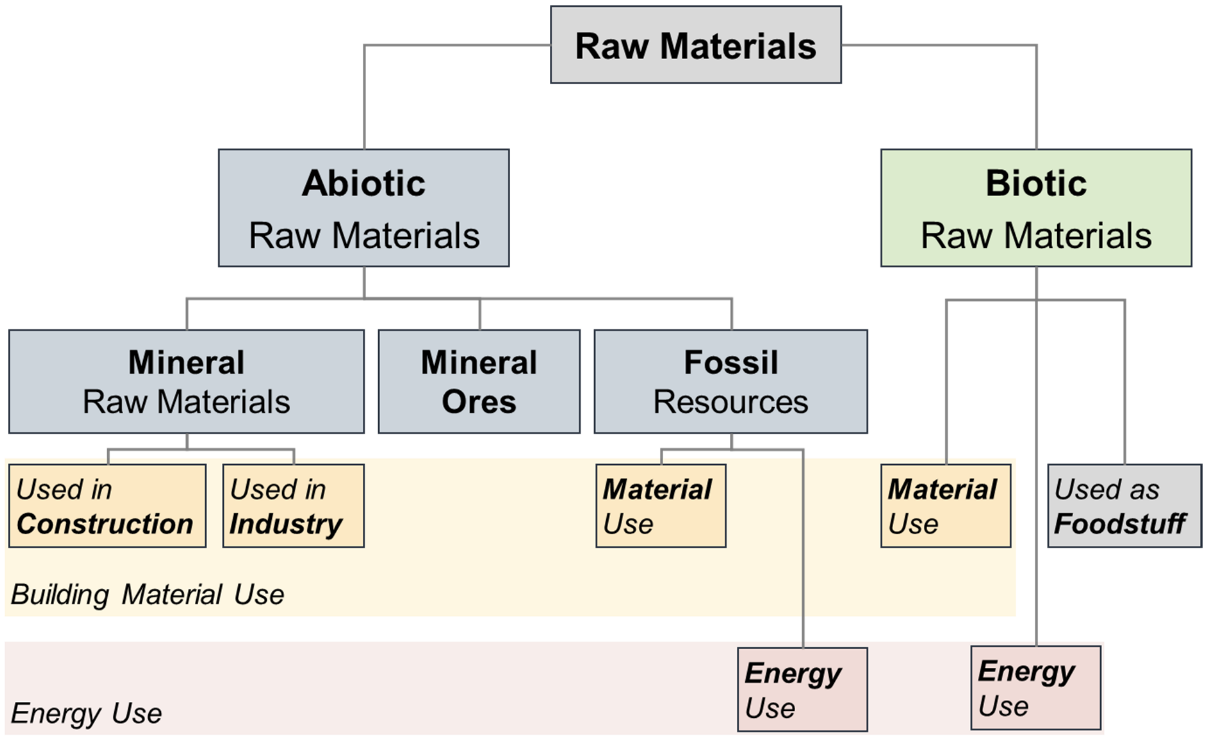


Figure 3-2: Illustration of the categorization of raw materials (BMUB, 2016, p.36)

For a more application-specific categorization of building materials, the structure of Deilmann et al (2017) is used, which is the basis for a material flow model of buildings. This categorization is consistent with the categorization of raw materials by the BMUB (2016). It includes the groups of parts and offers a sufficient level of differentiation.

Table 3-2: Classification of materials to groups of materials (Deilmann et al., 2017, p.18)

Group of parts / Products		*Separate parts, elements and building materials*
Abiotic Materials	Concrete	*e.g. concrete of all quality specifications C8/10 – C25/30, lightweight concrete, wood fibre concrete, concrete bricks*
	Red brick	*e.g. solid bricks, vertical coring brick, tiles*
	Calcium silicate brick	*e.g. calcium silicate brickwork*
	Aerated concrete block	*e.g. wall element with windows*
	Mineral Insulation Materials	*e.g. mineral wool, rock wool, closed cell cellular glass, expanded clay, blast furnace slag*
	Other mineral materials	*e.g. lime mortar, lime gypsum mortar, lime cement mortar, cement screed, lightweight concrete boards, fibre cement, slate, asbestos cement (boards), sand, crushed and loose gravel, adobe, natural stones (marble, basalt, granite etc.), ceramic tiles*
	Glass	*e.g. sheet glass, armoured glass, glass blocks*
	Gypsum board	*e.g. plasterboard, gypsum fibre board, gypsum fibre cement board*
	Other gypsum materials	*e.g. gypsum plaster and mortar, anhydrite screed*
	Metal (Mineral ores)	*e.g. steel, copper, aluminium, lead, brass, tin and others,*
	Synthetic insulation materials	*e.g. polystyrene hard foam (expanded EPS, extruded XPS), polyurethane (hard) foam (PU), phenolic resin (PF) rigid foam*
	Synthetic window / door profiles	*e.g. PVC window and door profiles*
	Synthetic roofing sheeting	*e.g. synthetic roofing membrane, PVC membrane, PE membrane*
Biotic Materials	Construction timber	*e.g. cross laminated timber (CLT), glue laminated timber, sawn timber etc.*
	Renewable insulation materials	*e.g. wood fibre, cellulose, hemp, straw, cork*
	Other wooden materials	*e.g. medium density board, oriented strand board (OSB), particleboard, plywood, hardboard, softboard, timber shingle etc.*

3.1.3 Categorising Construction as a Process

Behind the final product of the specific building structure lies a multitude of processes which create the ultimate product. In the following, these processes are gradually presented, summarized and structured for further application.

Staying inside the preceding definition of the building structure, the **process** of construction produces the **product** of construction. A multitude of problems need to be solved on the way to a suitable solution that fulfils the given goals of construction. This problem-solving process for technical systems can be generalized – from the abstract to the concrete – as described in VDI Guideline 2221 (1993). This general **process of developing and designing** technical systems and products comprises seven essential work stages:

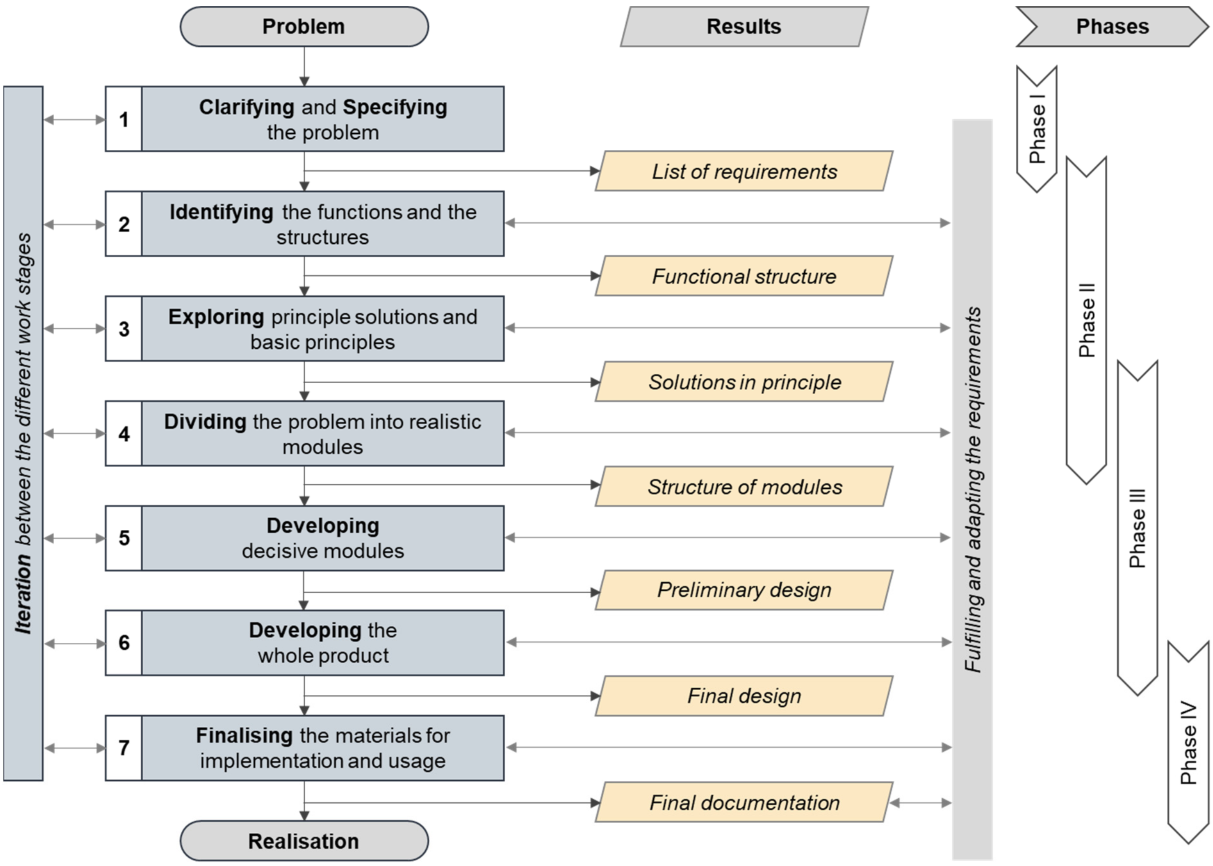


Figure 3-3: General procedure for development and design (VDI 2221, 1993)

This general development process can be condensed and adapted to different settings. In their work on construction theory, Pahl and Beitz (1997) describe the development and construction process in even more detail. Their approach was transferred to the **design process of building structures** by Moro et al (2019):

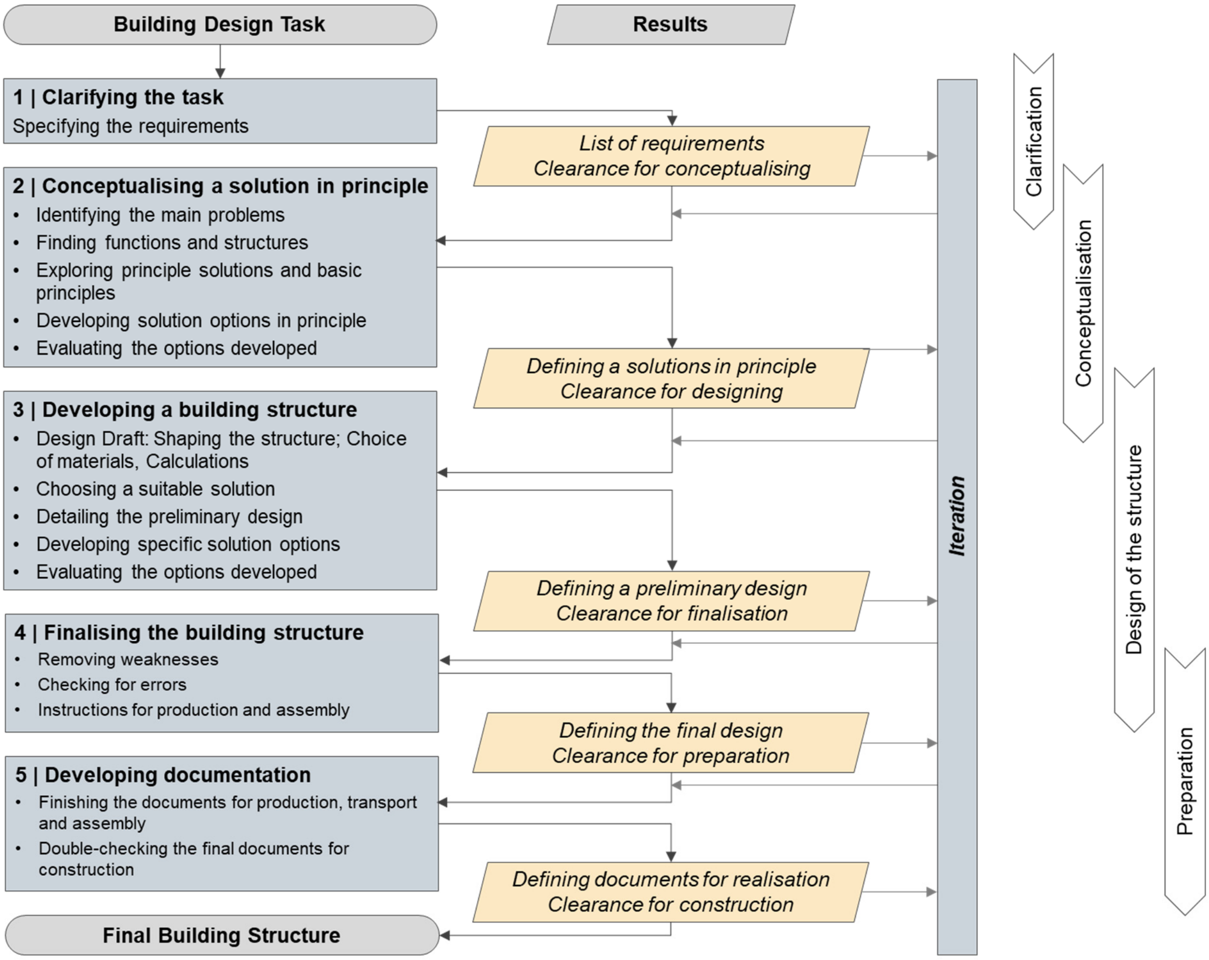


Figure 3-4: Illustration of the design process of buildings structures (Moro, 2019b, p.8; Pahl and Beitz, 1997)

The key changes are the translation of general modules and their products into the building structure as well as the additional step of clearance after each iteration and before proceeding to the next design step. The development of a building structure design is generally called ‘planning’ and is predominantly theoretical, trying to anticipate real results with models of thought, simulations and real models.

In addition to planning the realisation of the building as a product, the different stages the product experiences itself are summarily called the **lifecycle of a building**. These processes are illustrated by considering individual stages of the building in its lifecycle according to the method of lifecycle assessment (DIN EN 15978, 2012):

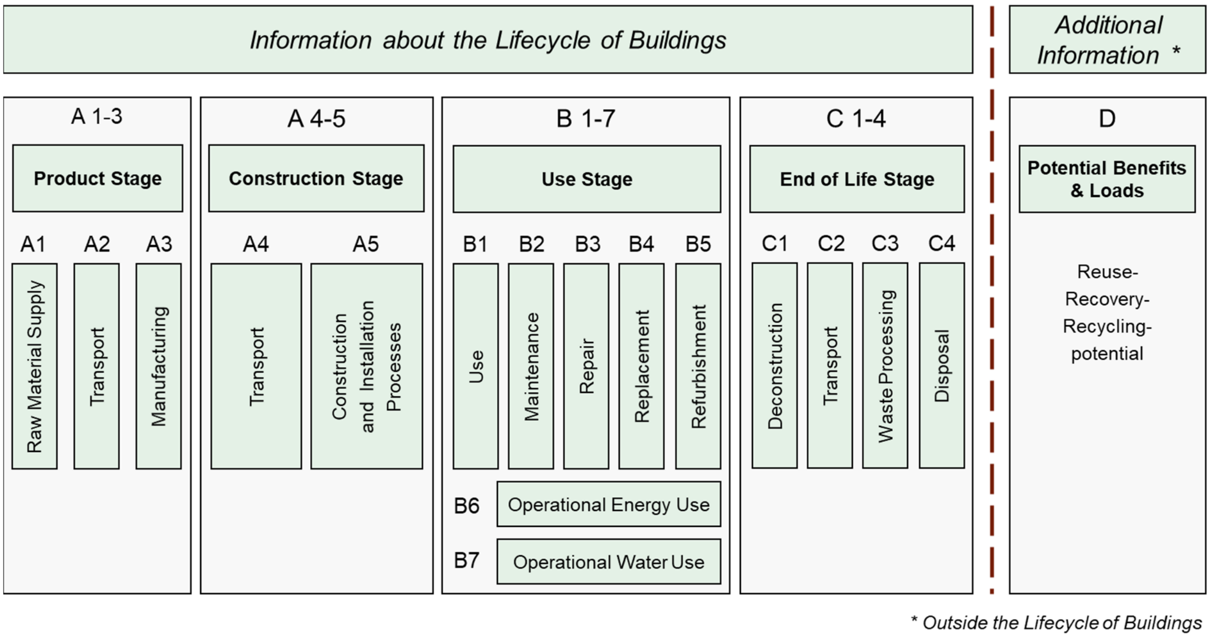


Figure 3-5: Categorisation of the lifecycle stages according to DIN EN 15978 (2012)

Since all processes are also associated with costs, a cost structure can be used in analogy to the structure of the product 'building'. The HOAI (German: “Honorarordnung für Architekten und Ingenieure” English: Cost Structure for Architects and Engineers) describes nine essential service phases (SPH; German: “Leistungsphasen, LPH”):

1. SPH 1 | Basic Evaluation
2. SPH 2 | Pre-Planning
3. SPH 3 | Draft Planning
4. SPH 4 | Approval Planning
5. SPH 5 | Execution Planning
6. SPH 6 | Preparation of the contract awarding
7. SPH 7 | Participation in the contract awarding
8. SPH 8 | Project Monitoring
9. SPH 9 | Property Supervision/Support

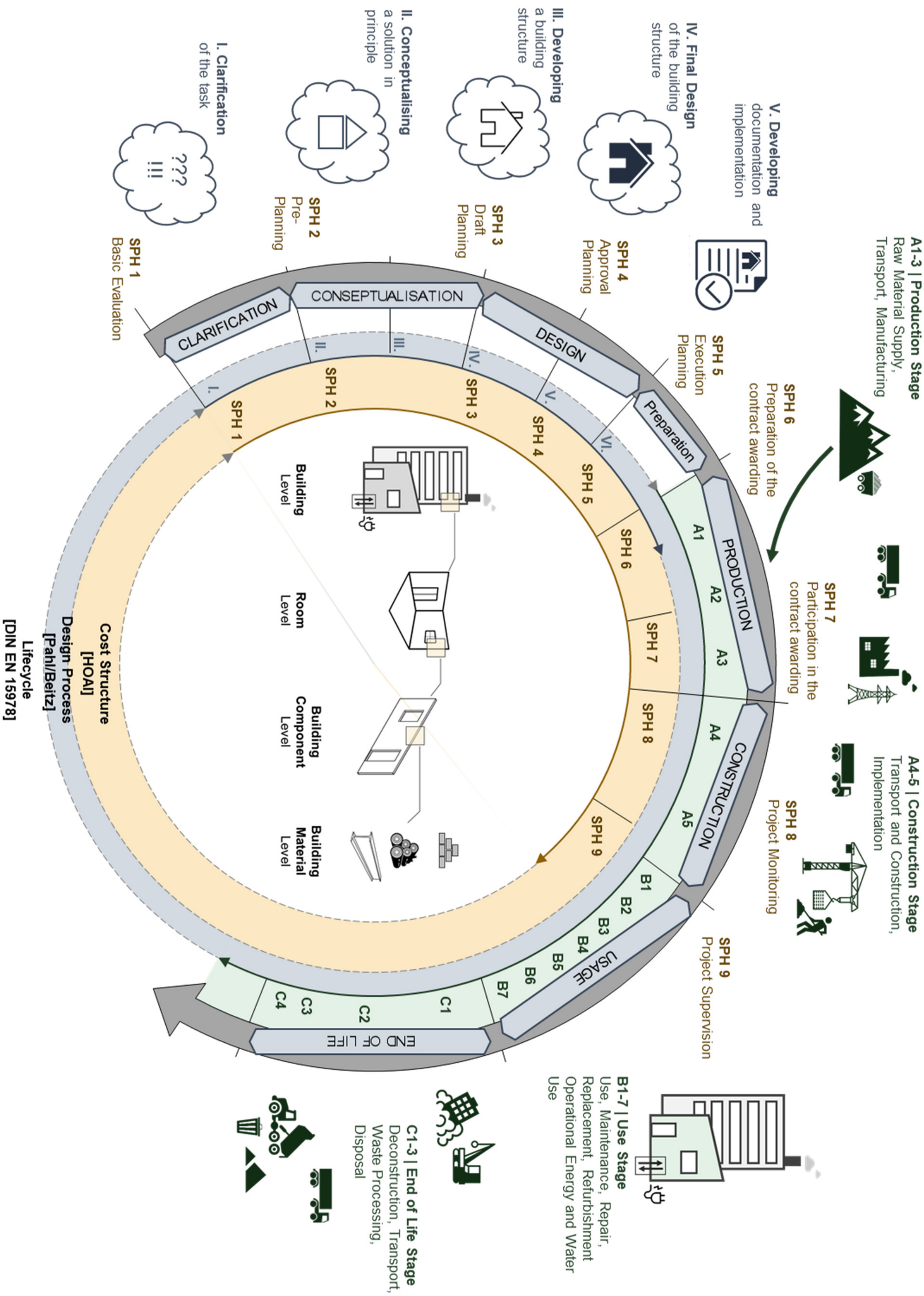


Figure 3-6: Cumulative structural order of all processes of a building

3.1.4 Categorising Construction After Its Functions

The sum of all functions of a building does not automatically reflect the intended goals that lie behind the activities of the actors involved. According to the definition of buildings (see chapter 3.1.1), these goals or objectives are modelled after the fundamental needs of humans and society without limiting or harming humans and the environment in the long term, while at the same time creating economic value. The ordering structure of individual objectives is therefore chosen according to their **underlying values**, derived from human needs and supplemented with the values of technical action (VDI 3780, 2000). The following Table 3-3 compares the list of human needs according to Max-Neef (see Table 2-1) with the technical value octagon according to the VDI Guideline 3780 (see Figure 2-1)[16].

Table 3-3: Comparison of human needs and values in technical action

<table>
<tr><th></th><th>Human Needs according to Max-Neef (1991)</th><th>Values in technical action according to VDI 3780 (2000)</th></tr>
<tr><td rowspan="2">Existence</td><td rowspan="2">Subsistence</td><td>Health</td></tr>
<tr><td rowspan="2">Safety</td></tr>
<tr><td>Safety</td><td>Protection</td></tr>
<tr><td rowspan="2">Relationship</td><td>Affection</td><td>-</td></tr>
<tr><td rowspan="2">Participation</td><td>Societal Quality</td></tr>
<tr><td rowspan="2">Effectiveness</td><td rowspan="3">Functionality</td></tr>
<tr><td>Understanding</td></tr>
<tr><td>Recreation</td><td>Idleness</td></tr>
<tr><td rowspan="2">Development</td><td>Creation</td><td rowspan="3">Personality Development</td></tr>
<tr><td>Identity</td></tr>
<tr><td>Autonomy</td><td>Freedom</td></tr>
<tr><td rowspan="2">Economy</td><td>-</td><td>Prosperity (macroeconomics)</td></tr>
<tr><td>-</td><td>Economy (microeconomics)</td></tr>
<tr><td>Ecology</td><td>-</td><td>Environmental Quality</td></tr>
</table>

In the above table multiple mentions of the same values were avoided as much as possible, since there is often a degree of interdependence between values – as mentioned in the VDI Octagon (VDI 3780, 2000). For example, environmental quality is seen as a value of its own, even though it also impacts areas like health, safety and others. In engineering, the value of functionality usually takes preference. Yet functionality and economy are not pursued for their

[16] An in-depth discussion on the compatibility of the values of technical action (according to VDI 3780) with the guiding values of sustainable development and the needs of mankind is conducted in the dissertation by A. Hermelink (2007)

own sake, but serve human development as a whole, where they can cause both positive as well as negative effects. Regarding the value of equilibrium, it is therefore necessary to counterbalance these values in order to identify and discuss the desired benefits as well as negative effects and potential conflicts of any given objective (VDI 3780, 2000, p.12 ff).

The goal of construction is to secure and improve the general value of human liveability through the development and sensible application of technical means (VDI 3780, 2000). Keeping human liveability in mind, three basic principles can be derived regarding the goals and requirements for buildings, which, as it turns out, were already formulated by the Roman building master Vitruvius in his "De Architectura Libri decem" (Ten Books on Architecture), the oldest documented work on architecture:

1. ‘firmitas’ [latin]: firmness, strength, steadfastness, endurance
2. ‘utilitas’ [latin]: usability, suitability, usefulness
3. ‘venustas’ [latin]: beauty, elegance, charm

The Council Directive on Construction Products of 1988 elaborates on these basic principles of construction. Building structures must be fit for their intended purpose, particularly in regard to the health and safety of persons involved throughout the life cycle of the object. Structures must fulfil these **basic requirements** for construction works under normal maintenance conditions for an economically reasonable period of time (CPD 89/106/EEC, 1988). In addition to Vitruvius' three principles, further elementary requirements for buildings are differentiated (CPD 89/106/EEC, 1988, ANNEX I):

1. **Mechanical resistance** and **stability**
   e.g. avoiding collapse, major deformation and general damage through stability, usability and robustness
2. **Safety in case of fire**
   e.g. load-bearing capacity in the event of fire; limiting the generation and spread of fire; escape and rescue; safety of rescue teams
3. **Hygiene**, **health** and the **environment**
   e.g. control/prevention of emissions of toxic gases, dangerous substances, greenhouse gases, dangerous radiation; protection against pollution of water and soil; control of moisture in and on the surfaces of the building
4. **Safety in use**
   e.g. prevention of hazards due to accidents and burglaries
5. **Protection against noise**
   e.g. no noise level that is hazardous to health; guarantee satisfactory night-time rest, leisure and working conditions
6. **Energy economy** and **heat retention**
   e.g. low energy consumption for heating, cooling, lighting and ventilation

In 2011, the Construction Products Directive (CPD) was replaced by the Construction Products Regulation (CPR). Its basic requirements were supplemented by **one further aspect;** some individual sub-items were slightly modified as well, as shown below (CPR 305/2011, 2011, ANNEX I):

1. ... (identical with CPD)
2. ... (identical with CPD)
3. ... (identical with CPD)
4. **Safety** and **accessibility during use**
   additionally: ensuring accessibility for disabled persons
5. ... (identical with CPD)
6. **Energy economy** and **heat retention**
   additionally: energy-efficiency during erection and dismantling
7. **Sustainable use of natural resources**
   e.g. reusability or recyclability of the construction/building materials; durability; use of environmentally compatible raw materials and secondary building materials

The technical literature often classifies these requirements and functions of buildings according to the product "building", i.e. its structural framework, building envelope and supply/disposal. From this perspective, describing the functions of a building serves the implementation and achievement of its given goals and requirements. Combining specific functions with their respective basic functions results in a large number of sub-functions and sub-goals that a building should fulfil (CPR 305/2011, 2011, Appendix 1; Moro, 2019b, p.475; Hegger et al., 2012, p.83):

Table 3-4: Essential functions of buildings

Basic Function	Specific Function
Load Bearing	Load bearing capacity Usability and serviceability Durability
Envelope	Fire Safety Protection against water (precipitation) Protection against moisture Protection against wind Thermal conditioning in summer and winter Air supply / natural ventilation Supply of daylight Protection of privacy and against dazzling / sunlight Noise and acoustic protection Acoustic conditioning Protection of health Protection against accidents and invasion Protection against harmful radiation and voltage
Supply & Disposal	Heat energy supply Dissipation of excess thermal energy (Cooling) Air supply / technical ventilation Fresh water supply and waste water disposal

	Electricity supply Artificial lightning

These basic requirements are supplemented by criteria and additional requirements that are set out in the sustainability analysis by certification systems. In Germany, the DGNB[17] covers the private sector, while the federal government's BNB[18] system covers all federal buildings. Rating and certification systems have been developed since 1990, and since 2008 the BNB and DGNB system has been the second generation of these systems, which attempt to take a holistic view of aspects of sustainability that have not been taken into account to date (Ebert et al., 2011, p.6 ff). The aim of the certification systems is to implement a holistic quality and to define the requirements for "sustainable" buildings (DGNB, 2018, 2020; BMI, 2018):

Table 3-5: Summary of the criteria of the BNB and DGNB certification systems

Criteria Category	Specific Criteria
Environmental quality	Building life cycle assessment Local environmental impact Sustainable resource extraction Potable water demand and waste water volume Land use Biodiversity at the site
Economic quality	Life cycle cost Flexibility and adaptability Commercial viability Spatial efficiency
Sociocultural and functional quality	Thermal comfort Indoor air quality Acoustic comfort Visual comfort User control Quality of indoor and outdoor spaces Safety and security Accessibility in general and for disabled persons Integration of art Design for all
Technical quality	Sound insulation Quality of the building envelope Use and integration of building technology

[17] German: Deutsche Gesellschaft für Nachhaltiges Bauen (English: German Sustainable Building Council)
[18] German: Bewertungssystem Nachhaltiges Bauen (English: Rating System Sustainable Buildings)

	Ease of cleaning building components Ease of recovery and recycling Immissions control (noise/light) Mobility infrastructure Resistance to natural hazards Ease of operation and maintenance of the TGA
Process quality	Comprehensive project brief Sustainability aspects in tender phase Documentation for sustainable management Urban planning and design procedure Integral planning Complexity and optimisation of planning Construction site/construction process Quality assurance of the construction Systematic commissioning User communication FM-compliant planning
Site quality	Local environment Influence on the district Transport access Access to amenities Relevant media / development

Summarizing all functions and requirements, a list of goals of the building industry at the current point of time can be created. This compilation of objectives should not to be understood as comprehensive or even completed, since it describes an alternating state which can be supplemented by subjective objectives. For the purpose of differentiation and comprehensibility, a clear description of values and objectives of the desired state is also required, which will be discussed in the subsequent chapter.

Comparing the mentioned requirements with the criteria of function, it becomes obvious how difficult it is to denote a categorical distinction between them. Not all requirements can be attributed precisely to a corresponding function of a structure and its parts. Some cases also have requirements for the effects and impacts the life cycle of a building has. A purely functional structure is therefore not sufficient. A preferable structure orients itself after values and goals. So, with the help of the order structure of values of technical action, the objectives of the building industry can be clearly structured and subdivided as follows:

Table 3-6: Overview of the goals of construction, ordered by the values of technical action

A	**Functionality**
A.1	Usability and serviceability
A.2	Durability and avoiding damage (technical perfection)
A.3	Hygrothermal conditioning of the interior
A.4	Acoustic conditioning of the interior
A.5	Visual conditioning of the interior
A.6	Air conditioning of the interior
A.7	Architectural design of the interior (geometry)
A.8	Supply with necessary operating resources (heat, electricity, water, etc.)
B	**Safety**
B.1	Structural Safety
B.2	Safety in case of fire
B.3	Safety in use
B.4	Prevention of accidents
C	**Health**
C.1	Protection against harmful substances
C.2	Protection against physiological harm due to visual effects
C.3	Protection against radiation and voltage
D	**Environmental Quality**
D.1	Minimising environmental impact
D.2	Economic use of natural resources
D.3	Economic use and protection of land resources
D.4	Economic use and protection of water resources
D.5	Protection and preservation of biodiversity
E	**Economic Quality**
E.1	Economic use of financial resources
E.2	Ensuring profitability
E.3	Long-term value retention of the building
F	**Prosperity**
F.1	Meeting the needs of society
F.2	Political economic benefit
F.3	Participation and equity of needs and performance
G	**Personality Development & Societal Quality**
G.1	Flexibility in the use & adaptability of the building
G.2	Influence and involvement (participation) of users
G.3	Cultural contribution and social acceptance of the building

3.1.5 General Goals of Building Construction

In order to show the holistic nature of goals and values that shape and influence building construction in many different ways, an overview of those goals is necessary. The approach towards this overview is structured along a list of values while briefly outlining the essential objective in each case. As the following is intended as an overview, it does not and cannot claim to be complete.

The value of **functionality** (A) describes the goal of making a building suitable for the intended purpose without any restrictions. This includes different geometrical, climatic, design and supply factors. The following aspects serve as sub-values of functionality:

- Usability
- Perfection and reliability
- Feasibility
- Effectiveness
- Technical efficiency

A.1 | The goal of structural **serviceability** includes the appearance, the well-being of the user and the proper functioning of the structure or component in relation to (DIN EN 1990, 2010, p.27 ff):

- Deformations
- Postponements
- Vibrations or
- Other damage (cracks, tightness)

Generally, *Usability* is the sub-value behind the goal of structural serviceability.

A.2 | In the context of functionality, sufficient **durability** plays a central role, adding a temporal aspect. Durability describes the avoidance of damage of any kind, of loss of function and – in the context of wear – loss of strength, in order to ensure the longest possible use. Accordingly, the most effective durability becomes synonymous with the maximum possible service life. The objective claims that buildings must be arranged, equipped and usable in a way that water, moisture, plant and animal pests and other chemical, physical or biological influences do not create hazards or unacceptable nuisance (MBO, 2016, §13). Current standards therefore define a minimum level of thermal insulation and moisture protection. On the side of technical service life, outcomes depend on a large number of parameters, such as the quality of materials and components as well as planning and execution, on environmental and usage influences (weather, maintenance, care) and, last but not least, maintenance and servicing.

However, actual service life can also be shortened for other reasons. If the whole or parts of the building become obsolete this is called obsolescence. Obsolescence can be traced back to various causes and significantly influences durability (König et al., 2010, p.31 ff):

- Technical obsolescence
- Functional obsolescence

- Physical obsolescence
- Legal obsolescence
- Economic obsolescence
- Formal obsolescence

Behind the goal of durability lie the sub-values of *perfection and reliability*.

A.3 | Coming back to the sub-value of usability, buildings must have thermal insulation, and their interior must be thermally conditioned according to its use and climatic conditions (MBO, 2016, §15). However, due to physical relations, principles of heat and humidity cannot be considered in isolation. Therefore, **hygrothermal interior conditioning** describes the functional goal of creating a humidity-related as well as thermally stable indoor climate sufficient for use, as well as preventing climate-related damage to human beings, animals and goods in relation to outdoor climate fluctuations. In a definition by Alexander von Humboldt that still holds up today[19], climate is vividly defined as all changes in the atmosphere that noticeably affect our organs (Humboldt, 1832). In warm and hot climates as well as during winter or summer months, the interior must be especially protected against either cooling or overheating. This includes a minimum level of health protection in regards to hypothermia as well as a maximum in regards to overheating. Essential functions of hygrothermal conditioning are:

- Heat and temperature conditioning (transmission, radiation, convection)
    - Control of transmission heat losses and gains
    - Temperature regulation of inner surfaces, enclosing surfaces and air
    - Thermal radiation (irradiation and radiation exchange)
    - Convection control (wind protection, air speed, air exchange)
- Moisture and humidity conditioning (precipitation, steam balance)
    - Protection from moisture ([driving] rain, snow, ground water, ice)
    - Regulation of relative room humidity
    - Moisture accumulation control

Since human beings are usually the centre of attention in regards to the use of buildings, the level of comfort of its users plays a significant role. Feelings of comfort differ between people, cultures, climatic regions and corresponding habits (Nicol and Humphreys, 2002, p.571). The hygrothermal conditioning of the interior is in thermoregulatory exchange with the human body, which is why, on an individual level, feelings of comfort are perceived differently and subjectively as well as being influenced by body surface and body temperature, activity levels, duration of stay and personal clothing (Klein and Schlenger, 2017, p.11; Häupl et al., 2017, p.363 ff).

A.4 | The goal of **acoustic conditioning of the interior** supplements the aspect of user comfort, adding acoustic sensations to the already established thermal sensations.

[19] As being demonstrated by the use in current specialized literature like Häupl et al. (2017, p.295).

> *"The construction works must be designed and built in such a way that noise perceived by the occupants or people nearby is kept to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions." (CPR 305/2011, 2011, ANNEX I-5).*

Describing the goal of optimal acoustic comfort comprehensively is difficult. Acoustic discomfort on the other hand can be easily defined by "noise" (both permanent and short-lasting noise events associated with a high sound level) (Hausladen and Tichelmann, 2010, p.40). Achieving optimal acoustic comfort therefore already includes a level of noise protection which guarantees aural health through its basic functional conditioning as well as good hearing conditions. The goal is to ensure appropriate room acoustics by excluding unacceptable acoustic disturbances, increasing concentration and performance, and satisfying the need for ease and confidentiality. Sound describes an energetic pressure fluctuation in a medium (e.g. air), meaning a transmission in the form of pressure waves from the sound source to the receiver. The aim of sound insulation is to keep the sound pressure level on the receiver as low as possible. The sound level difference between source and receiver is determined by the state parameters of room size and separating and flanking components. Since sound levels can vary depending on source strength and size of the receiving room, this imposes requirements on noise insulation. Standards demand a limited sound transmission of different sound sources and are codified in the *building sound reduction index*, the *standard impact sound level* and a maximum *standard sound pressure level* (DIN 4109-1, 2016, p.29).

A.5 | Successful **visual conditioning of the interior** aims at complete visual perception and comfort in regard to its intended use (Hausladen and Tichelmann, 2010, p.46). This includes a sufficient supply of natural daylight and artificial light (illuminance, luminance distribution) while simultaneously avoiding glare and excessive contrasts. Additionally, there should be sufficient visual contact with the outside area (DIN 5034-1, 2011, p.8 ff). This objective also follows the principle of usability of a building, while light can also have an effect on the mental and physical health of people (for this, see C.2).

A.6 | Indoor air quality contributes significantly to the performance and concentration of its users. Suitable **air conditioning of the interior** therefore aims at a healthy and comfortable level of indoor air quality for its users. Low emissions (VOC), avoiding of unpleasant smells, humidity regulation and CO2 concentration in the air increase the well-being, performance and satisfaction of users (DIN 1946-6, 2009, p.25), which can also have an effect on their health (see C.1). Even though the many effects and interrelationships between air quality and users have not yet been fully clarified, low-emission materials and construction as well as a sufficient supply of "fresh" air play an essential role.

A.7 | The focus of **architectural design of the interior** is the human being as a user and creator of criteria for the usefulness of spaces. With their physical and psychological possibilities but also their limitations, users form the central reference system for planning spatial environments and situations (Jocher and Loch, 2012, p.7). The geometry of rooms serves to enable certain functions like living, working, learning and others. This includes for example barrier-free use in public buildings or private cases where this is necessary (residential buildings, senior citizens' housing). This goal doesn't offer itself to standard solutions, therefore an individual comparison between defined or desired functions and specific solutions is always necessary.

A.8 | The **supply of necessary operating resources** includes the supply of potable water, the energy supply for heating, ventilation, cooling and hot water preparation, the operation of high and low-voltage systems as well as the drainage of buildings and the disposal of household waste (Laasch and Laasch, 2013, Preface). In the context of drinking water supply, the provision of drinking water without impairing hygiene (legionella growth) stands out. The aim of drainage is to drain off waste water and avoid the formation of odours. Energy supply aims at actively supplementing the hygrothermal conditioning (see A.3) if the passive structural measures are not sufficient, either by heating or cooling and supplemented by the provision of hot water. Also indispensable in contemporary buildings is the supply of sufficient electrical power (electricity). The goal is to achieve sufficient supply with a minimum of technology and energy expenses. Accordingly, passive systems, high efficiencies and existing possibilities and infrastructures are preferred.

The value of **safety** (B) includes the permanent guarantee of the physical integrity of those involved in construction as well as the users and the objective of minimizing general risk. Safety always includes an aspect of uncertainty and risk. Risk describes the combination of the probable occurrence of various effects with the aftermath of those effects, and balancing risk can be a challenging moral dilemma. This is why a social and therefore politically determined security level is often defined, which is then maintained and achieved by means of general technical rules. Accordingly, statistical and empirical studies or probability analyses are usually the backbone of the following safety aspects:

- Risk of damage
- Risk of failure
- Operating risk
- Economic risk (see values E and F)

B.1 | The goal of **adequate structural safety** describes the safety of people and structure in particular (DIN EN 1990, 2010, p.27). In a nutshell – structural stability: Every structural system must be stable as a whole and consist of individual parts that are stable on their own (MBO, 2016, §12). This includes the protection of people, animals and property from structural failure due to loss of position, component failure or fatigue. This reliability goal is achieved by planning and executing a supporting structure that can withstand all possible impacts and influences during construction and use. These impacts and influences consist of environmental influences (snow, wind, and earthquake), use, possible fire, explosion, impact or human error. Adequate reliability is outlined in the Eurocodes 1 to 9 series of standards and uses the semi-probabilistic safety concept (5% and 95% quantiles) (DIN EN 1990, 2010, p.22; p.32).

The load-bearing function is the sum of strength, stability and stiffness and accordingly avoids mechanical failure, loss of stability (sliding and tilting) as well as excessive deformation that affects serviceability (cf. A.1) (Knaack and Meijs, 2012, p.13).

B.2 | Safety in case of fire comprises the essential protection goals according to the Model Building Regulations (MBO, 2016, §14):

- Fire prevention or avoidance with regard to
  - formation of fire and smoke
  - spread of fire and smoke
- Escape (rescue of people and animals)
- Firefighting (rescue and extinguishing)

These goals are achieved by structural and technical *preventive* fire protection measures as well as *defensive* fire protection measures (fire brigade), which are divided into a multitude of different requirements and aspects and can also mutually compensate each other.

B.3 | Safety in use addresses risk of burglary and assault. Excluding extraordinary events like war or terrorist attacks, the most serious threats (next to fire) a building structure is exposed to are burglary and intrusion of privacy (Hebgen, 1980, p.106). The law does not prescribe universal protective requirements; these are therefore primarily promoted by insurance companies. However, protection and security of residents against burglary do not only concern material damage, but also immaterial damage (e.g. memories, pictures etc.) or psychological consequences for the residents. Occasionally, security against or prevention of breakouts may also be necessary (e.g. prisons).

B.4 | The **prevention of accidents** seeks to effectively obviate the risk of work accidents and to compensate for failures (e.g. of the energy supply). There are two main protection goals (except for environmental protection, see D.1-5) concerning manufacture, construction and disposal of a building (VDI 6010 Blatt 1, 2019, p.5 ff):

- Personal protection – right to life and physical integrity. Hazards may arise with regard to (GDA, 2013):
  - Danger of crashing
  - Danger of sinking / spilling
  - Danger from objects (working with explosives, elements with high dead weight, machines)
  - Danger from hazardous substances (chemical or biological agents, voltage and radiation or others)
- Property protection (e.g. protection of cultural assets)

The value of **health** (C) describes all goals of protection against negative influences on the physiological and psychological well-being of users and all those involved in the building construction and maintenance. The transition between the values of health, safety (B), environmental quality (D) and functionality (A) can be fluid. Aspects that are hazardous to health always impair functionality too, just as safety-critical aspects can threaten health. Concerning toxicity, substances toxic to humans often show also ecotoxic effects and are sometimes treated together. Therefore, listed below are only those objectives that focus on human health, are directly influenced by buildings and are not already covered by other objectives of functionality, environmental quality or safety (WHO, 2014, p.64), leading to the exclusion of the following objectives:

- *Environmental noise* – covered by room acoustic conditioning of recreational areas (see A.4)
- *Hypothermia or overheating* – covered by hygrothermal conditioning of the interior (see A.5)
- *Accidents* – covered by the objectives of safety in use and in case of fire (see B.2-4)

C.1 | Due to the long residence times of users, the quality of building materials used as well indoor air composition are highly relevant for the health of the users when designing cubature. The goal to **protect** people and users **against harmful substances** comprises the avoidance and minimization of releasing substances that are harmful to the human organism, toxic to reproduction (embryotoxic, teratogenic), mutagenic or carcinogenic. Furthermore, substances can be (very) persistent and (very) bioaccumulative. These substances, which are often toxic to humans, can be absorbed via respiration (inhalation), through skin contact, mucous membranes (dermal absorption) or via food (oral absorption). Critical pollutants are differentiated into (Ece, 2018, p.27 ff):

- VVOC – Very Volatile Organic Compounds (solvents)
- VOC – Volatile Organic Compounds (solvents, formaldehyde, isocyanates)
- SVOC – Semi Volatile Organic Compounds (pesticides, flame retardants, plasticizers, PAH, PCB)
- MVOC – Microbial Volatile Organic Compounds (bacteria, mould and yeast fungi)
- POM – Particulate Organic Matter (fibres, fine dust, particles, allergens)
- Radon (radioactive gas)
- Heavy metals (metals, metal salts, metal oxides)
- Harmful gases (irritant and sticky gases)

In order to avoid and minimise these substances, different levels regarding limit, guide and orientation/reference values have been issued. *Limit values* are usually legally binding, since exceeding them poses health risks. These are derived from hygienic-toxicological criteria. *Guide values* are derived from the same criteria but have a recommendatory character and are published by authorities, experts and specialist committees. In cases where neither limit values nor guide values are available, *reference values* from measurements and studies provide orientation (Bachmann and Lange, 2013, p.18 ff).

C.2 | The **effects of light** on the human organism through visual perception and processing in the brain plays an essential role in human health. The light-dark change in nature and the 24-hour rhythm of the day and night cycle as well as the wavelength, colour and intensity of light play an essential role in the vital function of the body and have visually induced physiological effects. The effects manifest themselves in form of winter depression, concentration difficulties or sleep disorders (Hausladen and Tichelmann, 2010, p.40 ff). The optimal physiological effects on the human body are caused by natural sunlight. It is therefore important to create the maximum possible supply of unadulterated daylight as well as connections to outside spaces.

Artificial lighting complements natural daylight in case of absence or shortage. Irritations and negative effects on the user due to insufficient light quality (colour rendering index, illuminance, light colour) must be avoided, both with regard to the transparent components and especially with artificial lighting (Häupl et al., 2017, p.567 ff).

C.3 | Humans are constantly exposed to the natural biological radiation climate. Parallel to the constantly increasing technologization of society, the human organism is exposed to increasing radiation exposure. This goal therefore describes a sufficient **protection against radiation and voltage** and refers to electric, magnetic and electromagnetic fields according to (Ece, 2018, p.24 ff):

- Low-frequency electric fields (by electric alternating voltage)
- Low-frequency magnetic fields (by alternating electric current)
- High-frequency radio waves (by transmitters: mobile radio, broadcasting, DECT, WLAN)
- Electrostatics (through direct voltage: screens, synthetics)
- Magnetostatics (through direct current: photovoltaics, also on metals)

The value of **environmental quality** (D) requires buildings to not negatively influence the environment in terms of functionality and regeneration ability due to the use of natural resources (availability, use, waste) and due to the effects of this use. Natural resources include (BMUB, 2016; VDI 4800, 2016, p.14):

- Raw materials (abiotic and biotic) for material and energetic use
- Land and area
- Biodiversity
- Water
- Air

Waste and landfills that reduce the quality of the environment are divided into different categories:

- Emissions (gaseous waste)
- Deposits and waste (material waste)
- Impurities (liquid waste)

D.1 | The goal of **minimising environmental impact** seeks to create less emissions or at least not more than are compatible with the regeneration abilities of ecosystems. Historically, this topic only came into focus when the effects of emissions and depositions started to affect humans significantly. It first began in the late 19th century, when an increase in lung diseases caused by soot in large European urban areas like London and the Ruhr area was noticed, caused by heating with coal instead of wood. Today we are aware that humans have a decisive influence on the ecosystems they are themselves part of, which in turn has impacts on humans. The aim is to record the contributions a building makes to the cause and spread of emissions that are responsible for ecological problems during its lifetime – above all the currently most urgent problem, Climate Change. The prevailing problems regarding emissions and deposits include (Bundesregierung, 2002):

- "Climate Change" – Global Warming
- "Acid rain" – Acidification of soil and water
- "Eutrophication" – Overfertilisation or enrichment of bodies of water with minerals and nutrients
- "Summer smog" – Photochemical ozone formation
- "Ozone hole" – Stratospheric ozone depletion
- “Resource depletion” – Scarcity of abiotic resources (fossil fuels and materials)
- "Environmental toxins" – Releasing toxins into the environment

D.2 | Analogous to economics (cf. E.1), the principle of rationality also applies to environmental aspects, aiming at an **economic use of raw materials**. This requires a sustainable use of raw materials in terms of both material and energy. It includes raw materials for material use, which can be subdivided into (BMUB, 2016, p.36):

- Mineral Ores (metals)
- Mineral raw materials
- Biotic raw materials (material use)
- Fossil resources (material use)

On the other hand, this goal also refers to fuels and energy sources:

- Biotic raw materials (energy use) – renewable energy
- Fossil resources (energy use) – non-renewable energy

The goal of sustainable use is based on the temporally and spatially limited availability of these raw materials, which as of now is limited to the planet Earth. It should be noted that all raw materials regenerate – even fossil resources –, but due to serious differences in regeneration cycles when comparing certain resources to the human generation scale, the distinction between renewable resources and non-renewable resources remains.

D.3 | Land areas represent valuable resources, their individual value determined by different demands for use. Depending on location parameters, an area can be used for example as a building site, a forest, an acre, a nature reserve, etc. (VDI 4800, 2016, p.8). Use of land resources includes areas for settlement, transport and recreation, as well as areas for raw materials, agriculture and forestry (BBodSchG, 1998, §2). The **economic use and protection of land resources** describes the goal of protecting the limited available areas of land from increased use for construction purposes and the associated soil sealing. In addition, the functions of soil resources are to be secured and harmful soil changes avoided (BBodSchG, 1998, §1).

D.4 | Drinking water is essential for the human organism. Humans use and pollute fresh water in many different ways (Hoekstra et al., 2011, p.1 ff). In the given context, the goal of **economic**

use and protection of water resources also applies to the lifecycle of building structures, including consumption of fresh water, water use and pollution throughout the entire life cycle of the building (VDI 4800, 2016, p.7).

D.5 | The goal of **protection and preservation of biodiversity** can be summarized into the protection of biotic (living) matter. This implies both a global as well as a local perspective. The built environment has a significant impact on local biodiversity, production and manufacture of building materials an analogous impact on global biodiversity. The protection of biological diversity of ecosystems includes the following aspects (BMUB, 2007, p.6):

- *Protection* of habitats and the protection of wildlife, plants, fungi and microorganisms
- *Sustainable use* of wild and farmed species and their genetic diversity
- *Access* to the world's genetic resources, the fair and equitable sharing of benefits arising from the use of these genetic resources and, in particular, improved development opportunities for economically poorer but biodiversity-rich countries.

In addition to the preservation of biodiversity, the protection of ecosystems against destruction by human action (e.g. deforestation), ecotoxic substances or landfills is also important.

The value of **economy** (E) can relate to microeconomic or macroeconomic aspects. With a microeconomic focus, buildings serve the goal of providing maximum benefit to all involved parties (including users) at minimum economic cost (cost efficiency or economic viability). This also includes the goals of profitability, self-preservation of the participating companies and economic growth.

E.1 | The goal of an **economic use of financial resources** no longer only includes production costs, but refers to the total life cycle costs of the building in the narrower sense (pure costs). If cost considerations are applied to the entire life cycle, the goal of cost planning and cost control can be defined as the optimization of the ratio of investment and follow-up costs to maintenance, the desired standard and the required quality (Kochendörfer et al., 2018, p. 191). In this way, the economic principle of rationality is pursued in terms of cost efficiency, trying to achieve maximum benefit from the use of economic resources. Alternatively, life cycle costs can also be considered in a broader sense, i.e. the capital value of the building in the form of the highest (discounted) revenue of the building minus the (discounted) costs incurred over the life cycle (DIN EN 15643-4, 2012, p.19 ff).

E.2 | Looking at the value of economic efficiency from the perspective of those involved in the construction, the rational principle is complemented by **ensuring profitability**, meaning the ratio of capital input to (company) profit. The principle of profitability becomes particularly clear in the form of profit realisation and maximisation (VDI 3780, 2000, p.14).

E.3 | Taking the long-term nature of the principle of rationality into account, the objective of **long-term value retention** of the building is decisive. Vacant or unused buildings are a misallocation of economic resources (DGNB, 2018, p.257). Closely related to this goal is the functional goal of durability (A.2) and the avoidance of obsolescence, in this case economic obsolescence. The German Federal Building Code BauGB (German: Baugesetzbuch) offers a definition of market value:

> *"The market value is determined by the price that could be obtained in the normal course of business at the time to which the determination refers, according to the legal circumstances and actual condition, as well as other characteristics and the location of the property, without regard to unusual or personal circumstances."*
> *(BBauG, 2017, §194)*

The value of a building structure can be influenced by:

- The condition of the building in terms of durability and technical service life of the building components, which are influenced by investment in the building and the level of care being applied in terms of use, cleaning, maintenance, repair and modernisation
- Investment and renting decisions
- User acceptance
- Flexibility and reutilization capability of the building

In addition to microeconomic aspects, a macroeconomic perspective includes social **prosperity**. Accordingly, buildings also serve and promote overall economic prosperity.

F.1 | The central objective of the German Federal Government's policy in the field of housing and urban development is to ensure that the population is provided with affordable housing in line with their needs and that urban development is carried out in an orderly manner (Deutscher Bundestag, 2017, p.13). A major goal of social prosperity is thus **meeting the needs of society**, e.g. the demand for commercial and residential buildings. Demand can vary considerably from region to region and over time, which is illustrated, for example, by the housing shortage in major German cities and the simultaneous oversupply of residential buildings in rural regions of the eastern federal states (Deutscher Bundestag, 2017, p.13 ff). In addition to the demand for residential buildings, this objective includes the need for an intact infrastructure and construction measures, such as bridges, halls, hospitals, etc.

F.2 | Together, land and real estate assets account for 87 percent of the total tangible assets of the German economy (Deutscher Bundestag, 2017, p.13). Accordingly, a major objective of building construction is their contribution to both tangible assets and the economic power of the German economy, which results in the associated **political economic benefit** of a building.

F.3 | The goal of **participation and equity of needs and performance** of all involved parties plays an important social role, especially in housing, and includes the possibility of acquiring residential property and the burden of additional costs and rent for housing. Critical attention goes to social housing, which has an indispensable supply function, especially for low-income households and for people who cannot provide for their own housing needs (BMUB et al., 2015, AG1 p.1).

The built environment contributes significantly to social structures, starting with individual living and recreation rooms and extending to office buildings and meeting places and their connection provided by appropriate infrastructure. Social goals in construction are fulfilled when buildings are useful to as many people as possible throughout their entire life, promote social cohesion and enrich them culturally without diminishing the basis of life for future generations by the burden they put on the environment (Greiff, 2012, p.20). Buildings serve social interests of social cohesion and personal development and thus shape the values of **social quality** and **personality development**.

G.1 | The goal of **flexible use and adaptability of the building** includes the highest possible degree of buildings conversion and their continued usability in the course of constant change and social transformation. By extending the service life and avoiding obsolescence, social needs and different uses are made possible on top of individual and overall economic interests (value retention of the property) (DGNB, 2018, p.236).

G.2 | The goal of offering **influence and involvement (participation) of users** leads to increased satisfaction, acceptance and well-being as well as a sense of responsibility for the building. The satisfaction of users with the built environment is related not only to subjective perceptions but also to the possibility of influencing said environment. In particular, individually adjustable room conditioning with regard to light conditions, sun and glare protection, heating and ventilation plays an important role. A high degree of automation may achieve an optimum in terms of planning, but can also lead to a high degree of rejection by users (DGNB, 2018, p.381). User involvement is not limited to the use stage however, but also includes user participation in earlier planning and production stages. Examples of housing cooperative projects show the potential of this. In addition, repeated protests against various public buildings (e.g. Stuttgart 21) illustrates the problems of a lack of citizen participation (Schäfers, 2014, p.194 ff).

G.3 | The theoretical architect F. Achleitner once stated that architecture is the only art humans cannot escape (Schäfers, 2014, p.218). Building structures shape our environment and constitute a significant cultural contribution to society. In its diversity, shape and function, the built environment reflects the social activity and enables individuals and social groups to express themselves and identify with it. Therefore, buildings should be a **cultural contribution** and achieve **social acceptance of the building** in society.

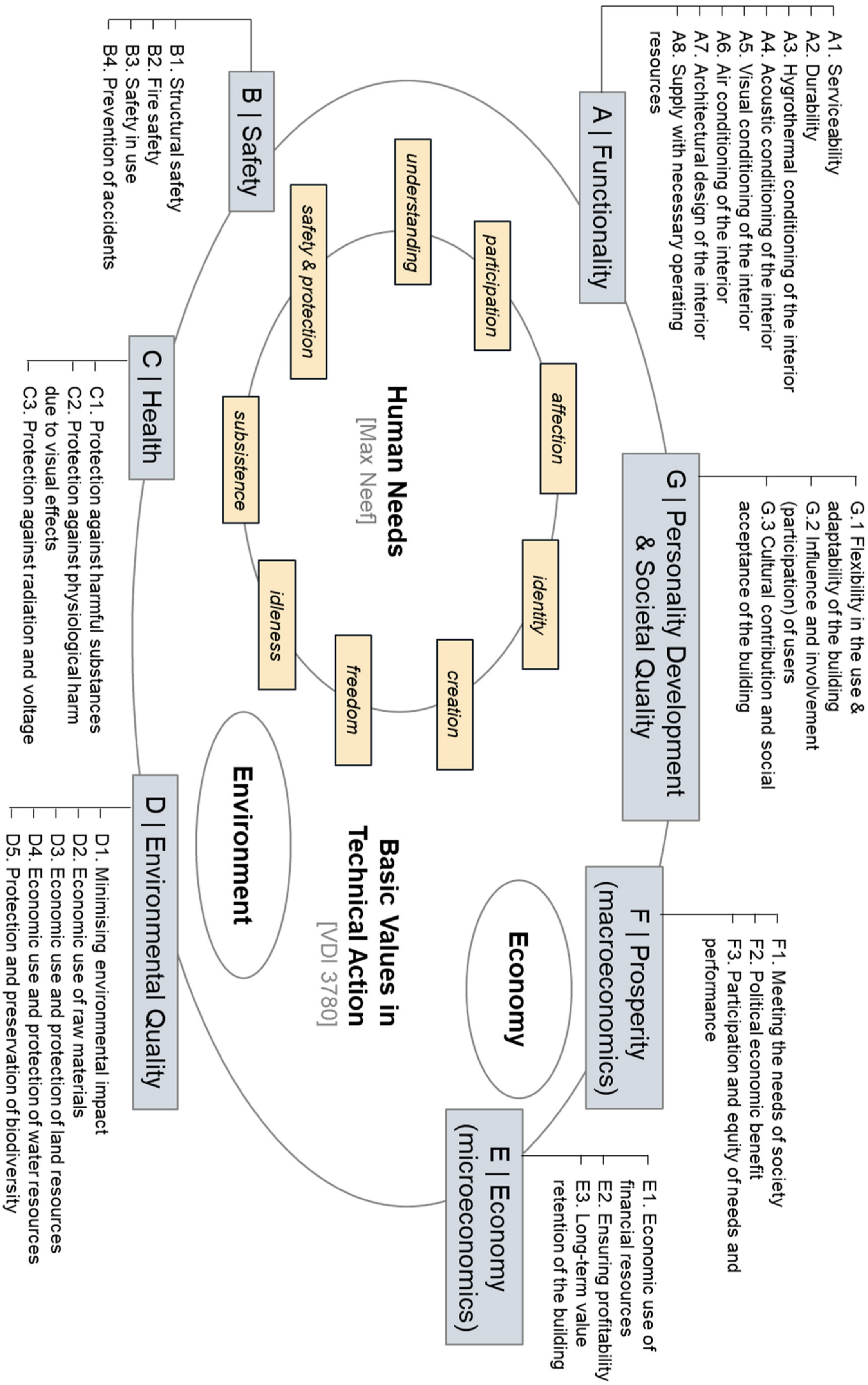


Figure 3-7: Overview of the general goals and underlying values of building construction

3.2 Modelling a System Model for Building Construction

"All insight is insight in models and through models." – Stachowiak[20]

3.2.1 General Approach for System Modelling

The aim of developing a system model of building construction is to create a holistic basis for decision-making processes. On the one hand, this increases complexity, simply from the amount of aspects which need to be considered. On the other hand, it reduces complexity due to a comprehensive and actionable structure and a systematic approach. System theory offers a common "language" for the diverse and fundamentally different disciplines to form an integral view of buildings. This "language", which was defined and outlined in chapter 2.2, will now be used to develop a general approach to a system model for construction.

The procedure for arriving at a system model for construction follows the principle of imitation modelling. It will attempt to depict the structure of the real system as much as possible, to the amount that quantitative data and relationships are known. At those points where imitation modelling is reaching its limits, mirror modelling is added to the modelling process to cover the behaviour of the model. The modelling process as a whole can therefore be considered as mixed modelling.

The addition of quantitative correlations to the model structure plays an important role here. To arrive at a general understanding of the system, the validity of the model (e.g. by revealing essential feedback) can be much more important than a high level of structural validity due to the presence of numerous data (Bossel, 2004).

In addition, the procedure for modelling as shown by Bossel (2004) and the working steps for modelling according to Sterman (2009) will be adduced and combined (cf. chapter 2.2.5). As a result, the work stages of modelling used in this work are reduced to six essential stages accompanied by iteration:

Stage 1: Problem & Goal – Identifying the model's purpose and goal
Stage 2: Dimensional Analysis – Identifying the model's elements and structure
Stage 3: Functional Analysis – Identifying the model's relations and behaviour
Stage 4: Developing a Flow Chart – Combination of structure and behaviour
Stage 5: Quantification – Operationalisation, filling the model with data for calculation
Stage 6: Validation – Testing for goal achievement, validity and improvement

Due to the problem-solving character of modelling, there is an obvious similarity to the design process, as seen in the following illustration:

[20] Own translation according to Ropohl (2012, p.185).

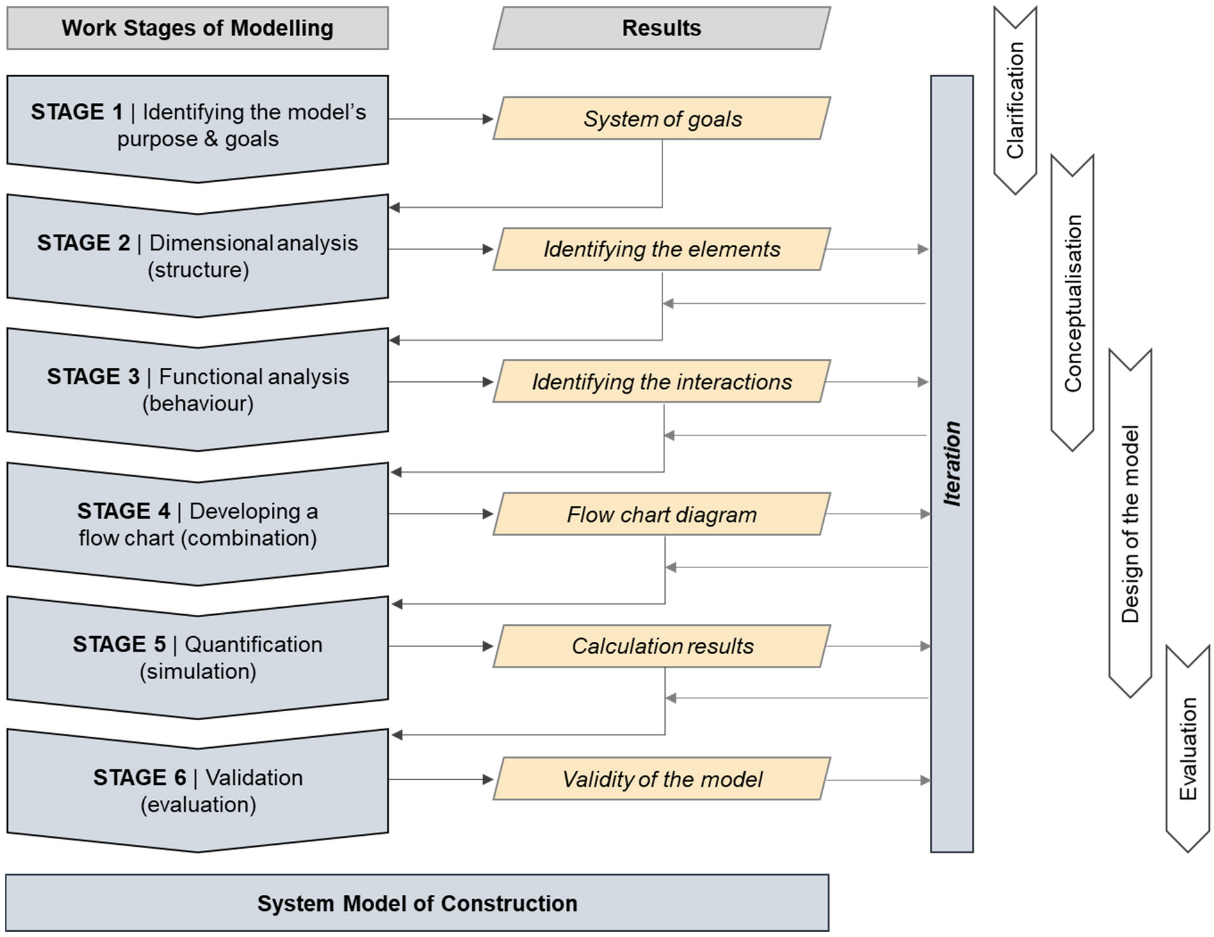


Figure 3-8: Flow chart of the work stages of system modelling in this work

To develop a system model within the scope of this work, the "language" of system theory (cf. chapter 2.2) is used to manage goals of different natures and disciplines. Additionally, the outlined "tools" (cf. chapter 3.1) will help to structure and categorize these group of themes.

Stage 1 | The description of different general goals and underlying values of building construction (system of goals) has already been developed (cf. chapter 2.1). The following chapters cover the derivation of indicators in general as well as the selection of specific goals (see chapter 3.2.2). This groundwork is followed by a more detailed description of four chosen indicators to describe the selected goals by one or multiple indicators. Developing indicators which describe the goal adequately is based on existing methods and standards (as far as those exist).

Stage 2 | Subsequent to the "goal-to-indicator" process, a 'model in words' outlines the different elements that describe, calculate or determine the indicator itself (see chapter 3.2). There will be a need for distinction between items, processes and attributes as well as inputs, states and outputs. All elements are categorized as matter, energy, information or processes and put in a hierarchical order according to sub- and supersystems. These elements provide the structural basis of the model.

Stage 3 | In addition to defining its elements, the ‘model in words’ also describes interactions between these elements. By depicting the nature of those interactions according to single relations, influences, linkages, functions or feedback, the system structure is supplemented and able to illustrate behaviour.

Stage 4 | The dimensional and functional analysis results in a flow chart diagram of the indicator model (see chapter 3.2.3 to 0), where elements and their interactions are depicted according to the concept of general systems (cf. Figure 2-18). Combined and merged, these indicator models will deliver an intermediate result of a system model of construction (cf. chapter 3.2.7).

Stage 5 | Quantifying the system model is essential for the subsequent application and parameter variation. Therefore, essential elements are outfitted with data and values, while the functions are translated into computable calculations. This will be shown in detail in chapter 4.1. The extent of these calculations is the primary reason for limiting the scope of the system model for the purpose of this work. In theory of course, the number of indicator models and therefore the size of the model can be extended to an arbitrary amount.

Stage 6 | The validation of the system model will be part of a discussion of the calculation results (cf. chapter 4.2). The validation comprises an evaluation regarding the effectiveness, sensitivity and interdependency of the different indicator models and the system model in general.

These work stages of modelling are provided so as to outline the further course of this thesis, showcasing the development of a holistic system model of building construction. As mentioned above, in order to keep the extent of this thesis to a rational limit, the system model demonstrated here will not comprise all available goals and indicators. However, the general approach and the specific implementation of a few but very different goals and indicator models sufficiently demonstrates its applicability to a bigger scope, making it possible to integrate any number of further goals and indicators into this system model.

3.2.2 Deriving Workable Indicator Models for Specific Goals

All general goals outlined in the previous chapter constitute the **system of goals** for a building structure. As shown, they can be grouped according to the value systems behind them. Remembering the different levels of perspective, the system of goals is continuously growing from material level to building level. Accordingly, the highest level contains all goals, while on lower levels like the building component or material level not all goals can be described adequately.

A large number of parameters come into play when describing a goal. The relations, interdependencies and contributions of individual parameters are depicted by indicator models for the respective goal, resulting in a **goal indicator** (**GI**). In practice, it is of course not always possible to properly collect and depict the respective goal indicators. In some cases, such goal indicators are of a qualitative nature or limited in terms of quality and availability, or are only described in a system model that is on a higher hierarchical level (component level, room level, building level). For this reason, individual parameters of the indicator model which already provide significant statements are often selected and used as separate indicators, here referred to as **sub-indicators** (**SI**).

Example: The goal of hygrothermal comfort (A.3) comprises a multitude of aspects and can eventually be described only in an elaborate simulation of the corresponding interior and its conditioning. However, since space heating and its loss play a significant role, special attention was paid to the partial aspect of thermal insulation. Meanwhile, numerous sub-indicators are used in planning, although they neither fully describe the goal of hygrothermal comfort (A.3) nor the goal of saving energy resources (D.2): Thermal conductivity of building materials (λ), heat transition coefficient (U-value) or specific heat capacity of building components (c_i), and others. These provide, if not conclusive, but still valuable information at a planning stage that can provide a complete statement on the stated objectives only in a very complex way.

When describing goal indicators, two major different types can be observed, depending on the way they depict the respective goal. Goal indicators either offer valid information on every level of perspective, merely adding up the total amount of information, or they only represent the goal on one specific level of perspective without giving reliable information on lower levels or adding important information on higher levels. Two categories of goal indicators therefore need to be distinguished:

- **Cumulative goal indicators** | The respective indicators already fully describe the objective qualitatively at different levels, but will be successively supplemented quantitatively by further addition. The sum of all indicators results in the cumulative goal indicator, which completely describes the goal qualitatively and quantitatively.
(Example: costs)
- **Specific goal indicators** | A specific goal indicator describes the goal in full, both qualitatively and quantitatively at a specific level. Specific sub-indicators together constitute the goal indicator while not being able to describe the goal individually.
(Example: comfort)

For the development of a system model, goal systems for each level of perspective are necessary to complement the complete **system of goals on the building level** described in previous chapters (see chapter 3.1.5). A full description of all indicators on each level of perspective would exceed the scope of this work at this point. However, the different possibilities to consider different indicators will be outlined.

For example, the **system of goals on the room level** covers all indicators that describe a goal regarding the user being located in the interior (such as hygrothermal, acoustic, visual comfort or aspects of air quality and health). On lower levels, only sub-indicators can be identified that, while unable to depict the actual goal, still play an essential role in painting the complete picture: e.g. heat transition coefficient or tightness of components, added pollutants of concern in materials, or material aspects like thermal conductivity, material stiffness, diffusion resistance etc.

Moving down the levels of perspective, on the **component level** only two goal indicators describe a general goal of building structures completely: The proof of sufficient load bearing capacity and serviceability is furnished for building components (e.g. proof of bending stress on beams) and their interrelationship (e.g. bracing).

Finally, it is non-trivial to note that none of the above-mentioned goals of building construction can be entirely fulfilled at the **building material level**. However, the building material level represents the starting point for the subsequent component, room and building levels, thus implying various decisive sub-indicators for describing higher-level goals. Furthermore, the cumulative type of goal indicators becomes apparent at this level: Though no statement concerning the entirety of costs, emissions or fresh water use can be made, the material level already depicts valid amounts of costs, emissions and fresh water use for the considered material. To arrive at a *full* depiction of these cumulative goal indicators, all that is needed is to expand the scope by additional materials and processes.

Table 3-7: Overview of the goals and indicator types on different levels of perspective

Goals and Values		Material Level	Compon. Level	Room Level	Building Level
A	**Functionality**				
A.1	Usability and serviceability	SI	GI	-	-
A.2	Durability and avoiding damage	SI	SI	-	GI
A.3	Hygrothermal conditioning of the interior	SI	SI	GI	-
A.4	Acoustic conditioning of the interior	SI	SI	GI	-
A.5	Visual conditioning of the interior	SI	SI	GI	-
A.6	Air conditioning of the interior	SI	SI	GI	-
A.7	Architectural design	-	SI	SI	GI
A.8	Supply with necessary operating resources	-	SI	SI	GI
B	**Safety**				
B.1	Structural safety	SI	GI	-	-
B.2	Safety in case of fire	SI	SI	SI	GI
B.3	Safety in use	-	SI	SI	GI
B.4	Prevention of accidents	-	-	-	GI
C	**Health**				
C.1	Protection against harmful substances	SI	SI	GI	-
C.2	Protection against physiological harm due to visual effects	-*	-*	GI	-
C.3	Protection against radiation and voltage	-*	-*	GI	-
D	**Environmental Quality**				
D.1	Minimising environmental impact	*GI*	*GI*	*GI*	*GI*
D.2	Economic use of raw materials	-*	-*	-*	GI
D.3	Economic use and protection of land resources	-*	-*	-*	GI
D.4	Economic use and protection of water resources	*GI*	*GI*	*GI*	*GI*
D.5	Protection and preservation of biodiversity	-*	-*	-*	GI
E	**Economic Quality**				
E.1	Economic use of financial resources	*GI*	*GI*	*GI*	*GI*
E.2	Ensuring profitability	-	-	-	GI

E.3	Long-term value retention of the building	-	-	-	GI
F	**Prosperity**				
F.1	Meeting the needs of society	-	-	-	GI
F.2	Political economic benefit	-	-	-	GI
F.3	Participation and equity of needs & performance	-	-	-	GI
G	**Personality Development & Societal Quality**				
G.1	Flexibility in the use & adaptability of the building	-	-	-	GI
G.2	Influence and involvement (participation) of users	-	-	-	GI
G.3	Cultural contribution & social acceptance	-	-	-	GI

Annotation:
SI = sub-indicator(s) available at this level of perspective
GI = goal-indicator describes the goal at this respective level, either partially (cumulative type) [*italic*] or entirely (specific type)
\- = no indicator on the respective level of perspective available
-* = ongoing discussions, indicator description not yet existing, finalized and/or implemented

Disclaimer: This list reflects a current state is open for change and (re-)development over time.

It's possible to derive ideal goals and indicators as well as (minimum) requirements within the categorization of the various functions of a building. According to the general requirements for indicators (cf. chapter 2.1.4), suitable indicators for the respective goals are described and defined. The description of appropriate goal indicators is based on the following criteria:

Table 3-8: Overview of the criteria for the development of indicators

Indicator Checklist	
DPSIR-Model	*What does the indicator describe?* • D | Driver • P | Pressure • S | State • I | Impact • R | Response
Type of Indicator (Type 1-4)	*How does the indicator describe the goal?* • Type 1 | Qualitative-Descriptive • Type 2 | Qualitative-Normative • Type 3 | Quantitative-Descriptive • Type 4 | Quantitative-Normative
Reference of Time and Location	*How does the indicator refer to time and location?* • Dynamic (it changes in regard to time/location) • Constant (it remains the same)
Holistic Approach	*How many aspects does the indicator describe?* • Singular (describing one aspect) • Multiple/aggregated (describing many aspects)

To keep the scope of the system model developed in this thesis manageable, the amount of goals considered has been artificially limited to four. Because of the exponential increase in complexity on the room and building levels of perspective, the formal logic of the development of a system model is demonstrated at the building component level – complex enough to imply other subsystems (material level) and simple enough to avoid errors due to complexity.

The selection of goals is based on their validity on the building component level, with either specific goal indicators (B.1) or cumulative goal indicators (D.1, E.1) being chosen. These choices were made in an attempt to cover a wide set of different values while contributing to the discussion of early stages of the development of indicators (D.2). Additionally, one sub-indicator (U-value) for the goal of hygrothermal comfort (A.3) was also included. In total, the following goals have been made the focus of further model development and analysis:

- B.1 Adequate Structural Safety
- D.1 Minimising environmental impact
- D.2 Economic use of natural resources
- E.1 Economic use of financial resources

The following section depicts the development of indicators for these goals as well as how to establish a model to deduce these indicators with all necessary influencing aspects and parameters according to the method of system theory (cf. chapter 2.2).

3.2.3 Indicator Model for 'B.1 – Structural Safety'

To achieve the goal of adequate structural safety, a proof of sufficient load-bearing capacity and structural resistance is used. This objective can be verified by calculating different limit states at different design situations (design concept according to limit states). The design of structural models is used for calculations which check whether the sum of all effects of actions (design value of the stress E_d) on the structure at the ultimate limit state is less or equal to the corresponding load-bearing capacity (design value of resistance R_d) (EN 1990, 2002/A1:2005, p.41 ff). Consequently, the indicator for the representation of structural safety is represented by verifying the ultimate limit state – the ratio of design values of stress and design value of resistance of the respective component of a structure:

$$E_d \leq R_d$$

The verification of the ultimate limit state is internationally accepted and standardized by the "Eurocode" with regard to the basic actions and design of structures of different materials and in different scenarios (e.g. an earthquake):

Table 3-9: Overview of the structural Eurocode programme

EN 1990 + NA	Eurocode 0: Basis of structural design
EN 1991 + NA	Eurocode 1: Actions on structures (consisting of 10 partial standards)
EN 1992 + NA	Eurocode 2: Design of concrete structures (consisting of 4 partial standards)
EN 1993 + NA	Eurocode 3: Design of steel structures (consisting of 20 partial standards)
EN 1994 + NA	Eurocode 4: Design of composite steel and concrete structures (consisting of 3 partial standards)

EN 1995 + NA	Eurocode 5: Design of timber structures (consisting of 3 partial standards)
EN 1996 + NA	Eurocode 6: Design of masonry structures (consisting of 4 partial standards)
EN 1997 + NA	Eurocode 7: Geotechnical design (consisting of 2 partial standards)
EN 1998 + NA	Eurocode 8: Design of structures for earthquake resistance (consisting of 6 partial standards)
EN 1999 + NA	Eurocode 9: Design of aluminium structures (consisting of 5 partial standards)

The process of verifying ultimate limit states covers different design situations and different ultimate limit states. This way, both the stability of the components as well as the structure as a rigid body and the mechanical strength of the building materials and components with regard to failure and excessive deformation are verified. Additionally, the cases of failure or excessive deformation of the subsoil, fatigue failure, loss of equilibrium due to buoyancy forces (water pressure, wind suction) and hydraulic lifting and lowering are taken into account as well (*multiple* indicator).

As a *state indicator*, the degree of utilisation describes the relationship between the energetic conditions of stresses and resistances (*quantitative*) as $UF = E_d / R_d \leq 1$, with the (*normative*) requirement that this value must be equal or less than one. The goal of sufficient load-bearing capacity with regard to "safety" is thus achieved by an utilisation factor of *one*, which fulfils the socially defined and required safety requirements. The lower the degree of utilisation, the less the component is optimised in regards to the defined limit of safety, the effect of this energetic state variable of utilisation resulting in deformation. On the other hand, exceeding the limit increases the risk of failure increases until real component failure. The goal of preventing mechanical failure, loss of stability and excessive deformations remains *constant* over time and independent of location.

Indicator Model

Model purpose | The indicator model describes the relationship between the effect of actions and component resistances to determine a degree of utilisation with regard to structural safety of components. Accordingly, the model should show linkage and feedback between individual items of the system.

Model in words | In order to describe the structural safety, two essential quantities of a components are compared: The *design value of the effect of actions* (E_d) and the *design value of resistance* (R_d).

The *design value of the effect of actions* (E_d) is composed of partial factors for uncertainties of modelling and actions in combination with the characteristic value of the effect of action, which in itself results from the calculation model and the characteristic value of actions. The partial factors considers uncertainties in the type of action (partial factor for actions) and factors for combined values of variable actions (e.g. permanent, temporary or extraordinary loads) as well as uncertainties of modelling by buckling, tilting and other coefficients. The calculation model differentiates between types of components and loads (e.g. static system, single or uniform load, etc.) and takes into account boundary parameters of the geometry (e.g. span width, cross-section, component size, etc.) as well as the calculation method (e.g. support and coupling reactions, flux of forces, buckling, etc.). The characteristic actions (external forces) consist of dead load, snow, wind, use and other actions, which can be divided into permanent, variable and extraordinary loads. One essential feedback consists in the dead load of the component, resulting from the mass state, which in turn stresses the component itself as a kind of permanent load (Zilch and Zehetmaier, 2006, p.48).

Example: The design value of the effect of actions of a wall under compressive stress results from the partial factor of the respective action and the effect of this action. The compressive stress results from the calculation model and is dependent on the characteristic action (e.g. normal force N from dead load) and other boundary conditions (load absorption area of the action, cross-sectional area A, etc.) as well as results from the ratio of the normal force N to the cross-sectional area A. For compressive loads, the stability in case of buckling must also be taken into account, which is covered accordingly by the calculation model. These and other load cases can also be superimposed to determine the maximum design value.

On the other side of the spectrum, the *design value of resistance* (R_d) is mainly composed of characteristic material properties (usually strength properties) and partial factors of uncertainties. The characteristic material property, e.g. strength with regard to bending, tension or compression, is related to the choice of material (concrete, steel, wood, etc.) and the corresponding quality of the building material (grading and quality classes). Partial factors for material properties (γ_m) and additional mean values of the conversion factor (η) for the consideration of volume and scale effects, moisture and temperature effects and other relevant parameters result from the material itself as well as from temporal and environmental parameters (EN 1990, 2002/A1:2005, p.43).

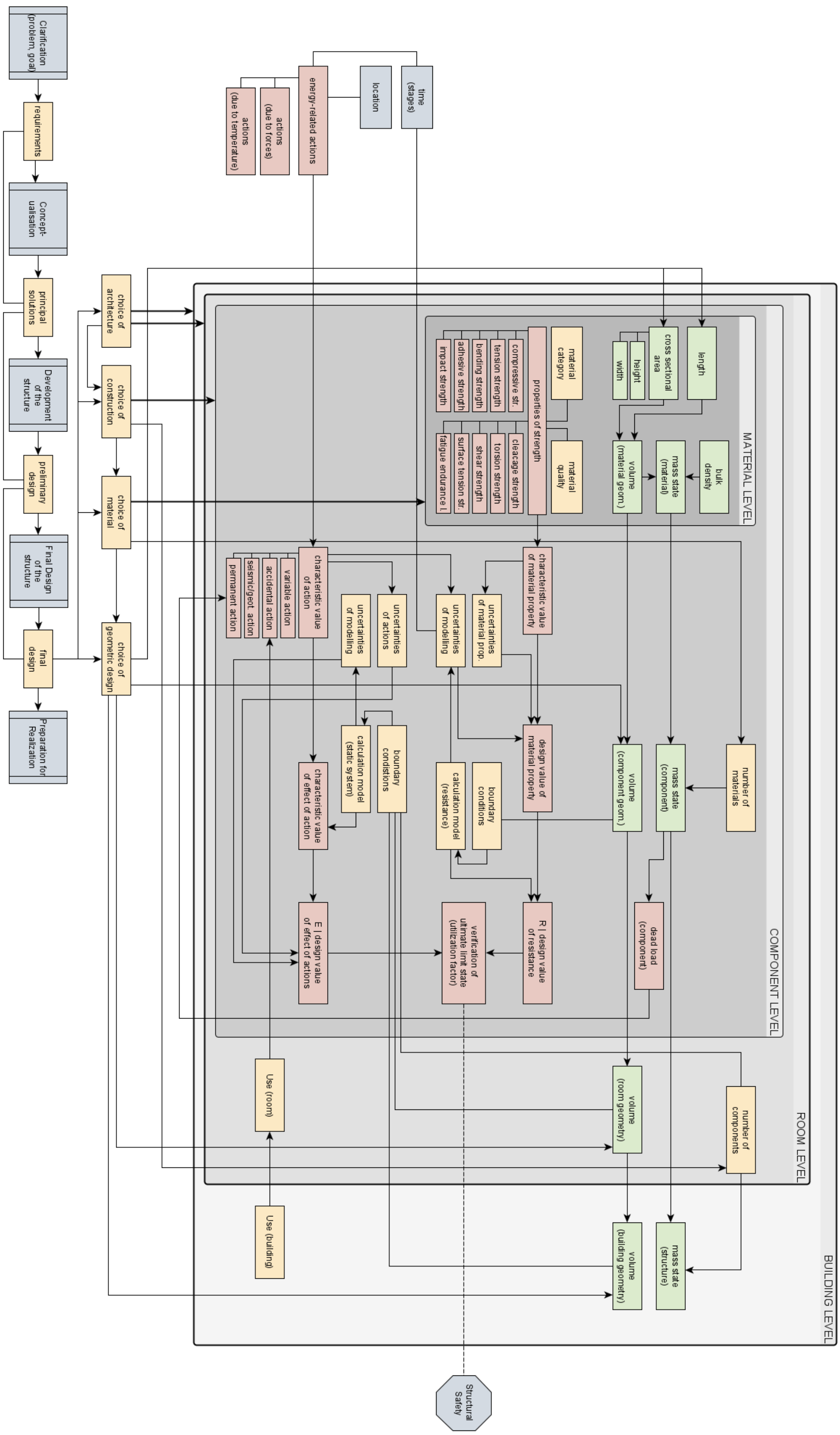


Figure 3-9: Flowchart of the indicator model ‘B.1 load bearing capacity’

3.2.4 Indicator Model for 'D.1 – Minimising Environmental Impacts'

To create a framework for the goal of minimising environmental impact, an existing and recognised method can be used: Life Cycle Assessment (LCA). The beginnings of Life Cycle Assessment date back to the end of the 19th century and took shape from 1970 onwards through the work of the REPA Institute ('Resource and Environmental Profile Analysis') as well as contributions by the 'Club of Rome'. From 1990 onwards, the SETAC ('Society for Environmental Toxicology and Chemistry') took a leading role in the development and harmonisation or the beginning of standardisation of the method (Klöpffer, 2014, p.4 ff). Through the process of standardization and the work of CEN/TC 350, an international consensus and general standard for the method and thus also for the selection of indicators was developed, as shown below:

Table 3-10: Overview of the standards for Life Cycle Assessment in the construction industry

EN ISO 14040:2006	Environmental management – Life cycle assessment – Principles and framework
EN ISO 14044:2006	Environmental management – Life cycle assessment – Requirements and guidelines
EN 15643-2:2011	Sustainability of construction works – Assessment of buildings – Part 2: Framework for the assessment of environmental performance
EN 15978:2011	Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method
EN 15804:2012 +A1:2013	Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products

The LCA is the only internationally standardised method of ecological product analysis. It is already based on the idea of system theory and thus on a simplified system analysis (Klöpffer and Grahl, 2014, p.4; König et al., 2010, p.13). LCA is defined as *"compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle"* (DIN EN 14040, 2009, p.7). This means that with the LCA method, systems of different size and scope can be evaluated, e.g. a building product, a component or even entire buildings which comprise these subordinate systems. The indicators therefore correspond to a cumulative characteristic, as they can be determined for building materials, components, individual rooms or the building as a whole. In each case they fully describe the objective in terms of quality.

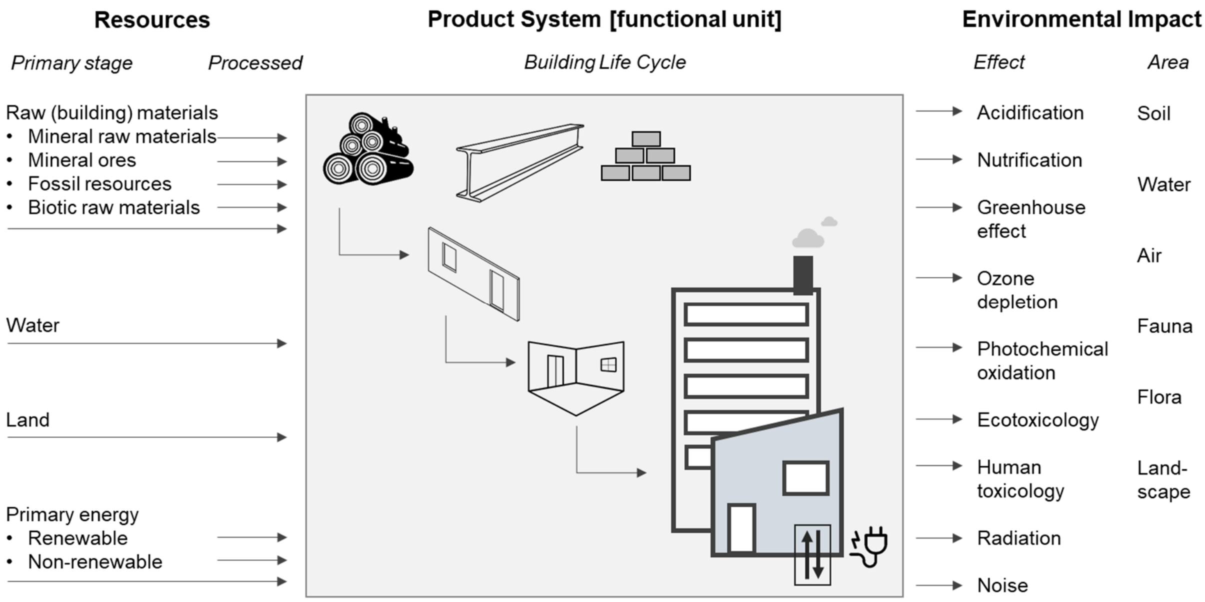


Figure 3-10: System model of all energy and material flows of an LCA of buildings, based on (König et al., 2010, p.12)

The LCA method is based on the principles of lifecycle perspective, environmental focus, relative (functional unit) and iterative approaches, transparency, comprehensiveness and prioritizing the scientific method. The procedure for balancing is divided into four phases (DIN EN 14040, 2009, p.14 ff):

1. Goal and scope definition
2. Life Cycle Inventory analysis (LCI)
3. Life Cycle Impact assessment (LCIA)
4. Interpretation

In accordance with the principle of a holistic approach (comprehensiveness), the LCA method covers and describes a wide range of environmental impacts as well as the input and output flows that constitute an environmental impact. In the context of the goal to minimize environmental impact (cf. 3.1.5), the LCA provides seven indicators that almost completely reflect these multiple objectives.

For the environmental problem of "toxicity to the environment", indicators with scientifically recognised calculation methods don’t exist yet (DIN EN 15978, 2012, p.43). The following table offers an overview of the corresponding (multiple) indicators of environmental impact and the associated problems (DIN EN 15804, 2014, p.34; Klöpffer and Grahl, 2014, p.223 ff):

Table 3-11: Overview of environmental impact categories and indicators

Environmental Problem	LCA Indicators for environmental impact		Unit
"Climate Change"	**GWP**	Global Warming Potential of different greenhouse gas emissions	kg CO_2 eq.
"Ozone Hole"	**ODP**	Ozone Depletion Potential; Depletion of the UV-protective stratospheric ozone layer	kg CFC 11eq.
"Over-fertilisation"	**EP**	Eutrophication Potential; aquatic & terrestrial eutrophication; excess supply of nutrients	kg $(PO_4)^{3-}$ eq.
"Acid Rain"	**AP**	Acidification Potential; acidification of unbuffered waters, soils and damage to forests	kg SO^{2-} eq.
"Summer Smog"	**POCP**	Photochemical Ozone Creation Potential; Formation of Photo Oxidants	kg ethene eq.
"Scarcity of Resources" *	**ADPe**	Abiotic Resource Depletion Potential of elements	kg Sb eq.
	ADPf	Abiotic Resource Depletion Potential of fossil fuels	MJ (heat value)
* The indicators describing the potential for abiotic resource depletion is still the subject of further scientific research. The application of this indicator will be reviewed with the revision of DIN EN 15804 (2014, p.34 annotation 1). For this reason, the indicators ADPE/ADPF will be calculated in the context of this work, but not explicitly illustrated and interpreted.			

The LCA method also offers the possibility of depicting other indicators and effects, which, for example, address the problem of resource consumption (see next chapter 3.2.5). Since environmental problems differ in time and location, these indicators are dynamic in relation to time (history) and place (local or global effects). Therefore, a corresponding set of indicators for representing environmental impact has to be continuously adapted. Their development within standardization procedures reflects this process, in which the topicality of the addressed environmental topics and their mapping through the use of indicators is continuously adapted, expanded and differentiated. For the preparation of life cycle assessments in the building industry, the German-speaking countries often refer to the following databases:

- GaBi – Comprehensive database of the company *thinkstep* (formerly *PE International*) with numerous processes and primary data (thinkstep, 2020)
- ecoinvent – Swiss database with numerous processes and primary data (ecoinvent, 2020)
- ÖKOBAUDAT – Free database of the BBSR with over 1,200 data sets for building products, based on the background database GaBi and in conformity with EN 15804 and the BNB assessment system for sustainable building (BMI, 2019)

Indicator Model

Model purpose | The indicator model describes the system for determining relevant emissions in regards to critical environmental impacts for the protection of ecosystems.

Model in words | The focus of the model lies on the processes of the life cycle of construction products and buildings as described in DIN EN 15804 (2014, p.33): To illustrate the product system, it must contain a simple flowchart of the processes covered by the LCA. These must be divided at least into the four life cycle phases of the product – production, construction, use and disposal.

In addition to the processes, the product "building" is broken down into its hierarchical levels (building – component – building material). *Volume* and *Mass States* serve as decisive material parameters, providing reference values for expended effort in the individual processes.

Influencing factors on the material state are the configuration of the building materials, components and the building as a whole, as defined in the design process. The configuration includes the choice of building materials as choices regarding geometry and arrangement in relation to the respective product status. The building material is an initial parameter of the product stage (A1-A3) (preliminary chains) and the components and the structure comprise all building materials and result from the construction stage (A4-A5).

The process of use is decisively influenced by the service life of the relevant building materials and specific building properties. Thus, the utilisation phase describes two essential aspects; operation (B1, B6 and B7) in the form of energy and water use on the one hand; 'consumption' of further products within the scope of maintenance (B2), repair, (B3) replacement (B4) and refurbishment (B5) of the building on the other.

Finally, all building materials, components as well as the entire structure serve as input variables for the deconstruction process, which is followed by waste disposal and treatment. There are also transport processes (A2, A4, C2) between the individual processes which cause additional emissions depending on transport routes. Within the framework of the Life Cycle Inventory, input and output variables are set for all processes, including all environmentally relevant emissions.

As an additional impact assessment step, the individual results (i.e. individual emissions) are assigned to the impact category (classification) and calculated (characterisation) with regard to their potential environmental impact, using characterization models in order to obtain a statement on the potential environmental impact of various environmental problems (DIN EN 14044, 2006, p.33 ff).

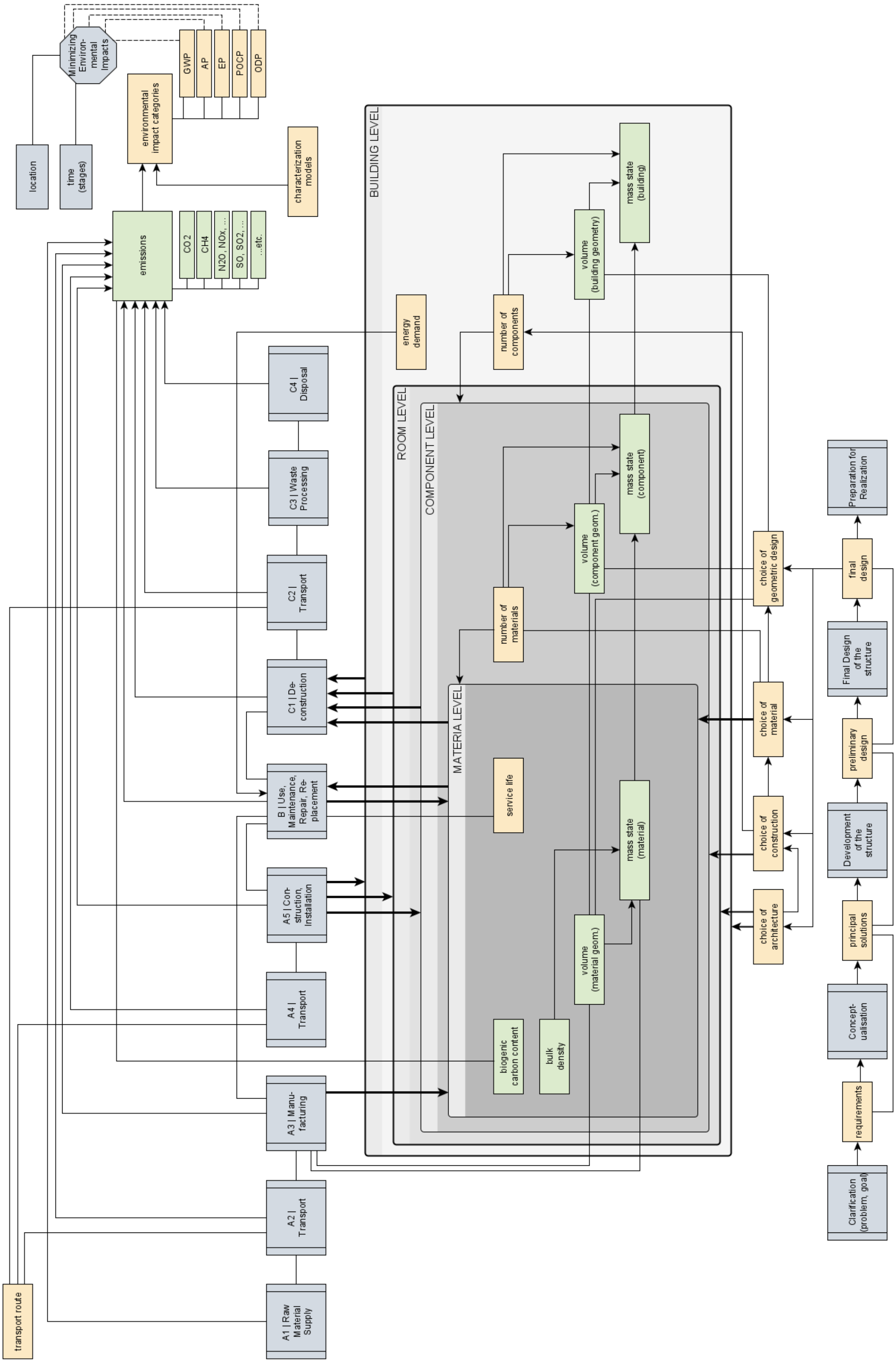


Figure 3-11: Flowchart of the indicator model ‘D.1 minimising environmental impacts’

3.2.5 Indicator Model for 'D.2 – Economic Use of Raw Materials'

To develop the indicator system for the goal of economy and conservation of raw materials, a distinction must be made between energetic and raw materials (cf. Figure 3-2). For the representation of raw materials for energy use, the method of life cycle assessment can be used in analogy to the description of environmental impacts. The following table provides an overview of the normative indicators for the use of energy resources (DIN EN 15804, 2014, p.35):

Table 3-12: Overview of the indicators for the use of resources and output material flows

LCA Indicators for use of resources		Unit
PERE	Primary Energy Renewable Energy; use of renewable primary energy	MJ (heat value)
PERM	Primary Energy Renewable Material; use of renewable primary energy resources used as raw materials	MJ (heat value)
PERT *	Primary Energy Renewable Total; total use of renewable primary energy resources	MJ (heat value)
PENRE	Primary Energy Renewable Energy; use of non-renewable primary energy	MJ (heat value)
PENRM	Primary Energy Renewable Material; use of non-renewable primary energy resources used as raw materials	MJ (heat value)
PENRT *	Primary Energy Renewable Total; total use of non-renewable primary energy resources	MJ (heat value)
CRU	Components for Reuse	kg
MFR	Materials for Recycling	kg
MER	Materials for Energy Recovery	kg
* The indicators PERT and PENRT are calculated automatically by summing up the renewable or non-renewable partial indicators		

The indicators PERT and PENRT are calculated automatically by summing up the renewable or non-renewable partial indicators (PERT=PERE+PERM and PENRT=PENRE+PENRM). Because they confound renewability of primary energy with the specific type of primary energy (energy use or material use), these total indicators have only been included because of their historical usage. Based on these LCA indicators, four additional characteristics can also be shown. On the one hand, the indicators of energy use (PERE+PENRE) can be employed to show how much total primary energy is required across a life cycle and, in addition, the share of renewable primary energy (PERE / [PENRE + PERE]) can be shown. Similarly, the indicators of primary energy resources used as raw materials (PERM+PENRM) show the energy content contained in the materials across their life cycle and which may be available at the end of their life for energy use. The share of renewable primary energy resources can also be depicted (PERM / [PENRM + PERM]). Generally, this energy content (PEMT) enters the system as a load (because it is not available for use anymore) and leaves the system as benefit (available for energy usage again). This implies a net balance over the life-cycle of zero (EN 16449, 2014). For a depiction of the energy content either the system's entering share (PEMT in stage A) or leaving share (PEMT in stage C) hast to be reported. How these indicators can be used as well as possible conclusions were already discussed with calculation results of the project “dataholz.eu” (Ebert and Ott, 2019). The focus of an economic use of raw materials for material use (as opposed to energy use) lies on closing material cycles through re-use and recycling, with the ecological premise being an efficient use of resources as well as avoiding, reducing and recycling residual materials, next to minimising environmental impact and increasing durability (VDI 2243, 2002, p.10).

The term recycling is defined by the VDI as *“re-use or recovery of products, parts of products and materials in the form of cycles"* (VDI 2243, 2002, p.35) and covers the use and recovery of products at the end of the use stage, without differentiating recovery in more detail. The German Recycling Law defines the term recycling and reuse as follows: *“Reuse is any process by which products or components [e.g. components] that are not waste are reused for the same purpose for which they were originally intended“* (KrWG, 2012, §3 Abs.21)[21]. Recycling means any recovery operation by which waste is transformed into products, materials or substances either for the original purpose or for other purposes; it includes the processing of organic materials but does not include energy recovery and processing into materials for use as fuel or for backfilling (KrWG, 2012, §3, Abs.25). An essential characteristic of the economic use of raw materials is which shares are reusable and recyclable building materials (to what extent material cycles are closed) as well as which building materials need to be disposed (to what extent material cycles are not closed). In the context of recyclable materials, distinctions exist between recycling, i.e. *reuse* (product recycling) and a repeatable cycle at an equivalent (material recycling) and inferior quality level (downcycling) and, on the other hand, a one-time closing of the cycle through final recovery (for material or energy substitution).

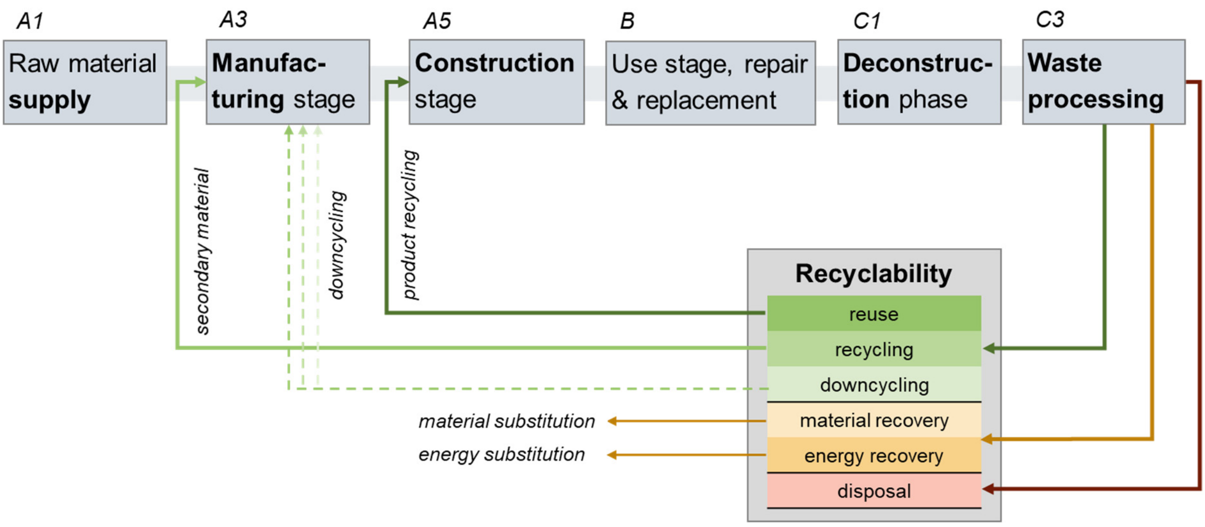


Figure 3-12: Visualization of material flows and recyclability paths

[21] German Source: „Wiederverwendung im Sinne dieses Gesetzes ist jedes Verfahren, bei dem Erzeugnisse oder Bestandteile, die keine Abfälle sind, wieder für denselben Zweck verwendet werden, für den sie ursprünglich bestimmt waren.”

As a result of the previous discussion of the differentiation and significance of indicators, and according to the definition of the material flow model for recyclability, the following *multiple* indicators result for the goal of an economic use of raw materials:

Table 3-13: Overview of the indicators for an economic use of raw materials

Indicators for an economic use of raw materials		**Unit**
PEET (1)	Primary Energy Energy use Total; total use of non-/renewable primary energy	MJ (heat value)
rs-PEET (2)	Renewable share of PEET	%-share
PEMT (3)	Primary Energy Material use Total; total use of non-/renewable primary energy resources used as raw materials entering the system in A1	MJ (heat value)
rs-PEMT (4)	Renewable share of PEMT	%-share
MRU	Material for Reuse; material and components for reuse or product recycling	kg / mass-%
MSM	Material for Secondary Material Use; material recycling resulting in equal material quality level (recycling)	kg / mass-%
MMR	Materials for Material Recovery; material recovery resulting in lower material quality levels (downcycling)	kg / mass-%
MMRf	Materials for Material Recovery (final); one-time recovery of the residual material	kg / mass-%
MERf	Materials for Energy Recovery (final); one-time energy recovery of the residual material	kg / mass-%
MWD	Materials Waste for Disposal; materials with no recycling potential declared as (non-/hazardous) waste disposed	kg / mass-%
Annotations: • Primary Energy Energy Use Total - PEET, resulting from the summation: PERE+PENRE • renewable share of PEET, resulting from the ratio: PERE / (PERE+PENRE) • Primary Energy Material Use Total - PEMT, results from the summation: PERM+PENRM entering the product system in the phase A1 • renewable share of PEMT, resulting from the ratio: PERM / (PERM+PENRM)		

One single indicator cannot describe the goal of an economic use of raw materials in its entirety, which is the reason for establishing multiple indicators, which can be determined *quantitatively* with a *normative* characteristic (e.g. material waste for disposal should be (nearly) zero). The indicators of the output material flows and the energy flows describe the *impact* of the studied system on its surrounding concerning the use of raw materials (e.g. how may resources are used and what resources will be available in what quality). The goal of an economic use of raw materials may also differ regarding the (dynamic) where and when of how raw materials are used. Any calculations of the indicator results have to consider the building as a whole, its use and the site with all of its exposures.

Indicator Model

Model purpose | The indicator model describes the system for determining relevant material flows concerning their recyclability and disposal in order to illustrate an economic use of raw materials.

Model in words | The model describes building components considering the recyclability paths of all material flows, covering aspects like material properties, jointing and separability of single building materials or components as well as construction and dismantling processes. The arrangement of the processes of the model orients itself after existing tools like Lifecycle Assessment (LCA) according to the standards DIN EN 15804 (2014) and DIN EN 15978 (2012), thereby linking it with another main goal, that of minimizing environmental impacts.

One of the main differences of this model to the ones established so far is the differentiation of levels of perspective between the building material level and the building component level. The choice of materials in the design phase contains the specific potential of building materials regarding a *re-usability* as shown in the model. However, a material's potential cannot always be fully exploited, since during the construction phase it becomes part of a building component and of the building itself through jointing and assembling. After dismantling, demolition and waste processing the construction materials are divided into different waste flows, which differ in purity of variety and material structure. Therefore, to merely focus on construction materials would lead to incomplete results (Ebert et al., 2020b).

The model's approach is to consider the construction phase (A4) including the amount of materials, the material diversity and especially the *jointing of materials*. This information is vital for the deconstruction phase (C1) which can be divided in three subphases:

- Dismantling
- Selective deconstruction
- Demolition

In general, a distinction is made between two procedures for the removal of structures, demolition and deconstruction. Both procedures can also be carried out selectively. The term demolition refers to a separation procedure without explicit consideration of the material stock. On the other hand, deconstruction is carried out with the aim of obtaining materials that are as unmixed as possible (Müller, 2018, p.19). Accordingly, deconstruction is often selective, controlled, systematic or even recyclable by performing a step-by-step dismantling, gutting and final demolition. Within the scope of the assessment of recyclability, a pure demolition process is excluded in favour of a dismantling and deconstruction process. Two parameters of the construction are crucial to decide in which subphase the deconstruction will take place:

- *Separability* of joints regarding damage
- *Material category* (raw material basis) regarding waste processing

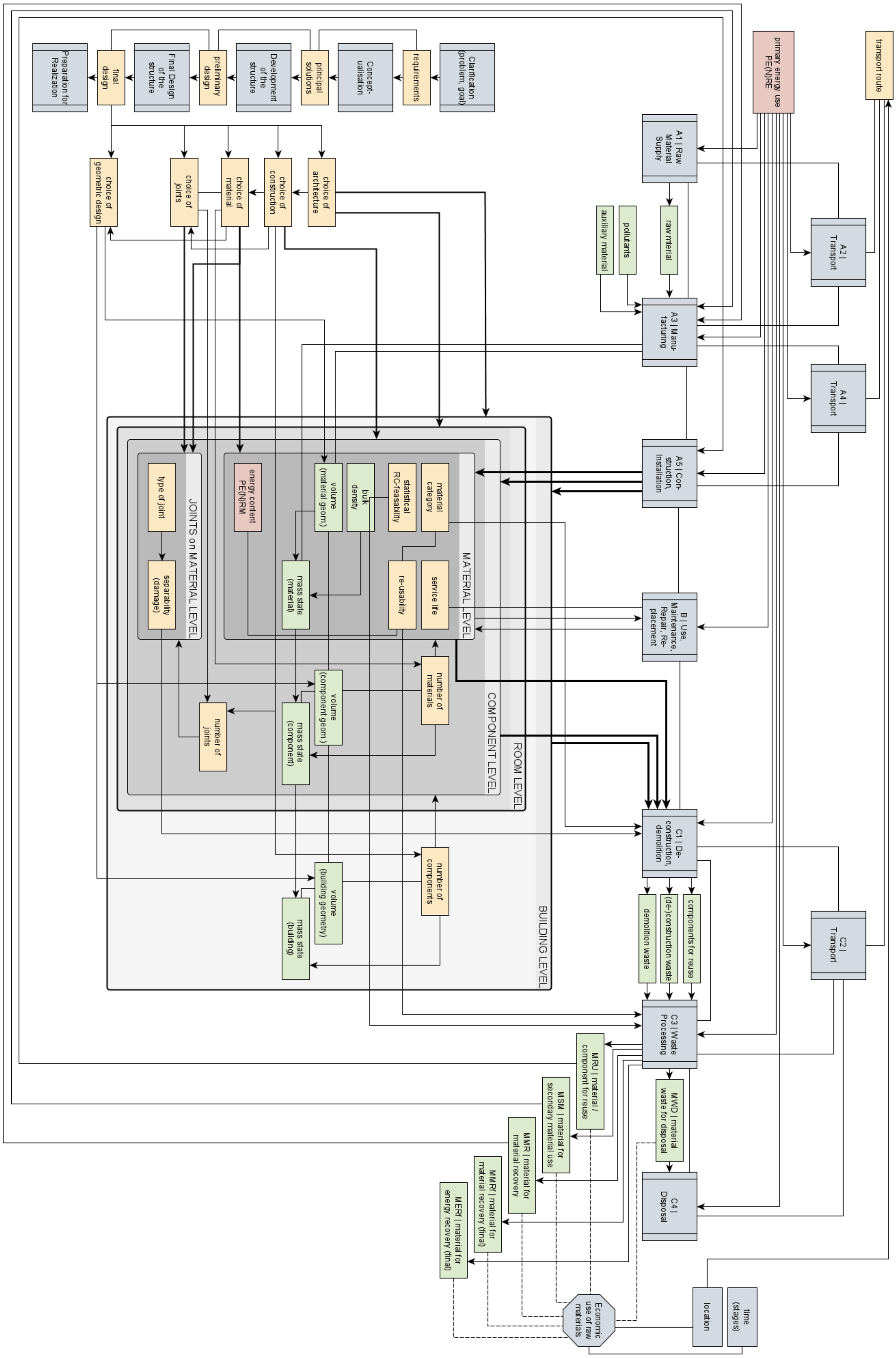


Figure 3-13: Flowchart of the indicator model of 'D.2 economic use of raw materials'

The combination of the materials recyclability's potential, the separability of materials joints and material categories define the subphase for deconstruction and the waste flow itself. Dismantling aims for the reuse of components and materials. Therefore, the material or the component itself must have a reusability potential as well as be separable without any damage. During selective deconstruction all pollutants and interfering substances have to be removed without increasing the demolition waste's heterogeneity. Separability is key for the varietal purity of waste material flows. Finally, all remaining structures are demolished and collected in different demolition waste categories. In this phase the separability only determines the effort of deconstruction. As a result, the deconstruction phase (C1) provides three different waste material categories:

- Material and components for reuse
- (De-)Construction site waste
- Demolition waste

All waste material flows are further processed in the waste treatment phase (C3). In principle, every waste can be processed into pure materials depending of the materials potentials and the amount of effort. Therefore, the *statistical feasibility* of actual recycling and waste processing distribution reflects the current compromise of economic cost and effort as well as time and energy effort. Only if the materials do not fulfil the criteria for useful waste (DIN EN 15804, 2014, p.50) the will be considered as material waste for disposal.

All these correlations lead to the indicator model's system structure and result in the amount of material flows with precise distinctions regarding the recyclability of the material outflow categories. The materials are grouped and categorized into similar substance groups according to Deilmann and Reichenbach (2017), and the waste flows are categorized according to the German waste directory (AVV, 2001). The method of jointing is modelled after international standards (DIN 8593-0, 2003), and the statistical distribution of waste flows is linked with the construction waste monitoring (Kreislaufwirtschaft Bau, 2018) and other existing material flow modelling approaches from the German environmental agency (UBA) by Steger and Ritthoff (Steger et al., 2018) und Hedemann/Meinhausen (Hedemann et al., 2017).

3.2.6 Indicator Model for ‘E.1 – Economic Use of Financial Resources’

Life cycle costs serve as indicator for the goal of economical use of financial resources. The ISO standard defines LCC as *“cost of an asset or its parts throughout its life cycle, while fulfilling its performance requirements”* (ISO 15686-5, 2017). However, as costs are volatile by nature, time of recording, scope and the object of LCC are decisive. Influencing factors and aspects are (BKI, 2019a, p.11):

- Utilization and special utilization requirements
- Market and economic situation
- Building geometry and project size,
- Building quality and execution standard
- Date of calculation and season of construction
- Site conditions and accessibility
- Effectiveness of rationalisation and design features

The German standard for construction costs (DIN 276, 2018) defines the term construction costs as:

> *“Expenditures on goods, services, taxes and duties required for the preparation, planning and execution of construction projects”.*[22]

The following classification is used to determine the construction costs (CC) according to DIN 276 (2018). The individual first levels can be further differentiated on the second and third levels (cf. chapter3.1.2). In accordance with the German standard for costs during the use of the building (DIN 18960, 2008), these costs are additionally differentiated into operational costs (OC). Last but not least the costs at the end of the life of a building (ELC) have to be considered. In addition to the cost structure according to DIN 276 (2018) and DIN 18960 (2008), the costs are assigned to the modules A to C of the life cycle of a building according to DIN 15978 and supplemented by further aspects (DIN EN 15643-4, 2012, p.21 ff).

Table 3-14: Overview of the indicators for an economic use of financial resources

Indicators for an economic use of financial resources			**Unit**
A	**CC 100**	costs for the building site	€
	CC 200	costs for preparatory measures	€
	CC 300	costs for building - building constructions	€
	CC 400	costs for building - building service installations	€
	CC 500	costs for external works and open spaces	€
	CC 600	costs for equipment and works of art	€
	CC 700	ancillary building costs	€

[22] German Source: “Aufwendungen, insbesondere für Güter, Leistungen, Steuern und Abgaben, die mit der Vorbereitung, Planung und Ausführung von Bauprojekten verbunden sind.“

	CC 800	costs for financing	€
B	**OC 100**	capital costs	€
	OC 200	property management costs	€
	OC 300	operating costs	€
	OC 400	renovation costs	€
C	**ELC**	end of life costs for deconstruction, transport, waste management, disposal and recycling	€
A-C	**LCC**	Life Cycle Costs *(the sum of all of the above)*	€

On lower hierarchical levels like the material level only parts of the life cycle costs can be calculated, since additional information is still lacking. Nevertheless, this information, e.g. material costs, already deliver valid and important information regarding the indicator of LCC, supplemented by accounting information on other levels. The indicator of LCC is accordingly compiled cumulatively and is supplemented and completed by partial indicators of the different areas considering all levels of perspective, from *building material* to *building*.

Indicator Model

Model purpose | The indicator model describes the system for determining all costs of building construction to depict an economic use of financial resources.

Model in words | The indicator of life cycle costs is composed of various parameters across the life cycle of a building. A basic distinction is that between costs for services and material costs. The cost groups according to DIN 276 for manufacturing costs as well as the usage costs according to DIN 18960 serve as orientation for the different costs. The model is built around the life cycle, for which the life cycle phases according to DIN EN 15804 are used (in analogy to environmental impacts across the life cycle, cf. 3.2.4).

A hierarchy of sub-models according to building material, component and room structure illustrates the factors influencing material condition. These are the configuration of building materials, components and the building as a whole, which in turn are included in the incidental building costs as planning costs.

The configuration includes the choice of building material, the construction method and the choice of geometry and arrangement in relation to building material, component, space and the building as a whole. The material condition of the building material is the result of the manufacturing phase (upstream of the building material: A1-3 Raw material extraction, transport and production) and results in specific material costs. The building components, rooms and the building comprise the building materials and result from the erection phase (preliminary chain of the building component: A4-5 Transport to the building site and installation/erection). The total costs of the "CG 300 building construction" and the "CG 400 building service installations" result from the already mentioned material costs and the services of the construction phase. In direct relation to the material condition are the disposal costs resulting from the disposal phase (C1-4 dismantling, removal, waste treatment and disposal). The costs within the use phase results in the operational costs.

These costs depend on the service life of the building and the (technical) service life of individual building materials. However, a large part of the relevant influencing factors is outside the system boundaries of the building construction. These are included as independent information in the cost calculation in the form of property costs, preparatory measures, outdoor facilities, equipment, further ancillary construction costs and costs for financing.

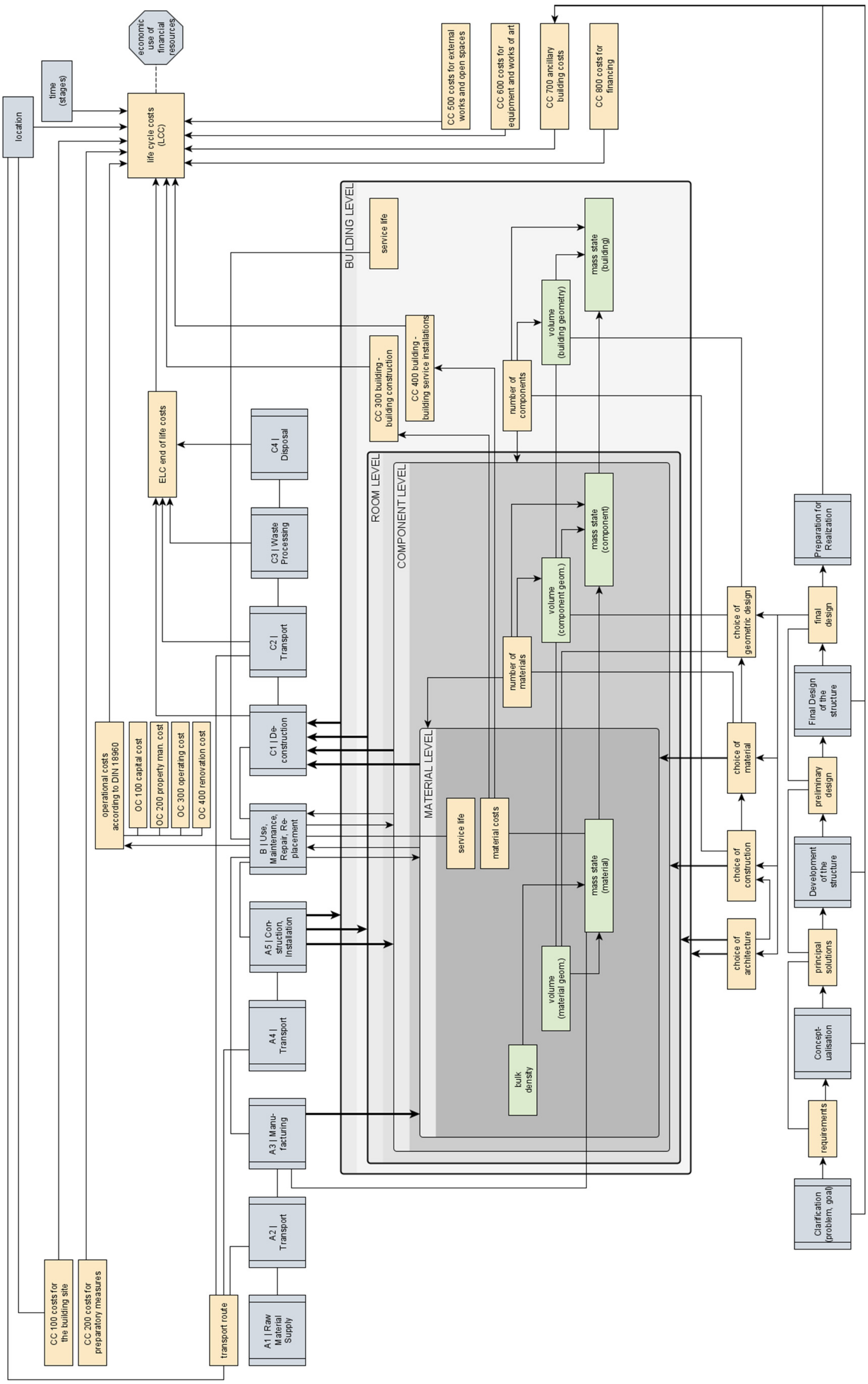


Figure 3-14: Flowchart of the indicator model of 'E.1 economic use of financial resources'

3.2.7 System Model for Building Construction

It bears repeating that the development of a complete system model of building construction exceeds the scope and the extent of this thesis by orders of magnitude. The focus therefore lies on deriving a general setup of a system model for building construction to showcase the logic and general procedure and to include as many aspects as necessary for different design tasks and study requirements. As a consequence, the aim of this approach is to create a possibility to set up – using the recent increase in computable modelling capacities and the transparency of computer models – a holistic system model of building construction covering the complete set of goals and all relevant elements and interactions.

Following the work stages of modelling, the system model of building construction is built up by carefully combining the indicator models with each other to create a system model with multiple indicators and goals. Therefore, the system model can be seen as a pile of layers of individual indicator models on top of each other (cf. Figure 3-15). This layering is accompanied by three steps:

1. Identifying a unifying hierarchical structure of sub- and supersystems
2. Identifying all double elements and replacing them by a single resulting element
3. Unifying all interactions of double elements in the resulting element

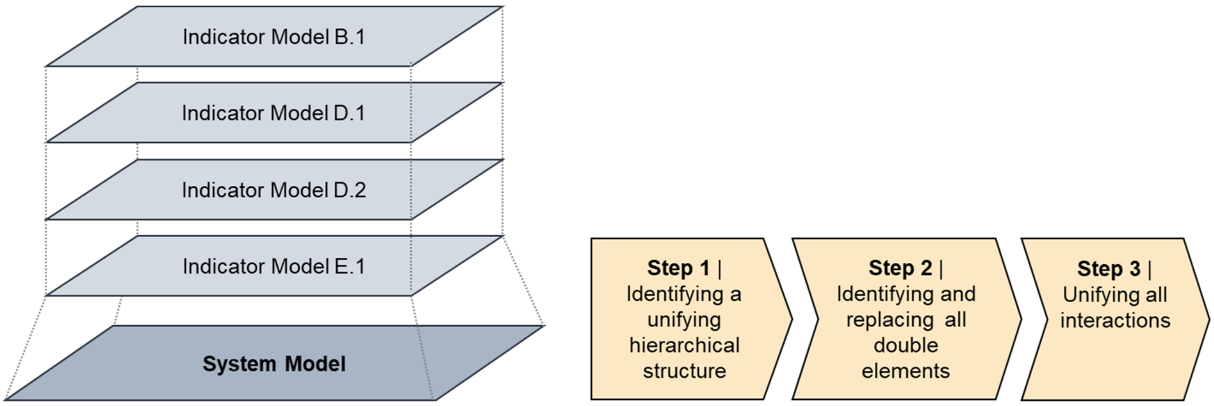


Figure 3-15: General procedure to combine a system model out of individual indicator models

Step 1 | Before delimitating the indicator models within the scope of building construction, their hierarchical structure itself has to be defined. Due to the obvious dependence of each product system on available resources and the direct mutual interaction between the environment and the product, there is a direct correlation between the global and local environmental system of earth. A primary focus is therefore put on the model system of the entire building, which can be subdivided further by three subsystems with regard to levels of perspective: room, building component and material level. As part of the technosphere, the man-made end product building is subject to the relations to the superordinate social and economic systems and is in direct relation to other product systems used in the manufacturing process. From the definitions of terms already cited, decisive relations between different subject areas can be filtered, which can be further abstracted as systems in a broader sense, in order to form and differentiate effective system boundaries and subject clusters (Ropohl, 2012, p.207).

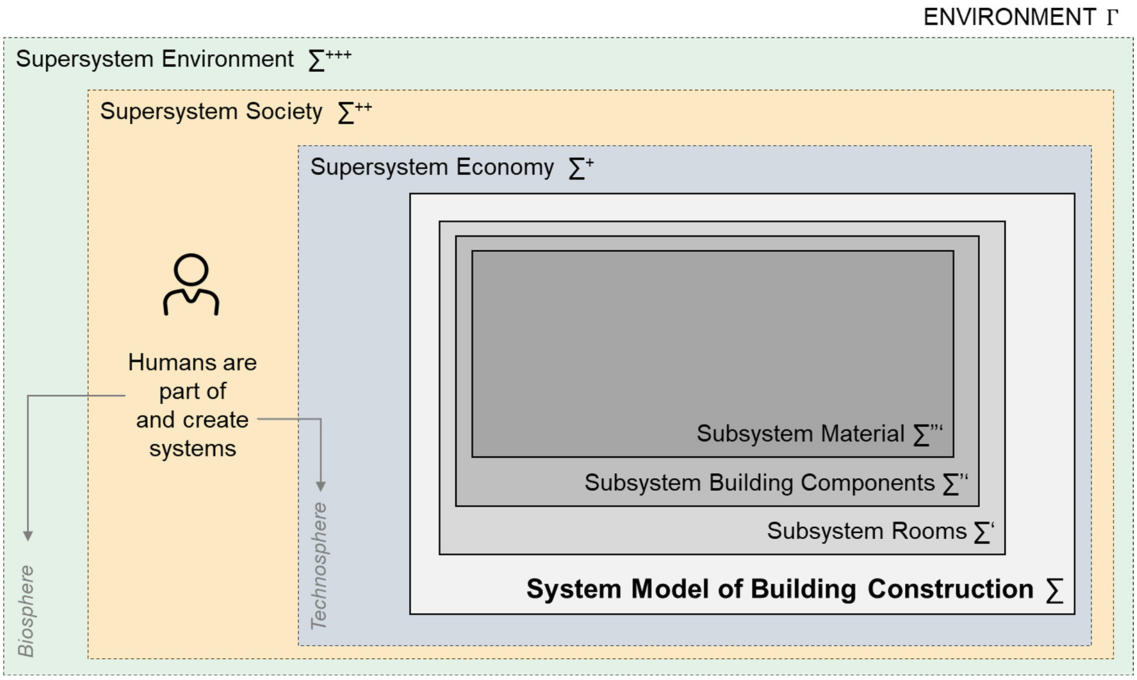


Figure 3-16: Hierarchical structure of the system model of building construction

Step 2 | Thanks to the “tools” of categorization, structuring of the individual indicator models can be done in a similar way. The dominant double elements are typical state variables like mass or volume as well as typical processes or life stages. A special focus is put on elements of information regarding the output of the final design stage:

- Choice of architecture
- Choice of construction
- Choice of material
- Choice of joints
- Choice of geometric design

A choice is the result of a decision. That is why these choices represent relevant decision factors (DF). These decision factors are mutually dependent and crucial for almost every indicator model and imply many different effects on indicator results. This is why relevant decision factors will be detailed in the following chapters (regarding options and variants), so they can be considered in the subsequent testing stage of the system model.

Step 3 | The final step for the creation of the system model of building construction is the implementation of all interactions. To achieve maximum comprehensibility of the system model, only two differences of interactions are used: linkages (→) with a direct effect and relations (—) with indirect effects. Functions are note displayed within the graphic but will be explained and used during the quantification and testing of the system model. The result is shown in Figure 3-17.

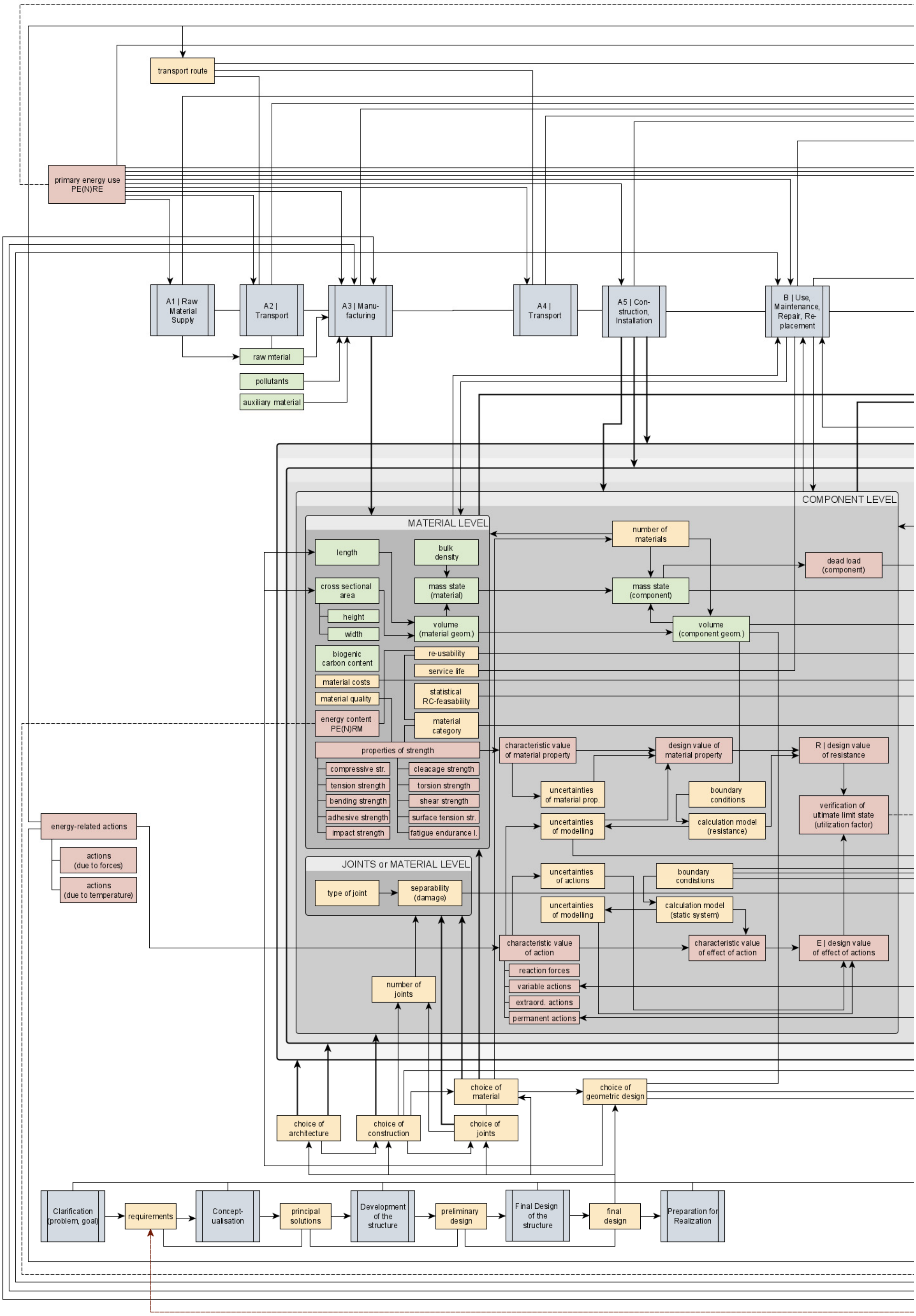
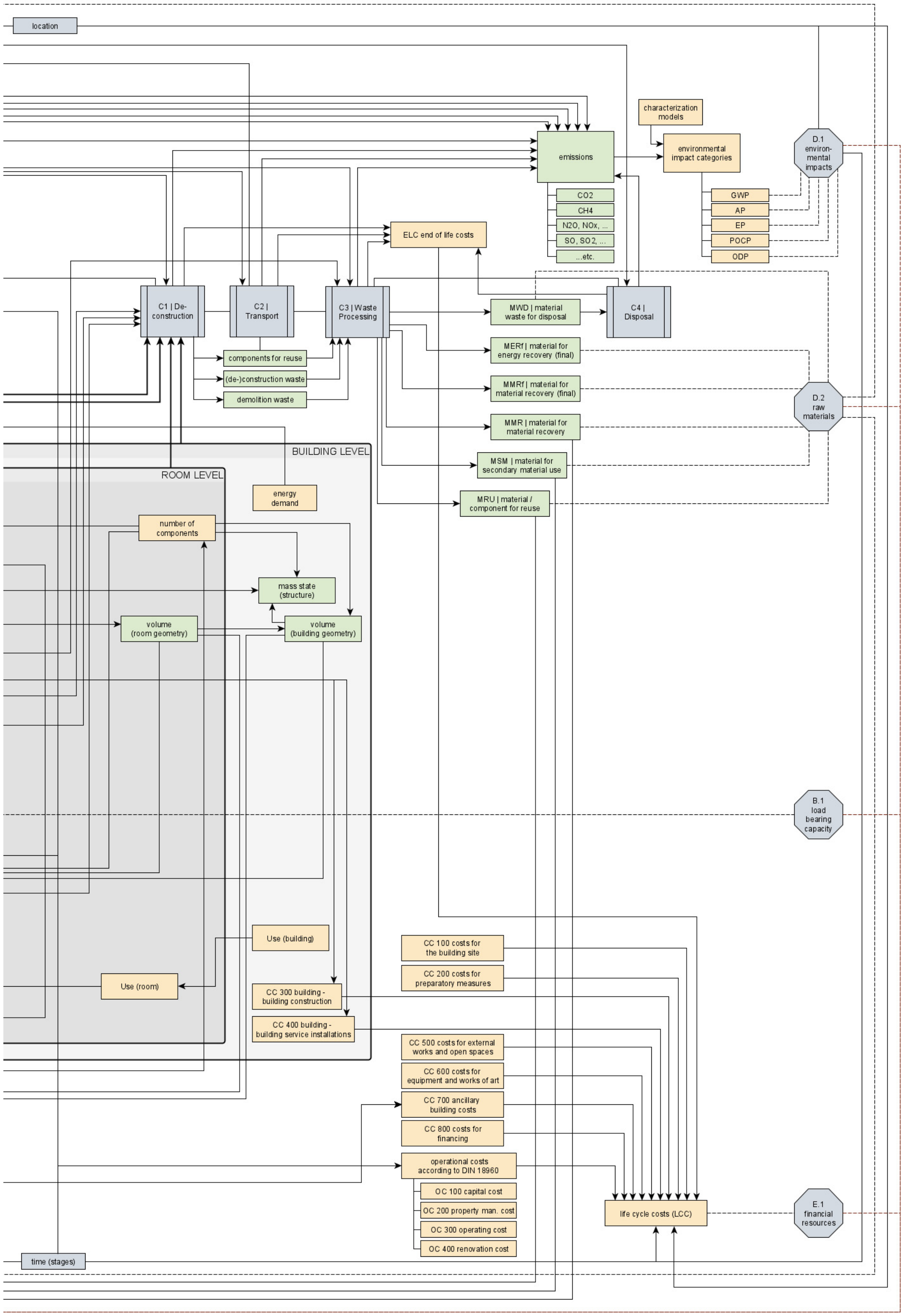


Figure 3-17: Flow chart of the reduced system model of buidling construction


location
characterization models
emissions
environmental impact categories
D.1 environ-mental impacts
CO2
CH4
N2O, NOx, ...
SO, SO2, ...
...etc.
GWP
AP
EP
POCP
ODP
ELC end of life costs
C1 | De-construction
C2 | Transport
C3 | Waste Processing
MWD | material waste for disposal
C4 | Disposal
components for reuse
(de-)construction waste
demolition waste
MERf | material for energy recovery (final)
MMRf | material for material recovery (final)
D.2 raw materials
MMR | material for material recovery
MSM | material for secondary material use
MRU | material / component for reuse
BUILDING LEVEL
ROOM LEVEL
energy demand
number of components
mass state (structure)
volume (room geometry)
volume (building geometry)
B.1 load bearing capacity
Use (building)
Use (room)
CC 100 costs for the building site
CC 200 costs for preparatory measures
CC 300 building - building construction
CC 400 building - building service installations
CC 500 costs for external works and open spaces
CC 600 costs for equipment and works of art
CC 700 ancillary building costs
CC 800 costs for financing
operational costs according to DIN 18960
OC 100 capital cost
OC 200 property man. cost
OC 300 operating cost
OC 400 renovation cost
life cycle costs (LCC)
E.1 financial resources
time (stages)

4 Application of the System Model for Building Construction

4.1 Scope of the Parameter Variation of Building Components

“There is nothing as useless as doing efficiently that which should not be done at all.” – Peter Drucker (US Economist), 1909-2005 (Drucker, 1963)

4.1.1 Goal and Scope of the Parameter Variation Selection

In the following chapter, the indicator models and the system model as a whole is transformed into computable models and tested via parameter variation. The quantification aims to test the model for its suitability as a meaningful basis for value-based decision-making within the complexity of multiple goals and holistic approaches. To comply with the scope of this thesis, the complexity of goals is limited to the indicator models already elaborated:

- B.1 | Adequate structural safety
- D.1 | Minimization of environmental impacts
- D.2 | Economic use of raw materials
- E.1 | Economic use of financial resources

The scope and the extent of the system model are determined by which kind of goal and therefore which indicator model are considered (as shown in chapter 3.2.7). Since the scope of an entire building – including the room, component and material level – cannot be implemented with necessary depth inside the scope of this thesis, four goals and indicator models were preselected. This selection has shown that it is possible to limit the extent of the analysis in this thesis to the levels of building components and building materials.

In the light of the set of problems outlined at the beginning (cf. chapter 1), the selection of different building components has been further limited to buildings from the "residential buildings" category. The variety of components has been additionally limited according to the structure of DIN 276, which excludes components regarding excavation (CG 319), installations (CG 370) and other (CG 390). Consequently, the system analysis of the model for building construction herein is concentrated on the following building components which will be outlined step by step:

- CG 330 | Exterior wall (EW)
- CG 340 | Interior wall (IW)
- CG 350 | Floor slab (FS)
- CG 360 | Pitched roof (PR) and flat roof (FR)
- CG 320 | Foundation (FO)

During the design process, different options of realisation for each component are determined. This includes different construction types and methods as well as individual building materials, layers, size, weight and alternative options of execution.

The final design, an iterative result of its consecutive design stages, is a display of the choices during its design process. As outlined in the system modelling, these choices can be displayed as decision factors (DF) and serve as a starting point for the definition of the scope of the parameter variation.

For the analysis of building components, three relevant decision factors are defined:

DF1. Choice of construction
DF2. Choice of material
DF3. Choice of geometric design

Every decision, and therefore every decision factor, contains the possibility for variation. The system analysis aims to investigate the extent, validity and interdependencies of these decision factors in regards to achieving their objectives.

Exterior Walls Components

Besides roofs, external walls are the central elements of the building envelope not in contact with the ground – literary giving the building its face in the form of the facade. External walls have to fulfil a multitude of functions in terms of functionality and because of their space-dividing design. Depending on the site-specific conditions, these functions include regulating the effects and fluctuations of the outside climate (heat, (air) humidity, precipitation, radiation, wind) as well as ensuring sufficient durability, load transfer, fire protection, noise protection, glare and visual protection and, protection against unwanted access (if necessary), daylight supply, integration of necessary operating resources and a sufficient fresh air supply. The design of the exterior wall components is shaped and in turn influences the socio-cultural context of the building and, based on the building materials and the underlying processes, causes cost and environmental effects (Herzog et al., 2017, p.9 ff; p.18).

The design of the exterior wall components is shaped by and in turn influences the socio-cultural context of the building and, based on the building materials and the underlying processes, causes cost and environmental effects (Herzog et al., 2017, p.9 ff; p.18).

The basic construction types of exterior walls (EW) distinguish between single-shell (EW1), double-shell (EW2) and homogenous or monolithic (EW0) types. In this thesis, a shell or leaf is understood as one of two different walls (ISO 6707-1, 2017) or a layer taking static loads (Herzog et al., 2017, p.28). Construction methods are already optimized and recognized types of construction that refer to material, construction technique or production methods (Moro, 2019b, p.12). With regard to parameter variations of exterior walls, the following *construction methods in regard to the material* (DF1.1) are considered:

- AC | Exterior walls made of aerated concrete
- BM | Exterior walls made of brick masonry
- CS | Exterior walls made of calcium silicate brick
- RC | Exterior walls made of (steel-)reinforced concrete
- ST | Exterior walls made of solid timber
- TE | Exterior walls made of timber elements/panels

Another difference in construction methods is the façade of exterior walls on the outside and therefore the appearance of the building. Since variations in geometry usually do not offer improved functionality, only a *variation of the façade design* (DF1.2) is considered. The facade design is differentiated into:

- p | Plaster facade or external wall insulation system (EWIS) with plaster layer
- t | Timber cladding on vertical/horizontal battens, if necessary with membrane
- f | Facing layer (as 2nd shell), facing or fair faced bricks with insulation

The following 20 basic versions result from the combination of construction type, material construction methods and facade design:

Table 4-1: Overview of the basic versions of exterior wall components

Construc-tion type	Material construction method						Facade design
	AC	BM	CS	RC	ST	TE	
0	EW0p-AC	EW0p-BM	-	-	-	-	p
1	EW1p-AC	EW1p-BM	EW1p-CS	EW1p-RC	EW1p-ST	EW1p-TE	
	EW1t-AC	EW1t-BM	EW1t-CS	EW1t-RC	EW1t-ST	EW1t-TE	t
2	EW2f-AC	EW2f-BM	EW2f-CS	EW2f-RC	EW2f-ST	EW2f-TE	f

Starting from these basic versions, essential building materials of the structural and insulation layer of an exterior wall are examined and variegated. By considering different material construction methods, the building material of the structural layer is already varied. The *variation of the structural layer* considers the direct relation between the choice of building material (DF2.1) and the building material geometry (DF3.1) on the one side and the load bearing capacity (B.1) on the other side. In addition, this variation also effects the other three objectives (D.1, D.2, and E.1).

A *variation of the insulation layer* with regard to building material (DF2.2) and geometry (DF3.2) not only reflects the obvious thermal function (A.3), but also the effects these decision factors have on the objectives of environmental impact (D.1), use of raw materials (D.2) and costs (E.1) – even if there is no relation to load bearing capacity. As far as possible, synthetic, mineral and natural building materials are included as insulation materials:

- MW | Mineral wool (rock wool/glass wool)
- EPS | Expanded polystyrene rigid foam
- PU | Polyurethane rigid foam
- WF | Wood fibre insulating materials
- CE | Cellulose insulation materials

Within the scope of the exterior wall analysis, the interior finish will be an internal plaster or an equivalent gypsum plasterboard. Further variations of the interior finish will be differentiated during the analysis of interior walls. In total, the selection of exterior wall components and their variation cover the following variations:

- Variation in construction type

- Variation in exterior finish
- Variation in structural layer
- Variation in insulation layer

In total, the variations of types, methods and parameters result in 544 component variations of the exterior wall (see chapter 4.1.6).

Interior Walls Components

In contrast to exterior walls, interior walls generally do not need to regulate climate differences (except when partitioning heated and unheated rooms). However, interior walls still have central functions as separating elements between different rooms inside the building. The more different the use and requirements of the separated rooms, the greater the functional expectations for the separating interior wall.

Depending on the situation, these include load transfer, fire protection, sound insulation or the integration of building services, as well as often also elements for improving the room acoustic, humid or visual conditioning of the rooms (Hausladen and Tichelmann, 2010, p.120 ff). Due to upstream and downstream processes, the design of interior walls also has an effect on the economic (E.1) and ecological quality (D.1 and D.2).

Concerning interior walls (IW), a distinction is made between *single-shell* (IW1) and *double-shell* (IW2) *construction types*. Single-shell interior walls usually separate individual rooms from each other, whereas double-shell interior walls often function as partitions between different residential or usage units.

Next, the following *material construction methods* (DF1.1) are investigated:

- AC | Interior walls made of aerated concrete
- BM | Interior walls made of brick masonry
- CS | Interior walls made of calcium silicate brick
- RC | Interior walls made of (steel-)reinforced concrete
- ST | Interior walls made of solid timber
- TE | Interior walls made of timber elements/panels

In analogy to the exterior walls, the combination of construction types and material construction methods results in the following 12 basic variants:

Table 4-2: Overview of the basic versions of interior wall components

Construction type	Material construction method					
	AC	BM	CS	RC	ST	TE
1	IW1-AC	IW1-BM	IW1-CS	IW1-RC	IW1-ST	IW1-TE
2	IW2-AC	IW2-BM	IW2-CS	IW2-RC	IW2-ST	IW2-TE

Being essential parameters for interior walls, the structural layer and the interior finish are differentiated. Considering different construction methods already covered a variation of possible construction materials of the base layer, which therefore only need to be supplemented by different designs in quality (DF2.1) and geometry (DF3.1).

The *variation of the interior finish*, similar to the exterior finish of external walls, does not offer any sensible options for variation of individual building materials or their geometry, but primarily a differentiation into different design variants (DF1.3). The options are structured as follows:

- in | Installation level
- pl | Interior plaster or simple planking
- pp | Double planking or thicker plaster
- vs | Visible surface, if necessary with paint
- ff | Facing framework (shell)

If interior walls are insulated, mineral wool is used with no further differentiation of insulating materials. The use of insulation material primarily serves soundproofing and fire protection functions, therefore its quantity is significantly lower compared to the components of the building envelope. Regarding different possible insulation materials and their effects, reference is therefore made to the analysis of the exterior wall and roof components.

In total, the following variations are covered with the selection of interior wall components:

- Variation of construction type
- Variation of interior finish
- Variation of structural layer

In total, the various variations and parameters result in 192 variants of interior wall components (see chapter 4.1.6).

Roof Components

Together with exterior walls, roof components are the central elements for the building's envelope. Roofs therefore fulfil a variety of functions analogous but different to exterior walls, depending on location. These include the function of load bearing (snow, wind, operational and dead loads), hygrothermal room conditioning (heat, [air] humidity, precipitation, radiation, wind), noise and fire protection as well as sufficient durability and, daylight (if required), fresh air and operating materials supply. Roof components are differentiated according to the roof shape and divided into two categories: pitched roof (PR) with a slope greater than 10° or flat roof (FR) with a slope of 10° or less (ISO 6707-1, 2017). A further design feature of roofs concerns the position of the sealing as well as the rear ventilation of the construction, which is why a distinction is made between ventilated (cold roof) and conventional unventilated roof (warm roof). Flat roofs can also be constructed with the insulation above the sealing, as an inverted roof (Sedlbauer et al., 2010, p.98 ff). Since the construction differs more in the arrangement of the layers than in the type of layers, these variants are not additionally differentiated and only non-ventilated flat roof constructions are investigated. With regard to roof category, type of use, and material construction method, the following roof components are considered:

- PR | Pitched roofs:
  - PR-ST | Pitched roofs made of solid timber
  - PR-TE | Pitched roofs made of timber elements/beams
- FR | Flat roofs:
  - FR-RC| Flat roofs made of (steel-)reinforced concrete
  - FR-ST | Flat roofs made of solid timber
  - FR-TE | Flat roofs made of timber elements/beams

Traditionally, flat roofs also offer the possibility of using the roof surface in the form of green roofs, roof coverings, gravel or other forms. The design of a usable flat roof has a much greater influence on the structural design, because it results in additional static loads and additional stresses for the roof finish (DF1.1). The use of the roof area and the resulting loads usually require a substructure or pressure-resistant building materials, which is why this differentiation is made regarding the basic variants. The possibilities of roof finishes are manifold and will be limited to the usual standard constructions in the context of this analysis.

The roof covering as exterior finish (DF1.2) is divided into roof finishes for pitched roofs, roof finishes for unused flat roofs and used flat roofs in particular:

- PR | Pitched roof:
  - m | Pitched roof with a metal roof
  - r | Pitched roof with roofing tiles
- FR | Flat roofs:
  - b | Flat roofs with bituminous flexible sheeting
  - s | Flat roofs with synthetic flexible sheeting
  - g | Flat roofs with a green roof and bituminous sealing

This selection results in the following 13 basic versions:

Table 4-3: Overview of the basic versions of roof components

Construction type	**Material construction method**			**Roof finish**
	RC	**ST**	**TE**	
PR0	-	PR0m-ST	PR0m-TE	**m** | Metal roof
	-	PR0r-ST	PR0r-TE	**r** | Roofing tiles
FR1	FR1b-RC	FR1b-ST	FR1b-TE	**b |** Bitumen sh.
	FR1s-RC	FR1s-ST	FR1s-TE	**s** | Synthetic sh.
FR2	FR2g-RC	FR2g-ST	FR2g-TE	**g** | Green roof

The *variation of the material construction method* (DF1.1) is accompanied by the variation of the structural layer, in particular regarding the *choice of material* used (DF2.1). This variation is supplemented by considering different *material geometries* (DF3.1) for the structural layer as well.

The variation of the thermal insulation layer on the one hand includes the *choice of building material* (DF2.2), on the other hand the *thickness of the insulation layer* (DF3.2). As far as possible, synthetic, mineral and natural building materials are analysed and classified according to their field of application (DIN 4108-10, 2015):

- External insulation in the roof as cavity insulation (DZ):
  - MW | Mineral wool (rock wool/glass wool)
  - EPS | Expanded polystyrene rigid foam
  - CE | Cellulose insulation
  - HW | Wood fibre insulation
- External insulation in the roof below the waterproofing membrane (DAA):
  - MW | Mineral wool (rock wool/glass wool)
  - EPS | Expanded polystyrene rigid foam
  - HW | Wood fibre insulation
- External insulation below the waterproofing and pressure-resistant (DAA-ds):
  - CG | Cellular glass
  - XPS | Extruded polystyrene rigid foam
  - PU | Polyurethane rigid foam

Frequently, the ceiling of the roof components also varies in structure and design. In order to avoid excessive variety due to additional variations of the interior finish, reference is made to the corresponding interior components (cf. exterior walls). Floor slabs cover different ceiling structures, whereas roof components are analysed with a simple planking or internal plastering.

In total, the following variations are covered within the selection of roof components:

- Variation of construction type
- Variation of exterior finish
- Variation of structural layer
- Variation of insulation layer

In total, the variations of construction types, methods, materials and parameters result in 234 variants of roof components (see chapter 4.1.6).

Floor Slab Components

Used as horizontal separating components, Floor Slabs primarily fulfil a supporting function within aspects of serviceability (e.g. deflection, vibration). Further functions, analogous to the interior walls, strongly depend on the requirements and differences of the rooms to be separated. These include – especially in the case of ceiling components between different usage units – sound insulation (particularly impact sound), fire protection, and the integration of supply and disposal systems (electricity, heat, water, and artificial light).

Additionally, ceilings also contribute to hygrothermal (e.g. thermal storage capacity), room acoustic (e.g. acoustic ceilings) and visual conditioning (e.g. lighting). With pre- and post-processes inherent in the building materials, any design changes of the ceilings also have an effect on the economic (E.1) and ecological quality (D.1 and D.2) (Moro, 2019a, p.856 ff).

For ceiling components, a division into shells is not appropriate, wherefore a distinction is made between flat floor slabs (GD2) and ribbed floor slabs (GD1). For the analysis of the floor slab components, types of construction are combined with material-specific construction methods (DF1.1):

- FS1 | Flat floor slabs:
  - FS1-RC | Flat floor slab made of (steel-)reinforced concrete
  - FS1-ST | Flat floor slab made of solid timber
  - FS1-HY | Flat floor slab made of composite timber-concrete slabs
- FS2 | Ripped floor slabs:
  - FS1-TE | Ripped floor slab made of timber elements/beams
  - FS1-HY | Ripped floor slab made of composite timber-concrete slabs

The result are the following five basic versions:

Table 4-4: Overview of the basic versions of floor slab components

Construction type	Material construction method			
	RC	ST	TE	HY
1 (flat)	FS1-RC	FS1-ST	-	FS1-HY
2 (ripped)	-	-	FS2-TE	FS2-HY

In principle, floor slabs can be divided into the flooring layer, the structural layer and the ceiling. The *variation of the material* of the load bearing structure (DF2.1) is directly linked with the choice of construction method and offers further *variations regarding geometry* (DF3.1). In addition to the load bearing structure, the decisive parameters for the construction method of floor slabs are the *flooring layer* above and possible *ceiling structures underneath* (DF1.3). The flooring structure includes the flooring layer and influences the sound insulation in regard to impact sound. It also protects against the effects of fire from above and is suitable to include installations. The specific flooring structure correlates with the specific ceiling structure, which is why a uniform flooring structure is used for all variants: filling (if necessary), separating layer, impact sound insulation and floating floor (Moro, 2019a, p.862 ff).

The interior finish in the form of the floor structure can also change during its life cycle. The decision in residential construction usually rests with the owner or user rather than with the designer. The following variants are distinguished for floor construction:

- tl | Tile flooring
- li | Linoleum flooring
- pa | Parquet (solid wood) flooring
- pc | PVC floor coating
- ca | Carpet flooring

In addition to general appearance, suspended ceilings serve to improve the thermal, acoustic and acoustic properties of the ceiling, to guarantee fire protection and to integrate installations

(Moro, 2019a, p.890 ff). With regard to the possibilities of ceiling structures a distinction is made between:

- sc | Suspended ceiling
- in | Installation level
- pl | Interior plaster or simple planking
- vs | Visible surface, if necessary with paint
- ff | Facing framework (shell)

Accordingly, the scope of floor slab components comprises the following variations:

- Variation of construction type
- Variation of interior finish - flooring
- Variation of interior finish - ceiling
- Variation of structural layer
- Variation of insulation layer

In total, the variation of flooring, ceilings, materials and other parameters result in 230 variants of floor slab components (see chapter 4.1.6).

Foundation Components

Foundation components form the lower end of the building towards the ground. Changing with the load situation, the load bearing system and ground conditions, foundation components transfer the load to the ground as foundation slabs. Alternatively, if the loads are transferred via supporting and strip foundations, it is floor slabs which form the outer boundary to the ground. Floor slabs are not only exposed load transfer, but to increased moisture load, which can consist of soil moisture (W1-E) or pressing water (W2-E) depending on the location (DIN 18533-1, 2017). In the case of water under pressure, the foundation is often made from water-impermeable concrete (WU concrete).

On this basis, the different construction variants are differentiated into foundation slabs with protection against soil moisture with drainage (1) and foundation slabs with protection against pressing water in WU quality (2). It is also assumed that the basement is used and thus inside the thermal envelope. The foundation slab therefore also has a thermal insulation function (Moro, 2019a, p.406 ff).

For the examination of the foundation slab components, the material construction method is specified (reinforced concrete) and it is divided into two construction variants (DF1.1):

- FO1-RC | Foundation slab made of (steel-)reinforced concrete against soil moisture
- FO2-RC | Foundation slab made of (steel-)reinforced concrete against pressing water

As an essential feature for the structural design of foundation slabs, the exterior finish concerning the insulation (DF1.2) also factors into the analysis. Concluding to the position of the insulation layer in the foundation, two possibilities are considered:

- i | Internal insulation
- x | Perimeter insulation

Combined, the following four basic variants become available for foundation components:

Table 4-5: Overview of the basic versions of foundation slab components

Construction type	Insulation (exterior finish)		Material construction method
	i	x	
1 | soil moisture (WE-1)	FO1i-RC	FO1x-RC	**RC** | (steel-)reinforced concrete
2 | pressing water (WE-2)	FO2i-RC	FO2x-RC	

The analysis of foundation slabs is further split between the *geometry of the structural layer* (DF3.1), the *geometry of the different insulation layers* (DF3.2) as well as the *interior flooring layer* (DF1.3).

The variation of the insulation layer includes on the one hand the choice of building material (DF2.2) and on the other hand the thickness of the insulation layer (DF3.2). With regard to the construction method, insulation materials for the interior floor (DEO) and exterior perimeter insulation materials (PB) are investigated (DIN 4108-10, 2015):

- Internal insulation materials (DEO):
  - MW | Mineral wool (rock wool/glass wool)
  - EPS | Expanded polystyrene rigid foam
  - PU | Polyurethane rigid foam
  - HW | Wood fibre insulation
- Perimeter insulation materials (PB):
  - CG | Cellular glass
  - XPS | Extruded polystyrene rigid foam

The interior finish in the form of the flooring layer is also part of the analysis. The different flooring options mirror the options from the analysis of floor slabs:

- tl | Tile flooring
- li | Linoleum flooring
- pa | Parquet (solid wood) flooring
- pc | PVC floor coating
- ca | Carpet flooring

Accordingly, the analysis of foundation slab components comprises the following variations:

- Variation of construction type
- Variation of interior finish - flooring
- Variation of structural layer
- Variation of insulation layer

In total, the various variations and parameters result in 280 variants of foundation slab components (see chapter 4.1.6).

4.1.2 Parameters for 'B.1 – Structural Safety'

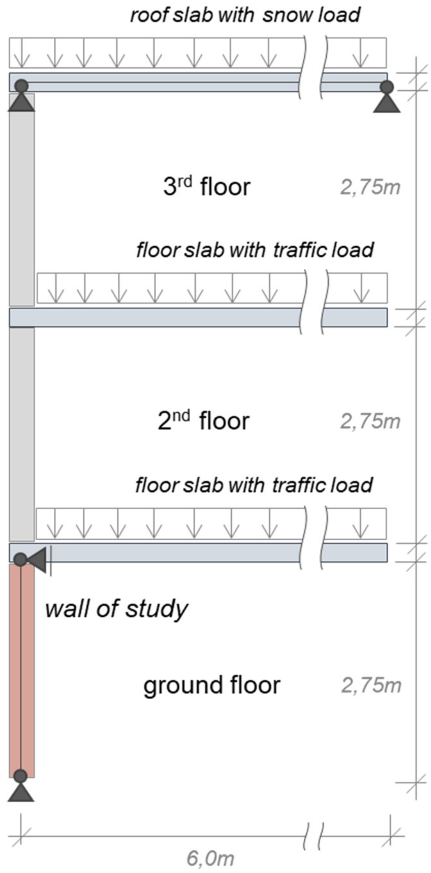
In the following sections, the previous assumptions about which components should be considered within the scope of this thesis' system analysis (cf. chapter 5) are further differentiated on the basis of the established goal indicators (cf. chapter 3.2), and the scope and limits of individual parameters of each indicator system are worked out. In doing so, the crucial decision factors (DF) that influence planning and design are used as a starting point.

Regarding the indicator to verify the ultimate limit state for the goal of adequate structural safety, the selection and variation of different building materials for the load bearing structure already determines the essential parameters of the material (bulk density, building material group, building material quality, strength properties, etc.). It is the basis from which the design value of resistance can be determined. To determine the ultimate limit state requires the design value of the effect of all actions. This value is calculated for each component specifically, depending on the calculation model. A standardized approach for all load bearing building components in this parameter variation in general would only be possibly achieved using a large number of simplifications and assumptions due to boundary conditions like room and building geometry, the surrounding components, or the use of the rooms and building. Similarly, the normative nature of indicators to reach the optimal utilization factor of one – ideally not less, but definitely not more – this indicator displays a very special nature (cf. chapter 5.2.1).

To illustrate this special nature of managing structural safety issues in construction, an exclusive showcase for the load bearing capacity of just the exterior walls is performed. This **showcase** study will determine necessary assumptions which cannot represent any universal settings, as each building and building component has unique boundary conditions. Having set arbitrary but reasonable boundary conditions for exterior wall components in a simple setting, the next step is to determine the design value of the effect of actions and the utilisation factor as the verification of the ultimate limit state of the wall component. In reality, the verification procedure can be manifold and cover a multitude of limit states and settings. This approach offers the possibility to illustrate and discuss the special nature of the goal of structural safety without having to reduce the analysis to a one-sided analysis of either the maximum design value of resistance or the minimum design value of the effect of random actions.

To determine the design value of resistance, a setting with only vertical normal forces is chosen, and the design value of the minimum effect of the actions as normal force N_{Ed} (in kN/m) as well as the maximum absorbable normal force N_{Rd} (in kN/m) is determined for the wall components. For a uniform consideration and a consistent basis for comparison, the boundary conditions for determining the design values, based on conditions typical of residential construction and design engineering, are defined as follows:

Table 4-6: Boundary conditions of the showcase for a simplified load case of an exterior wall

Exterior wall components		**Sketch of the static system**
Geometry of the wall component	– Height of the wall: h = 2.75 m – Length of the wall: L = ‘running metre’ – Width: individual widths of components	
Connected component	– Wall of study: wall at ground floor level – Three stories on top – Floor slab on top of the wall in the ground floor, 1st, and 2nd floor – Roof slab on top of the wall in 3rd floor	
Static system	– Wall plate with free rotation and fixed translation on top and bottom end (Euler’s critical load case 2). – Embedded depth: (a) full width of the wall or (b) 2/3 of the width of the wall for homogeneous one-shell walls. – Floor/roof slabs as single-span beams or slabs with a span width of 6.0 m	
Actions	– **Snow load:** s_k = 1.2 kN/m² (assumption) – **Traffic load:** q_k = 2.0 kN/m² (assumption) – **Dead load:** Roof: g_k = 5.0 kN/m² (assumption) Slabs: g_k = 6.0 kN/m² (assumption) Wall: individual dead load of components (calculation)	
Context	– Loadbearing structure – Indoor conditions, no direct weathering of the structure	
Basis of Design	– Brickwork (AC, BM, CS): *DIN EN 1996-3 with NA; chap. 4.2* – Steel-reinforced concrete (RC): *DIN EN 1992-1-1 with NA: chap. 12.6* – Timber construction (ST, TE): DI*N EN 1995-1-1 with NA: chap. 9.2.4*	

The design value of the effect of action N_{Ed} (in kN/m) is calculated according to EN 1990:2005 chapter 6.3.2 as:

$$N_{Ed} \leq 1.35 \cdot G_k + 1.5 \cdot Q_k + 1.5 \cdot 0.6 \cdot S_k \tag{4-1}$$

G_k	Total dead loads of all relevant components (as vertical forces in kN/m);
Q_k	Total traffic loads (as vertical forces in kN/m);
S_k	Total snow loads (as vertical forces in kN/m)

Horizontally acting forces resulting from the bracing structure of the building are not taken into account. According to the specific showcase scenario, the design value of the effect of actions (based on equation 4-1) can be simplified to:

g_k	Dead load of the wall component (in kN/m^2)
G_k	$= 2 \cdot 2.75m \cdot g_{k,EW} + (6.0/2) \cdot (2 \cdot g_{k,FS} + g_{k,FR})$
Q_k	$= (6.0/2) \cdot 2 \cdot q_k$
S_k	$= (6.0/2) \cdot s_k$

$$N_{Ed} \leq 1.35 \ \cdot (2 \cdot 2.75 \ \cdot g_{k,EW} + 51.0) + 21.2 \text{ [kN/m]} \tag{4-2}$$

The design value of resistance – here the maximum normal pressure force N_{Rd} (in kN/m) – that can be absorbed by wall components is calculated according to the basis of design by each material as:

Concrete according to EC2: DIN EN 1992-1-1:2011, chap. 12.6.5(1) equation (12.10):

$$N_{Rd} \leq b \ \cdot \ d \ \cdot f_{cd,pl} \ \cdot \ \phi \tag{4-3}$$

b	Total width of the cross section (here: one running meter);
d	Total thickness of the cross section;
$f_{cd,pl}$	Design pressure strength according to equation (3.15) (EC2);
Φ	Factor for considering the load centre, including the effects according to theory II. order and the normal effects of creep according to equation (12.11) (within the same standard: EC2)

Masonry according to EC6: DIN EN 1996-3/NA:2012, chap. 4.2 equation (4.4):

$$N_{Rd} \leq b \ \cdot \ d \ \cdot f_d \ \cdot \ \phi_S \tag{4-4}$$

b	Total width of the cross section (here: one running meter);
d	Total thickness of the cross section;
$f_{cd,pl}$	Design pressure strength of the masonry according to Annex D;
Φ_S	Reduction coefficient to take account of the slenderness and the load centre according to 4.2.2.3. (within the same standard: EC6)

Solid Timber according to EC5: DIN EN 1995-1-1/NA:2010 chap. 6.1.5 und chap. 6.3.2, the lower value is decisive:

Pressure perpendicular to the grain direction on the bottom plate will not be considered, since there are many solutions to solve this issue (Kaufmann et al., 2018). Bending and buckling of the wall panel according to equation (6.23):

$$N_{Rd} \leq \left(\frac{1}{k_{c,y} \cdot A \cdot f_{c,0,d}} + \frac{a}{W \cdot f_{m,d}} \right)^{-1} \tag{4-5}$$

a	Load centre referred to the wall axis;
A	Effective contact area of the CLT plate;
W	Effective area moment of inertia of the CLT plate;
$f_{c,0,d}$	Design value of the compressive strength along the fibre;
$f_{m,d}$	Design value of the bending strength;
$k_{c,y}$	Buckling coefficient according to equation (6.25) for buckling around the y-axis (within the same standard: EC5)

Timber Panel Walls according to EC5: DIN EN 1995-1-1/NA:2010 chap. 6.1.5 und chap. 6.3.2, the lower value is decisive:

Pressure perpendicular to the grain direction on the top/bottom plate:

$$N_{Rd} \leq k_{c,90} \cdot f_{c,90,d} \cdot A_{eff}/e \tag{4-6}$$

$k_{c,90}$	Coefficient to take into account the type of action, the risk of splitting and the degree of compression deformation according to 6.1.5 (2)/(3)/(4) around the y-axis (within the same standard: EC5);
$f_{c,90,d}$	Design value of compressive strength perpendicular to the fibre;
A_{eff}	Effective contact area under pressure perpendicular to the grain direction;
e	Centre distance of the studs/posts;

Bending and buckling of the wall panel according to equation (NA.60):

$$N_{Rd} \leq \left(\frac{e}{k_{c,y} \cdot A \cdot f_{c,0,d}} + \frac{a \cdot e}{k_{crit} \cdot W \cdot f_{m,d}}\right)^{-1} \tag{4-7}$$

e	Centre distance of the studs/posts;
a	Load centre referred to the wall axis;
A	Effective contact area of the stud;
W	Effective area moment of inertia of the stud;
$f_{c,0,d}$	Design value of the compressive strength along the fibre;
$f_{m,d}$	Design value of the bending strength;
$k_{c,y}$	Buckling coefficient according to equation (6.25) for buckling around the y-axis (within the same standard: EC5)

The building materials of the load bearing layers (strength properties) and the building material geometry (cross-sectional areas and thickness) in addition to the construction method (verification procedure) are the parameters that influence the goal of sufficient load bearing capacity. There are of course many additional design choices to be made, which is reflected in the context and all of the assumptions made for the showcase scenario. The importance and effects of these assumptions is not part of the parameter variation but have to be considered, too. Due to the scope of the showcase only the exterior walls are investigated. The following decision factors on the level of building components are relevant for the goal B.1 and therefore part of the variation:

- DF1 Construction
  - DF1.1 Construction: Type of construction
- DF2 Choice of material
  - DF2.1 Choice of material: Structural layer
- DF3 Choice of geometric design
  - DF3.1 Choice of geometric design: Structural layer

4.1.3 Parameters for 'D.1 – Minimizing Environmental Impacts'

Determining the indicator values for the goal of minimizing environmental impact rests on the methodology of life cycle assessment. Only the essential aspects and boundary conditions of the study are summarized at this point. Special focus within the scope of the study is put on the essential principles of life cycle assessment according to DIN EN 14040 (2009, p.15 ff):

(a) Life cycle perspective
(b) Environmental focus
(c) Relative approach and functional unit
(d) Iterative approach
(e) Transparency
(f) Comprehensiveness
(g) Priority of the scientific approach

Table 4-7: Overview of the goal and scope of the LCA study in this thesis

LCA according to DIN EN 14040/44, DIN EN 15804 and DIN EN 15978	
Goal of the study	The goal of the study is to illustrate and calculate the environmental impact of different building components, varying in building type, material, geometry and function.
Impact Categories	The **environmental focus** (b) of the building components will be displayed on the basis of the following impact categories: • GWP – Global Warming potential • EP – Eutrophication potential • AP – Acidification potential • ODP – Ozone depletion potential • POCP – Photochemical Ozone Creation potential • ADPE – Abiotic resources Depletion Potential (elements) • ADPF – Abiotic resources Depletion Potential (fossil fuels)
Scope of the study	The LCA calculation includes all component variants developed within the scope of this work on exterior and interior wall, roof, ceiling and foundation components.
Functional Unit	The study lays a focus on building components. The basic function of building components can be abstracted to the creation of spaces through surfaces. Accordingly, one square meter of the undisturbed component is defined as a **functional unit** (c): 1.0 m² component area

Database	Basis: ÖKOBAUDAT of the BMUB Version: 2019-III of 29.05.2019, which is based on the background database GaBi. Procedure: With regard to data quality, datasets were thoroughly chosen according to the intended purpose and the conformity to the requirements of DIN EN 15804. A prioritization of the data set types results: (1) 1. Representative dataset 2. Average dataset 3. Generic dataset 4. Specific dataset For this reason, in some cases specific datasets were used if no average data sets were available.
Allocation procedure	Specific allocation procedures are not applied, but reference is made to the allocation procedures according to the respective data sets and EPDs.
Reference Study Period (RSP)	50 years (2) Respected service life (RSL) of the materials and components according to "service life of components for life cycle analysis according to BNB" (BBSR, 2017).
Regional system boundary	The choice of background data from ÖKOBAUDAT (German average data sets – critically reviewed life cycle assessment data), includes a regional focus on and system boundary of Germany.
Life Cycle Stages (temporal system boundary)	The calculation refers to the life cycle from cradle to gate with options. • A | Manufacturing and construction • B | Use (related to the construction) • C | Deconstruction and disposal In the use phase (B), only the stages of maintenance (B2) and replacement (B4) of the building materials with a shorter service life was considered. Data records that do not cover the disposal phase (C) are additionally linked to corresponding end-of-life data records.
Cut-Off criteria	All material flows are cut-off, if the individual material flow is less than 1.0% of the mass input and all cut off material flows do not account for more than 5.0% in total (if necessary). The same rule applies with regard to the relationship between material flows and the results of the impact categories.
Annotations: (1) Data record classification according to the ÖKOBAUDAT-Handbook Version 1.0 of the BBSR of 18.03.2018 (2) Referring to German certification procedure by BNB and DGNB and based on EN 1990:2002/A1:2005, table 2.1	

Since the focus of the analysis is on building components, manufacturing and construction aspects play a primary roll, considering the goal is to minimize environmental impacts. In addition to environmental impacts caused by manufacturing and construction processes, impacts due to the operation of the building (heating energy, warm water, electricity etc.) may play a decisive role in the overall environmental impacts of a building. For example, depending on the age, the use and the building envelope the ratio between impacts caused by the building structure (the product) and impacts due to the use of a building can make up to 30-45% of GWP in new multi-storey residential buildings (Mahler et al., 2019, p.49 ff).

For this reason, it is not yet possible to make a conclusive statement on the environmental impacts of a building as a whole by considering the impacts caused by construction. Yet it is an important first step and the best possible statement at the component level. Furthermore, various insulation layers of the envelope components (exterior wall, roof and foundation) as an early indicator for the performance during the use phase are considered. The variations of the insulation layer have an influence on the hygrothermal conditioning as well as on the energy demand of the building during operation and therefore have additional major impact, aside from the structural layer and the windows (Mahler et al., 2019, p.51). Therefore, the thermal transmittance value of building components **(U-value)** is calculated and displayed as a side-indicator for the goal of 'A.3 hygrothermal conditioning of the interior'. For the purpose of the **life cycle perspective** (a) the parameter variation covers the maintenance (B2) and replacement (B4) of materials and components as well. For the goal of **transparency** (e) the LCA study carried out in the context of this thesis for exemplary building components can be found in the Appendix. Furthermore, the selection of suitable datasets for the different materials and layers can also be found in the 'LCA material list' (see Appendix).

In conclusion, the choice of construction method (construction type, number of building materials), the choice of building materials and joints (upstream chains) and the choice of geometric design (volume and mass) in particular influence the amount of environmental impacts. These choices are part of the following decision factors, which are relevant for the goal of minimizing environmental impacts:

- DF1 Construction
  - DF1.1 Construction: Type of component
  - DF1.2 Construction: Exterior finish
  - DF1.3 Construction: Interior finish
- DF2 Choice of material
  - DF2.1 Choice of material: Structural layer
  - DF2.2 Choice of material: Insulation layer
- DF3 Choice of geometric design
  - DF3.1 Choice of geometric design: Structural layer
  - DF3.2 Choice of geometric design: Insulation layer

4.1.4 Parameters for 'D.2 – Economic Use of Raw Materials'

The determination of indicator results (cf. Table 3-13) for the goal of an economic use of raw materials is based on two approaches. The indicators of raw materials used for energy purposes (Primary energy) are calculated according to the LCA method (cf. chapter 4.1.3). The approach to determine the recyclability of building materials is based on the material flow model (cf. Figure 4-1) resulting from an ongoing research project (Ebert et al., 2020a), which will now be described in more detail.

In addition to the selection of building materials, the choice of joining these building materials to building components as well as joining building components to each other, to rooms, and to the building as a whole are important decision factors in the planning process. Connections between building materials and building components can be differentiated into form interlocking (FIJ), friction-locked (FLJ) and firmly bonded joints (FBJ) and depend on the joining method. The possible selection of joining methods is based on the systematics of the German Standard for joining methods (DIN 8580, 2003). Based on the chosen joining method during planning and construction, the separability of this connection can be predicted (DIN 8593-0, 2003, p.4). The separability of the joints is therefore classified with a three-step assignment in:

- + … can be separated **without** any damage
- o … can be separated with sufficiently little damage
- – … can only be separated **with** damage

On this basis, each joint between the building materials is assigned to one of these three categories. A distinction is made between inconclusive joining methods, in case they are damaged, or their solubility is otherwise limited due to lack of accessibility, high number or other influences. The overview can also be extended at any time with regard to new developments of joining methods in the building industry or, if necessary, further differentiated.

Table 4-8: Overview of Joining Methods and their Separability

Joining Method	German Abbreviation	Type	Separability
Assembling			
Laying, Attaching, Layering (loose)	AUF-l	FIJ	+
Laying, Attaching, Layering (magnetic)	AUF-m	FIJ	+
Inserting, Fitting (e.g. pivot, misalignment, jamming)	EIN	FIJ	+
Plugging (e.g. bolts and dowels)	INEIN	FIJ	+
Mounting (e.g. springs)	HÄNG	FIJ	+
Sorting (e.g. zippers, hook and loop fastener)	RENK	FIJ	+
Latching (e.g. spring lock)	SPREI	FIJ	+
Filling			
Pouring	FÜL	FIJ	+
Soaking; Saturating; Impregnating	IMP	FBJ	-
Pressing on and Forcing in			
Screwing – preformed	vSRA	FLJ	+
Screwing – self drilling (e.g. wood screws)	sSRA+	FLJ	o
Screwing – self drilling (hidden, or high number)	sSRA-	FLJ	-
Clamping (e.g. rope clip)	KLEM	FLJ	+
Clipping	KLAM	FLJ	+
Press Fitting (e.g. interference fit, shrinking, stretching)	PRESS	FLJ	o
Nailing, Pinning, Driving in (e.g. wood nails)	NAG+	FLJ	o
Nailing, Pinning, Driving in (e.g. staples, high number)	NAG-	FLJ	-
Wedging	KEIL	FLJ	+
Bracing	SPANN	FLJ	+
Primary Shaping			
Grouting (e.g. in-situ concrete)	AGIE	FBJ	o

Embedding	EIBET	FBJ	-
Casting (e.g. two parts together)	VGIE	FBJ	-
Galvanizing	GALV	FBJ	-
Coating	UMM	FBJ	-
Caulking	KIT	FBJ	-
Transforming			
Joining by Transforming wire-shaped materials	UMFD	FIJ	o
Joining by Transforming sheets, pipes and profiles	UMFB	FIJ	o
Joining by Riveting	NIET	FIJ	-
Welding			
Pressure Welding	PSCHW	FBJ	-
Fusion Welding	SSCHW	FBJ	-
Soldering			
Soft Soldering	WLÖT	FBJ	-
Hard Soldering	HLÖT	FBJ	-
Adhesives			
Physical Binding Adhesives	PKLEB	FBJ	-
Chemical Binding Adhesives	CKLEB	FBJ	-
Soluble Adhesives	KLEB+	FBJ	o
Coating with Liquid Materials			
Painting, Varnishing	STR	FBJ	-
Coating with Plastic Materials			
Puttying	SPA	FBJ	-
Coating with Pasty Materials			
Plastering, Rendering	PUT	FBJ	-

In order to make a statement as to which extent the joined materials are dismantled or recovered as components, or leave the construction site as construction or demolition waste, two types of information must be compared:

- Information regarding the separability of the joint
- Information of the material category.

Within this combination, three cases are distinguished:

(1) One of the joined building materials or components is suitable for reuse and all its joints are solvable without or with sufficient little damage (+ or o).
→ The joint is separated in the course of **dismantling** and the building material can be reused as **material or components for reuse (MRU).**

(2) One of the two joined building materials represents a pollutant, a disturbing substance, construction site waste or gypsum construction waste due to its building material group.
→ The joint is separated during **selective deconstruction**, the building materials are separated and go the usual disposal route of their respective waste category as **(de)construction site waste (DS)** or **demolition waste (DW).**

(3) For all other cases in which the joined construction materials are neither suitable for reuse nor represent a pollutant or disturbing substance in the construction waste

→ The joint is irrelevant and is, if at all, separated during **demolition** of the building. The materials are further processed as **demolition waste (DW).**

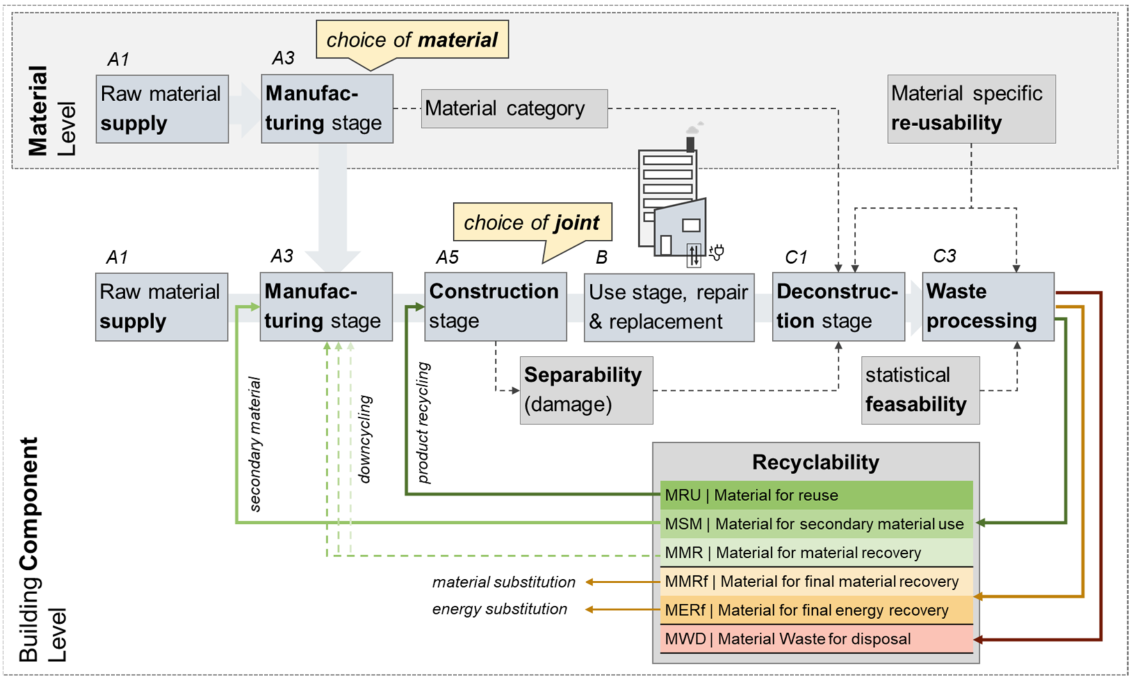


Figure 4-1: Simplified structure of the linkage to determine the recyclability of material flows

According to this distribution, the individual materials and building materials can be sorted as materials and components for reuse, as (de-)construction site waste or as demolition waste. Their recyclability cannot be exclusively attributed to the separability of the building materials; it also depends on the sorting and the feasibility of the recycling process. Furthermore, economic aspects in terms of effort, costs and benefits can have a considerable influence on the implementation of a closed loop recycling system. For these reasons, the material flow model uses current statistical distributions to determine the extent to which the waste flows from (de-)construction site waste and demolition waste can be assigned to the different material categories

The breakdown of the statistical feasibility of the recycling processes is based on the waste categories as outlined in the work of [1] Deilmann & Reichenbach (2017), [2] Steger & Ritthoff et al (2018) and the [3] monitoring report of Kreislaufwirtschaft Bau (2016):

Table 4-9: Overview of the statistical distribution of waste flows

Material Category (waste flow)	MRU(1)	MSM	MMR	MMRf	MERf	MWD	Sources
Concrete (DW)	n/s (2)	0,0%	77,7%	16,1%	0,0%	6,2%	[2] / [3]
Brickwork (DW)	n/s (3)	0,0%	77,7%	16,1%	0,0%	6,2%	[1] / [3]
Calcium Silicate (DW)	n/s	0,0%	77,7%	16,1%	0,0%	6,2%	[1] / [3]
Aerated Concrete (DW)	n/s	0,0%	77,7%	16,1%	0,0%	6,2%	[1] / [3]

Tiles & ceramics (DW)	n/s	0,0%	77,7%	16,1%	0,0%	6,2%	[1] / [3]
Other minerals (DW)	n/s	0,0%	77,7%	16,1%	0,0%	6,2%	[1] / [3]
Mineral insulation (DS)	n/s	0,0%	64,9%	28,9%	0,0%	6,2%	[1] / [3]
Gypsum Boards (DS)	n/s	0,0%	4,5%	40,1%	0,0%	55,4%	[3]
Other gypsum (DS)	n/s	0,0%	4,5%	40,1%	0,0%	55,4%	[3]
Sheet glass (DS)	n/s	0,0%	83,3%	0,0%	0,0%	16,7%	[2]
Solid timber (DS)	n/s (4)	0,0%	11,5%	0,0%	88,5%	0,0%	[2]
Wood-based material (DS)	n/s (4)	0,0%	11,5%	0,0%	88,5%	0,0%	[2]
Paper (DS)	n/s	0,0%	11,5%	0,0%	88,5%	0,0%	[2]
Other timber materials (DS)	n/s	0,0%	4,3%	0,0%	95,7%	0,0%	[1] / [2]
Synthetic insulation (DS)	n/s	0,0%	25,3%	0,0%	72,3%	2,4%	[1] / [2]
Synth. windows/doors (DS)	n/s (6)	0,0%	36,6%	0,0%	61,0%	2,4%	[1]
Synth. membranes (DS)	n/s	0,0%	25,3%	0,0%	72,3%	2,4%	[1] / [2]
Other synth. materials (DS)	n/s	0,0%	25,3%	0,0%	72,3%	2,4%	[1] / [2]
Steel, iron (DS)	n/s (5)	97,5%	0,0%	0,0%	0,0%	2,5%	[2]
Aluminium, copper, zinc, plumb (DS)	n/s (5)	91,2%	0,0%	0,0%	0,0%	8,8%	[2]

Annotations:
(1) No statistical data for reuse is available; therefore, the material flow model is used. Examples of reuse are given.
(2) E.g. prefabricated elements or facade elements
(3) E.g. solid bricks and clinker
(4) E.g. large-sized slabs, plates and beams, depending on the geometry
(5) E.g. large format carriers, depending on geometry and use
(6) Depending on the damage and the condition of the elements

Two main decision factors during the planning phase are the choice of construction method (DF1) and the choice of material (DF2) and thus the group of building materials behind it and the choice of joining, which significantly influences the goal of an economic use of raw materials. The choice of joints is included and varies with the different construction methods in the form of basic versions and the type of construction, the exterior or interior finish. Construction methods that have a high degree of separability regarding the type of joining have not yet become standard in civil engineering and often represent special cases of construction (Hillebrandt et al., 2019, p.138 ff). For these reasons, further differentiation and variation of the joints is not explicitly considered.

The determination of an economic use of raw materials and in particular energy resources is based on the LCA method. This is why all decisions that influence the mass and volume of the material and components are relevant for the indicators of energy resources (PEET, PEMT) as well as the indicators of the raw material flows. In total, the following set of decision factors have an influence on the goal ‘D.2 economic use of resources’:

- DF1 Choice of construction
  - DF1.1 Choice of construction: Type of component
  - DF1.2 Choice of construction: Exterior finish
  - DF1.3 Choice of construction: Interior finish
- DF2 Choice of material

  - DF2.1 Choice of material: Structural layer
  - DF2.2 Choice of material: Insulation layer
- DF3 choice of geometric design
  - DF3.1 Choice of geometric design: Structural layer
  - DF3.2 Choice of geometric design: Insulation layer

4.1.5 Parameters for 'E.1 – Economic Use of Financial Resources'

The indicator Life-Cycle-Costs (LCC) describes all costs of building construction in order to depict an economic use of financial resources. The basis used to calculate the indicator Life-Cycle-Costs on building components level is the accounting method according to German Standard (DIN 276, 2018) and data from the German 'Baukosteninformationszentrum' (BKI). This method is hierarchically structured according to cost groups (cf. chapter 3.1.2) and provides different levels of detail. To be able to calculate costs for different building components the calculation is based on the detailed level of building elements – positions.

The BKI database for 'building elements – positions' lists construction costs in tabular form as gross and net prices with 'minimum', 'from', 'average', 'to' and 'maximum' prices. The 'from', 'average', and 'to' prices represent the usual range of position prices and are used in this work. The positions are structured according to the service areas of the standard service book and illustrated and explained by reviewed specimen texts for the tender phase (BKI, 2019b, p.30 ff). With the BKI database in the background, each building component is split into positions which are allocated to the respective position of the database, represented by a specific Position-ID. The calculation of the total costs is done by multiplying the costs from the database with a factor according to the respective reference unit of the position (e.g. m^2, m^3 or kg), resulting in the construction costs with 'from', 'average', and 'to' prices. The different prices for positions already cover different option of execution in regard to material quality and geometry. To be able to consider further options the calculation factor can be interpolated linearly between existing datasets.

Regarding the system boundaries of the calculation of the life cycle costs (cf. chapter 0), the available BKI database only covers construction costs. Referring to the life-cycle of a building the construction costs depict a mix of services and materials and cover parts of the product (upstream of the building material: A1-3 | Raw material extraction, transport and production) and construction stage (implementing the materials: A4-5 | Transport, Construction, Installation). However, not all positions and materials (especially newer and not yet widespread solutions) are covered in detail, for which carefully balanced assumptions have to be made. All assumptions are derived from detailed investigation, comparisons with example costs and total costs of the component. Due to the principle of transparency and to offer the possibility to exchange the underlying assumptions with better data (when available), Table 4-10 gives an overview of the assumptions made. It goes without saying that due to the underlying assumptions and the general volatility of costs, the calculation results are to be interpreted with care and can change rapidly. The calculation nevertheless offers important and representative results in regard to the current situation in the first quarter of the year 2019. Furthermore, the selection of suitable datasets for the different materials and layers can also be found in the 'LCC material list' (see Appendix).

Table 4-10: Overview of necessary assumptions in the cost calculation

Material	Position-ID	Position Name
Cross laminated timber	361.16.P06	GLT, coniferous timber, GL24h, industrial quality (1)
Massive timber slabs	351.16.P80	Plank slab or dowel laminated timber, massive timber slab < 14cm, planed, with recesses (2)
	351.16.P81	Plank slab or dowel laminated timber, massive timber slab < 16cm, planed, with recesses (2)
	351.16.P82	Plank slab or dowel laminated timber, massive timber slab < 20-22cm, planed, with recesses (2)
Composite timber-concrete slabs	351.13.P63	Floor slab, in-situ concrete, C25/30, < 25 cm (3)
	331.13.P115	Steel-reinforcement (reinforcement mattresses) (4)
	361.16.P06	GLT, coniferous timber, GL24h, industrial quality (1)

Annotations:
(1) German: BSH, Nadelholz, GL24h, Industriequalität
(2) German: Brettstapel, Massivholzdecke bis 14/16/20-22cm, gehobelt, inkl. Aussparungen
(3) German: Decke, Ortbeton, C25/30, bis 25cm
(4) German: Bewehrung (Betonstahlmatten)

Furthermore, the entire system analysis focuses on building components (CG 300), which constitutes a lower hierarchical level where, since additional information is still lacking, only parts of the life cycle costs can be calculated. To serve the aspect of a holistic life-cycle approach, the use phase was considered, too, based on the life-cycle assessment approach described earlier. In the use phase (B), only the stages of maintenance (B2) and replacement (B4) of the building materials with a shorter respected service life (RSL) than the respected study period (RSP) of the building component or building were considered. The RSP for the building component is 50 years. The RSL of the materials and positions is considered according to “Service life of components for life cycle analysis according to BNB” (BBSR, 2017).

The calculation only covers construction and operational costs of building components (CG 300) without the costs for deconstruction and disposal. This is due to missing data for the end of life stage of buildings. This approach is based on the official procedure used in the BNB system methodology (BMI, 2018). The indicator LCC is compiled cumulatively and is supplemented and completed by partial indicators like construction costs, operational costs and others. In total, the following set of decision factors influence the goal ‘E.1 economic use of financial resources’:

- DF1 Choice of construction
  - DF1.1 Choice of construction: Type of component
  - DF1.2 Choice of construction: Exterior finish
  - DF1.3 Choice of construction: Interior finish
- DF2 Choice of material
  - DF2.1 Choice of material: Structural layer
  - DF2.2 Choice of material: Insulation layer
- DF3 Choice of geometric design
  - DF3.1 Choice of geometric design: Structural layer
  - DF3.2 Choice of geometric design: Insulation layer

4.1.6 Overview of all Parameters and Variations

The individual versions of building components result from the variation of the decision factors and the combination of these among themselves. The following section provides a more detailed definition of individual parameters and an overview of the extent of the parameter variation.

First, in order to provide a basis for further detailed definition of the variations, an overview of all decision factors and different choices is necessary.

Table 4-11: Overview of decision factors and variations

DF	Variation of the different decisions
DF1 – Choice of construction	**DF1.1** *Choice of construction method* – **variation of construction type:** − Different types of building components (EW, IW, PR, FR, FS, FO) − Variation of construction type (0/1/2/…)
	DF1.2 *Choice of construction method* – **variation of exterior finish:** − Different facade design on exterior walls (f, p, t) − Different roofing for pitched and flat roofs (b, s, g, m, r) − Different insulation layers for foundations (i, x)
	DF1.3 *Choice of construction method* – **variation of interior finish:** − Different finish on interior walls (vs, pl, pp, in, ff) − Different ceilings for floor slabs (vs, pl, in, sc, ff) − Different flooring for floor slabs and foundations (tl, li, pa, pc, ca)
DF2 – Choice of material	**DF2.1** *Choice of material* – **variation of structural layer:** − Different materials for wall components (AC, BM, CS, RC, ST, TE) − Different materials for roof components (RC, ST, TE) − Different materials for floor slab components (RC, ST, TE, HY)
	DF2.2 *Choice of material* – **variation of insulation layer:** − Different façade insulation materials (MW, EPS, PU, WF, CE) − Different insulation materials for pitched roofs (MW, EPS, WF, CE) − Different insulation materials for flat roofs (MW, EPS, XPS, PU, WF, CG) − Different insulation materials for foundations (MW, EPS, XPS, PU, WF, CG)
DF3 – Choice of geometric design	**DF3.1** *Choice of geometric design* – **variation of structural layer:** − Different wall thickness − Different roof slab and beam height − Different floor slab and beam height − Different foundation slab height
	DF3.2 *Choice of geometric design* – **variation of insulation layer:** − Different thickness of wall insulation − Different thickness of roof insulation − Different thickness of insulation in foundation

All these different variations result in different versions of building components. To be able to conclusively identify every version, the following notation for a version of a building component is used in the parameter variation, including all different possibilities of variations:

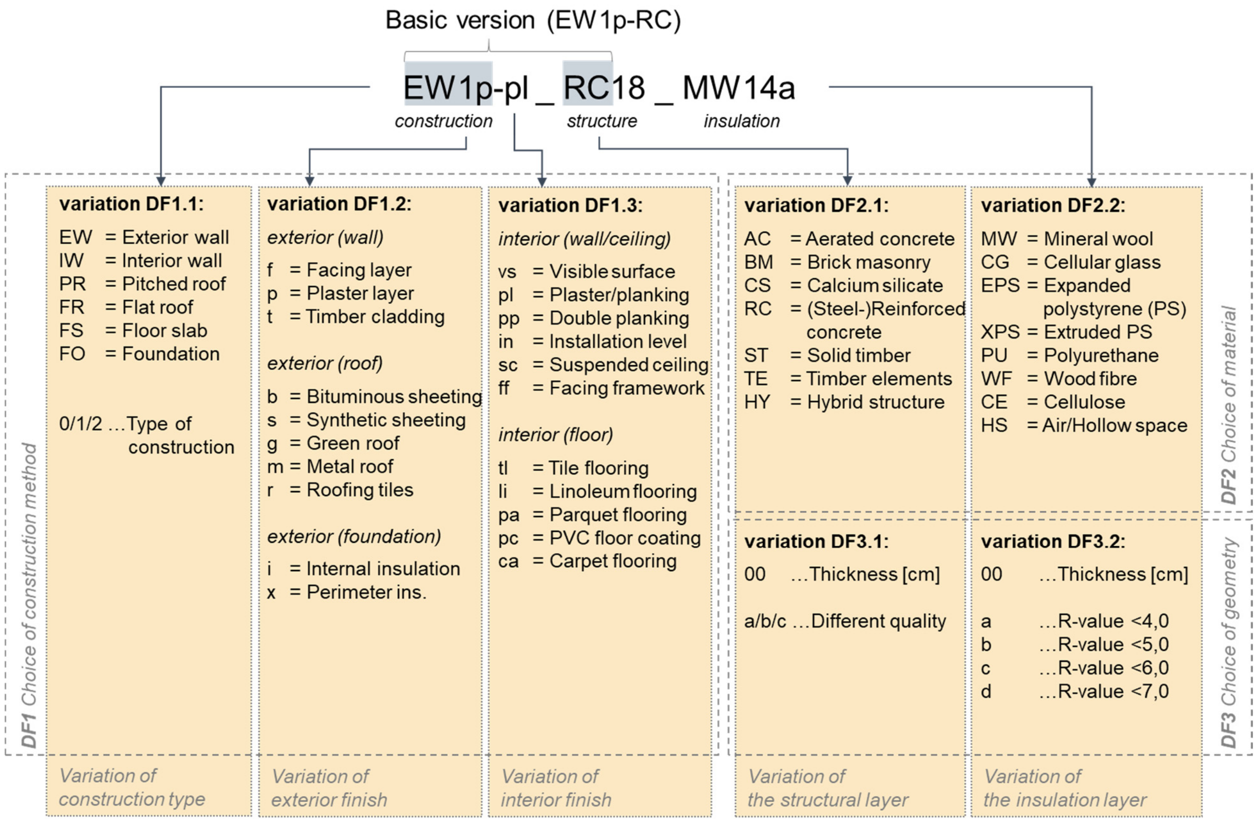


Figure 4-2: Example and overview of the parameter variation and version notation

Example (cf. Figure 4-2): The example can be identified as far and as unambiguously as possible by the notation alone. The basic version is a single-shell exterior wall made of steel reinforced concrete with a thermal insulation composite system (EW1e_RC). The in-situ reinforced concrete base layer has a thickness of 180 mm (RC18). The insulation layer of mineral wool has an insulation thickness of 140 mm (MW12).

In the following passage, each variation will be defined in detail, for transparency and to be able to reconstruct the parameter variation and the indicator results. The choice of construction method often defines the number, location and functions of layers and is the basis for further decisions regarding the choice of materials or geometric design. This is why the parameter variation differs the main layer bundles of exterior, insulation, structural and interior layer of building components.

The construction type of building components is based on the basic structures of components: single-shell, double-shell, multi-compound, ripped and membrane structures (Moro, 2019c, p.120). In addition to these basic structure specific functions like traffic loads (cf. roof components), or water resistance (cf. roof and foundation components) are included as well. Whereas the structural layer and the insulation layer are analysed with different materials and geometry, the exterior and interior finishes are analysed only by different typical design options (Moro, 2019b, p.344 ff; Hausladen and Tichelmann, 2010, Part C).

Table 4-12: Parameter variations of the construction type, exterior and interior finish

DF1.1 – Variation of construction type		DF1.2 – Variation of exterior finish	DF1.3 – Variation of interior finish
EW	0 = Single-shell, monolithic 1 = Single-shell 2 = Double-shell	f = Facing layer p = Plaster layer t = Timber cladding	pl = Plaster/planking
IW	1 = Single-shell 2 = Double-shell	-	vs = Visible surface (1) pl = Plaster/planking pp = Double planking (2) in = Installation level ff = Facing framework
PR **FR**	0 = Pitched roof 1 = Flat roof with no traffic 2 = Flat roof with foot traffic	b = Bituminous fl. sheet. s = Synthetic fl. sheet. g = Green roof m = Metal roof r = Roofing tiles	pl = Plaster/planking
FS	1 = Flat slab 2 = Ripped slab	-	vs = Visible surface (3) pl = Plaster/planking in = Installation level sc = Suspended ceiling ff = Facing framework ----------------------------- tl = Tile flooring li = Linoleum flooring pa = Parquet flooring pc = PVC floor coating ca = Carpet flooring
FO	1 = Soil moisture (WE-1) 2 = Pressing water (WE-2)	i = Internal insulation x = Perimeter insulation	tl = Tile flooring li = Linoleum flooring pa = Parquet flooring pc = PVC floor coating ca = Carpet flooring

Annotations:
(1) Visible surfaces on interior walls only usual in exposed concrete, calcium silicate bricks and solid timber wall components.
(2) Double planking for interior walls only usual in solid timber, timber panel wall or metal stud wall components.
(3) Visible surfaces on floor slab ceilings only usual for exposed concrete and solid timber slabs.

As a result of the variation of the construction method, **basic versions** of the construction components can be identified by considering the type of component, the construction type with the exterior finish and the main construction material. The interior finish can be adapted and changed more easily than the basic version as a whole. Thus, the basic version defines the principle layout of the component and the basis for further variations.

Though the structural layer primarily serves the load bearing function (which is calculated only for the exterior wall components), the choice of material and geometric design also impacts the other three goals of the parameter variation. The choice of different materials for the structural layer follows the premise to cover typical construction materials and their geometric design. Of course, not all different specific options of construction methods and design options can be depicted. It is also not the goal to cover components with exactly the same functionality, but rather to demonstrate the different performance levels. In addition to the variation of the main structural materials, the quality and different options of the structural layer are considered as well: e.g., the wall thicknesses vary according to the usual use in terms of minimum thickness, brick formats or state of the art.

Table 4-13: Parameter variations of the structural layer

DF1.1	**DF2.1** *Choice of material* **– Variation of structural layer**		**DF3.1** *Choice of g. design* **– Variation of structural l.**
EW0-AC	**AC (1)**	AC engineering bricks in thin-bed laying RDK 0.5 or 0.8 an SFK 2 or 4	d = 300/365/425/480/500 mm
EW1/2-AC		AC engineering bricks in thin-bed laying RDK <0.8 & SFK 4	d = 175/240 mm
IW-AC		AC engineering bricks in thin-bed laying RDK <0.8 & SFK 4	d = 115/150/175/200 mm
EW0-BM	**BM (5)**	HLz(2) with insulation filling in thin-bed laying, RDK(3) 0.75 and SFK(4) 6 or 10	d = 300/365/425/490 mm (6)
EW1/2-BM		HLz in thin-bed laying, RDK 1.2 and SFK 12	d = 175/240 mm (6)
IW-BM		HLz in thin-bed laying, RDK 1.4 and SFK 12	d = 115/175/240/300 mm (6)
EW-CS	**CS (6)**	Calcium silicate engineering bricks in thin-bed laying RDK 1.8 an SFK 12	d = 150/175/200 mm
IW-CS		CS engineering bricks in thin-bed laying RDK 1.8 an SFK 12	d = 115/150/175/200/240 mm
EW-RC	**RC (8)**	In-situ concrete C 25/30, with 1,0 Vol.-% steel reinforcement	d = 140/180/220 mm (7)
IW-RC		In-situ concrete C 25/30, with 1,0 Vol.-% steel reinforcement	d = 140/180/220 mm (7)
FR-RC		In-situ concrete C 25/30, with 2,0 Vol.-% steel reinforcement	d = 200/250 mm
FS-RC		In-situ concrete C 25/30, with 2,0 Vol.-% steel reinforcement	d = 200/250 mm
FO1-RC		In-situ concrete C 25/30, with 1,0 Vol.-% steel reinforcement	d = 250/350 mm
FO2-RC		In-situ concrete C 25/30 WU, with 2,0 Vol.-% steel reinforcement	d = 250/350 mm
EW-ST	**ST (10)**	Cross Laminated Timber (CLT) Panels, 3/5 layers, C24	d = 100/120/140 mm
IW-ST		CLT Panels, 3/5 layers, C24	d = 60/80/100/120 mm
PR-ST		CLT Panels, 3/5 layers, C24	d = 160/200 mm
FR1-ST		CLT Panels, 3/5 layers, C24	d = 160/200 mm
FR2-ST		CLT Panels, 3/5 layers, C24	d = 200/240 mm
FS-ST		CLT Panels, 3/5 layers, C24	d = 180/220 mm

EW-TE	TE (10)	Construction timber KVH C24, width of 80 mm, e = 625 mm	d = 120/160/200/240 mm (9)
IW-TE		Construction timber KVH C24, width of 60 mm, e = 625 mm	d = 120/160/200/240 mm (9)
PR-TE		Glue laminated Timber (GLT), GL24h, width of 80 mm, e = 625 mm	d = 180/240/300 mm
FR1-TE		Glue laminated Timber (GLT), GL24h, width of 120 mm, e = 1,0 m	d = 240/280 mm
FR2-TE		Glue laminated Timber (GLT), GL24h, width of 120 mm, e = 1,0 m	d = 280/320 mm
FS-TE		Glue laminated Timber (GLT), GL24h, width of 180 mm, e = 1,0 m	d = 280/320 mm
FS1-HY	HY (10)	CLT Panels, 3 layers, C24 with in-situ concrete C 25/30	d = 120+100/160+140 mm
FS2-HY		GLT GL24h, width of 180 mm, e = 1,0 m with in-situ concrete C 25/30	d = 240+120/320+120 mm

Annotations:
(1) Typical construction types and dimensions based on (Bundesverband Porenbetonindustrie e.V., 2018)
(2) HLz = “Hochlochziegel” [German for: vertical corning brick]
(3) RDK = “Rohdichteklasse” [German for: bulk density class of masonry]
(4) SFK = “Steinfestigkeitsklasse” [German for: strength grade of stones]
(5) Typical construction types and dimensions based on the delivery program of Schlagmann/Poroton: monolithic: e.g. Poroton FZ8/9 or Poroton S8/9; EW: engineering brick T1,2; IW: engineering brick T1,0
(6) Typical construction types and dimensions based on (Bundesverband Kalksandsteinindustrie e.V., 2018)
(7) Minimum thickness for concrete walls: 140mm (in-situ concrete), see DIN EN 1992-1 NCI chapter 12.9, p.90 (DIN EN 1992-1-1, 2011; DIN EN 1992-1-1/NA, 2013)
(8) Typical construction types and dimensions based on (InformationsZentrum Beton GmbH, 2020)
(9) Due to the average tree diameter, a height of 240mm for solid timber should not be exceeded.
(10) Typical construction types and dimensions based on (Kaufmann et al., 2018, Part C) and the “dataholz.eu”-database (HFA, 2020)

The building envelope includes an insulation layer, which is the basis for further variation. The insulation effects not only the effort in regard to costs, energy and impacts during manufacturing and construction, but also the use phase of a building. The quality of the building envelope has recently received ever increasing attention due to increasing requirements by politics (EnEV, 2007).

The choice of insulation material is dominated by the functionality of the insulation in regard to moisture, durability and pressure (DIN 4108-10, 2015). The thickness of the insulation layer is guided by typical thermal insulation standards (like the German ENEV), expressed by the R-value to consider the different thermal conductivity (λ) of the insulation materials. Furthermore, the delivery program of most insulation manufacturers (20 mm steps) is considered as well.

Table 4-14: Parameter variations of the insulation layer

DF1.1 *Choice of construction*	**DF2.2** *Choice of material* **– Variation of insul. layer**	**DF3.2** *Choice of geom. design* **– Variation of insulation layer**
EW components	**Wall insulation**	**R-value of 4.0/5.0/6.0**
EW0p | Single-shell, monolithic exterior wall	- Insulation bricks with mineral wool - AC bricks	d = Thickness of the exterior wall d = Thickness of the exterior wall
EW1p | Single-shell exterior wall with EWIS (WAP)	- Mineral wool - EPS rigid foam - PU rigid foam - Wood fibre	λ = 0.35; d = 140/180/220 mm λ = 0.35; d = 140/180/220 mm λ = 0.25; d = 100/140/160 mm λ = 0.40; d = 160/200/240 mm
EW1t | Single-shell exterior wall with cladding and cavity insulation below membrane (WH/WAA) (2)	- Mineral wool - EPS rigid foam - Wood fibre - Cellulose	λ = 0.35; d = 140/180/220/260 mm λ = 0.35; d = 140/180/220/260 mm λ = 0.40; d = 160/200/240/280 mm λ = 0.40; d = 160/200/240/280 mm
EW2f | Double-shell exterior wall with facing layer and cavity wall insulation (WZ)	- Mineral wool - EPS rigid foam - PU rigid foam	λ = 0.35; d = 140/180/220 mm λ = 0.35; d = 140/180/220 mm λ = 0.25; d = 100/140/160 mm
Roof components	**Roof insulation**	**R-value of 4.0/5.0/6.0/7.0**
PR0 | Pitched roof with roof insulation as cavity insulation (DZ)	- Mineral wool - EPS rigid foam - Wood fibre - Cellulose	λ = 0.35; d = 140/180/220/260 mm λ = 0.35; d = 140/180/220/260 mm λ = 0.40; d = 160/200/240/280 mm λ = 0.40; d = 160/200/240/280 mm
FR1 | Flat roof with no traffic and insulation below the waterproofing membrane (DAA-dm)	- Mineral wool - EPS rigid foam - Wood fibre	λ = 0.35; d = 140/180/220/260 mm λ = 0.35; d = 140/180/220/260 mm λ = 0.40; d = 160/200/240/280 mm
FR | Flat roof with foot traffic and pressure-resistant insulation below the waterproofing membrane (DAA-dh/ds)	- XPS rigid foam - PU rigid foam - Cellular glass	λ = 0.35; d = 140/180/220/260 mm λ = 0.25; d = 100/140/160/180 mm λ = 0.40; d = 160/200/240/280 mm
FO components	**Floor insulation**	**R-value of 2.0/3.0/4.0**
FO1 | Foundation with internal insulation	- Mineral wool - EPS rigid foam - PU rigid foam - Wood fibre	λ = 0.35; d = 80/120/140 mm λ = 0.35; d = 80/120/140 mm λ = 0.25; d = 60/80/100 mm λ = 0.40; d = 80/120/160 mm
FO2 | Foundation with perimeter insulation (PB)	- XPS rigid foam - Cellular glass	λ = 0.35; d = 80/120/160 mm λ = 0.45; d = 100/140/180 mm

Annotations:
(1) Data is based on: Material characteristics according to DIN EN ISO 10456:2010-05
(2) The EW1t-TE as a timber panel construction, offers a cavity insulation layer between the studs, which substitutes the additional external insulation layer.

On top of the boundary conditions for the variations regarding every material, every basic version of a building component is linked with a real example of a component in residential buildings. All these variations lead to 55 basic versions of building components with 1472 versions of building components in total.

Catalogue of Building Components

For most of the basic versions of the exterior wall components a real reference building can be found in the Appendix.

Table 4-15: Overview of all exterior wall components and variations

DF1	DF1.2	DF1.3	DF2.1	DF3.1	DF2.2	DF3.2	∑
EW0p_AC	p	pl	SFK2 | SFK4	300/365/425/480/500	HS	-	7
EW1t_AC	t	pl	SFK4	175/240	MW/EPS/WF/CE	R=4,0/5,0/6,0	24
EW1p_AC	p	pl	SFK4	175/240	MW/EPS/PU/WF	R=4,0/5,0/6,0	24
EW2f_AC	f	pl	SFK4	175/240	MW/EPS/PU	R=4,0/5,0/6,0	18
EW0p_BM	p	pl	SFK10 | SFK6	300/365/425/490	MW/HS	-	8
EW1t_BM	t	pl	SFK12	175/240	MW/EPS/WF/CE	R=4,0/5,0/6,0	24
EW1p_BM	p	pl	SFK12	175/240	MW/EPS/PU/WF	R=4,0/5,0/6,0	24
EW2f_BM	f	pl	SFK12	175/240	MW/EPS/PU	R=4,0/5,0/6,0	18
EW1t_CS	t	pl	SFK12	150/175/200	MW/EPS/WF/CE	R=4,0/5,0/6,0	36
EW1p_CS	p	pl	SFK12	150/175/200	MW/EPS/PU/WF	R=4,0/5,0/6,0	36
EW2f_CS	f	pl	SFK12	150/175/200	MW/EPS/PU	R=4,0/5,0/6,0	27
EW1t_RC	t	pl	C25/30	140/180/220	MW/EPS/WF/CE	R=4,0/5,0/6,0	36
EW1p_RC	p	pl	C25/30	140/180/220	MW/EPS/PU/WF	R=4,0/5,0/6,0	36
EW2f_RC	f	pl	C25/30	140/180/220	MW/EPS/PU	R=4,0/5,0/6,0	27
EW1t_ST	t	pl	C24	100/120/140	MW/EPS/WF/CE	R=4,0/5,0/6,0	36
EW1p_ST	p	pl	C24	100/120/140	MW/EPS/PU/WF	R=4,0/5,0/6,0	36
EW2f_ST	f	pl	C24	100/120/140	MW/EPS/PU	R=4,0/5,0/6,0	27
EW1t_TE	t	pl	C24 | MW/EPS/WF/CE	160/200/240/280	MW/EPS/WF/CE	-	16
EW1p_TE	p	pp	C24 | MW/EPS/WF/CE	160/200/240	MW/EPS/PU/WF	R=2,0	48
EW2f_TE	f	pp	C24 | MW/EPS/WF/CE	160/200/240	MW/EPS/PU	R=2,0	36
20	*basic exterior wall versions*			*Number of exterior wall components:*			**544**

Table 4-16: Overview of all interior wall components and variations

DF1	DF1.2	DF1.3	DF2.1	DF3.1	DF2.2	DF3.2	∑
IW1_AC	-	in/pl/ff	SFK4	115/150/175/200	-	-	12
IW2_AC	-	in/pl/ff	SFK4	115/150/175/200	-	-	12
IW1_BM	-	in/pl/ff	SFK12	115/175/240/300	-	-	12
IW2_BM	-	in/pl/ff	SFK12	115/175/240/300	-	-	12
IW1_CS	-	in/pl/vs/ff	SFK12	115/150/175/200/240	-	-	20
IW2_CS	-	in/pl/vs/ff	SFK12	2x115/150/175/200/240	-	-	20
IW1_RC	-	in/pl/vs/ff	C25/30	140/180/220	-	-	12
IW2_RC	-	in/pl/vs/ff	C25/30	2x140/180/220	-	-	12
IW1_ST	-	in/pl/pp/vs/ff	C24	60/80/100/120	-	-	20
IW2_ST	-	in/pl/pp/vs/ff	C24	2x60/80/100/120	-	-	20
IW1_TE	-	in/pl/pp/ff	C24 b=60	60/80/100/120	-	-	16
IW2_TE	-	in/pl/pp/ff	C24 b=60	2x60/80/100/120	-	-	16
13	*basic interior wall versions*			*Number of interior wall components:*			**184**

Table 4-17: Overview of all roof components and variations

DF1	DF1.2	DF1.3	DF2.1	DF3.1	DF2.2	DF3.2	∑
PR0m_ST	m	si	C24	120/160	MW/EPS/WF/CE	R=5,0/6,0/7,0	24
PR0r_ST	r	si	C24	120/160	MW/EPS/WF/CE	R=5,0/6,0/7,0	24
PR0m_TE	m	pl	GL24h | MW/EPS/WF/CE	180/240/300	MW/EPS/WF/CE	-	12
PR0r_TE	r	pl	GL24h | MW/EPS/WF/CE	180/240/300	MW/EPS/WF/CE	-	12
FR1s_RC	s	pl	C25/30	200/250	MW/EPS/WF	R=5,0/6,0/7,0	18
FR1b_RC	b	pl	C25/30	200/250	MW/EPS/WF	R=5,0/6,0/7,0	18
FR2g_RC	g	pl	C25/30	200/250	XPS/PU/CG	R=5,0/6,0/7,0	18
FR1s_ST	s	pl	C24	160/200	MW/EPS/WF	R=4,0/5,0/6,0	18
FR1b_ST	b	pl	C24	160/200	MW/EPS/WF	R=4,0/5,0/6,0	18
FR2g_ST	g	pl	C24	200/240	XPS/PU/CG	R=4,0/5,0/6,0	18
FR1s_TE	s	pl	GL24h	240/280	MW/EPS/WF	R=5,0/6,0/7,0	18
FR1b_TE	b	pl	GL24h	240/280	MW/EPS/WF	R=5,0/6,0/7,0	18
FR2g_TE	g	pl	GL24h	280/320	XPS/PU/CG	R=5,0/6,0/7,0	18
13	*basic roof versions*			*Number of roof components:*			**234**

Table 4-18: Overview of all floor slab components and variations

DF1	DF1.2	DF1.3	DF2.1	DF3.1	DF2.2	DF3.2	∑
FS1_RC	tl/li/pa/pc/ca	vs/pl/in/sc/ff	C25/30	200/250	-	-	50
FS1_ST	tl/li/pa/pc/ca	vs/pl/in/sc/ff	C24	180/220	-	-	50
FS2_TE	tl/li/pa/pc/ca	pl/in/sc/ff	GL24h	280/320	-	-	40
FS1_HY	tl/li/pa/pc/ca	vs/pl/in/sc/ff	C24 | C25/30	120+100 / 160+140	-	-	50
FS2_HY	tl/li/pa/pc/ca	pl/in/sc/ff	GL24h | C25/30	240+120 / 320+120	-	-	40
5	*basic floor slab versions*			*Number of floor slab components:*			**230**

Table 4-19: Overview of all foundation components and variations

DF1	DF1.2	DF1.3	DF2.1	DF3.1	DF2.2	DF3.2	∑
FO1i_RC	i	tl/li/pa/pc/ca	C25/30	250/350	MW/EPS/PU/WF	R=2,0/3,0	80
FO2i_RC	i	tl/li/pa/pc/ca	C25/30 WU	250/350	MW/EPS/PU/WF	R=2,0/3,0	80
FO1x_RC	x	tl/li/pa/pc/ca	C25/30	250/350	XPS/SG	R=2,0/3,0/4,0	60
FO2x_RC	x	tl/li/pa/pc/ca	C25/30 WU	250/350	XPS/SG	R=2,0/3,0/4,0	60
4	*basic foundation versions*			*Number of foundation components:*			**280**

4.2 Outcome of the Parameter Variation for Building Components

4.2.1 Approach and Presentation of the Results

The basis of this chapter is to present the results of the parameter variation. These are structured after the different indicators (cf. chapters 4.1.2 to 4.1.5) and grouped according to the decision factors identified for each indicator.

The level of detail in this chapter is increasing, starting from an overview of all components, to individual building component groups and, if necessary, to specific versions of components. The reader has to bear in mind that while the parameter variation is extensive, it is neither complete nor represents a real statistical distribution. This is not problematic for this thesis, since completeness would only lead to an increase of possible design choices without changing the results for the design options being considered. A set of components with a sample size weighted according to 'one' real distribution – amongst many in regard to the scope (like for Germany, Munich, worldwide, etc.) – would therefore lead to distorted results. The outcomes of a study with such an underlying distribution would lead to conclusions that are only valid for and representative of this specific case of the study and would be unusable for general conclusions. This is the reason why the scope of the parameter variation and the sample of building components were developed the way they were: to find general conclusions and interdependencies concerning the indicator results and the decision factors.

The goal of the depiction of variation results of individual indicators and parameters is to derive conclusions regarding those indicators. The discussion of the results regarding effectiveness in achieving the indicator targets or the correlation of the individual indicator results is presented in the subsequent chapter (cf. chapter 5).

The illustration of the results uses the Box-Plot-Diagram to depict their variety and distribution in regard to different clusters or structural orders of the results. The Box-Plot consists of four basic elements (Kosfeld et al., 2016, p.113 ff):

- The x in the box represents the **mean value**.
- The horizontal line in the box represents the **median**, which divides the data into a bottom and a top half.
- The **box** itself represents 50% of the data and is also called the interquartile range (IQR), with its bottom line representing the median of the bottom half – the first quartile (25%) –, and the top line representing the median of the top half – the third quartile (75%).
- The **whiskers** extending the box on top and bottom represent the minimum and maximum limits of the data – except for outliers which exceed a distance of 1.5 times the IQR below or above the box.

A simple example of the different masses of the parameter variation serves to illustrate the approach.

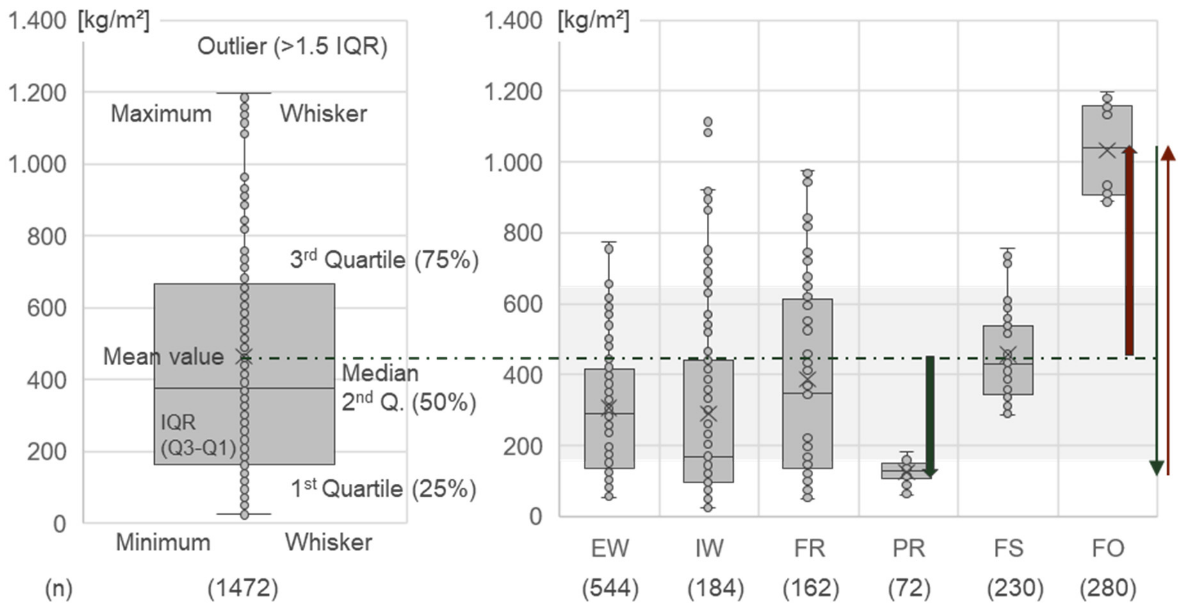


Figure 4-3: Example of the illustration of the results, depicting the mass of different building components, grouped according to the type of component

The example clearly demonstrates the possibilities for interpretation and conclusions. The mean value (465 kg/m²) differs from the median (376 kg/m²), which shows an imbalance towards higher masses. The mean 50% of all components lie between 166 kg/m² and 667 kg/m² – the bigger the box, the bigger the discrepancy between the data included.

In the distribution according to building components (on the right) pitched roofs (PR) covering only solid timber and timber element components give an example for little discrepancy (small box). It can be stated that the smaller the box, the better the distribution fits the underlying effect for the indicator under consideration. At the same time, the pitched roof components show to be the lightest group of all components with a mean value of only 27% (126 kg/m²) of the mean for all components, which constitutes a decrease in mass of -73%. Furthermore, all foundation components can be declared as especially heavy considering the mean value to be +221% (1033 kg/m²) of the general mean value, which constitutes an increase of +121%. The total dataset of foundation components lies between the 3rd quartile and the maximum of all components. The mean value of the other component groups fluctuates between 62% and 98% of the general mean value, with the data showing higher discrepancies. As a result, the choice of component type can lead to a total decrease of the mean value of mass of up to 88%.

For flat roofs and wall components, the high discrepancy of the data shows the need for another group arrangement; e.g. flat roofs already show different “groups” of datasets at the level of ~180 kg/m², ~400 kg/m² and <600 kg/m².

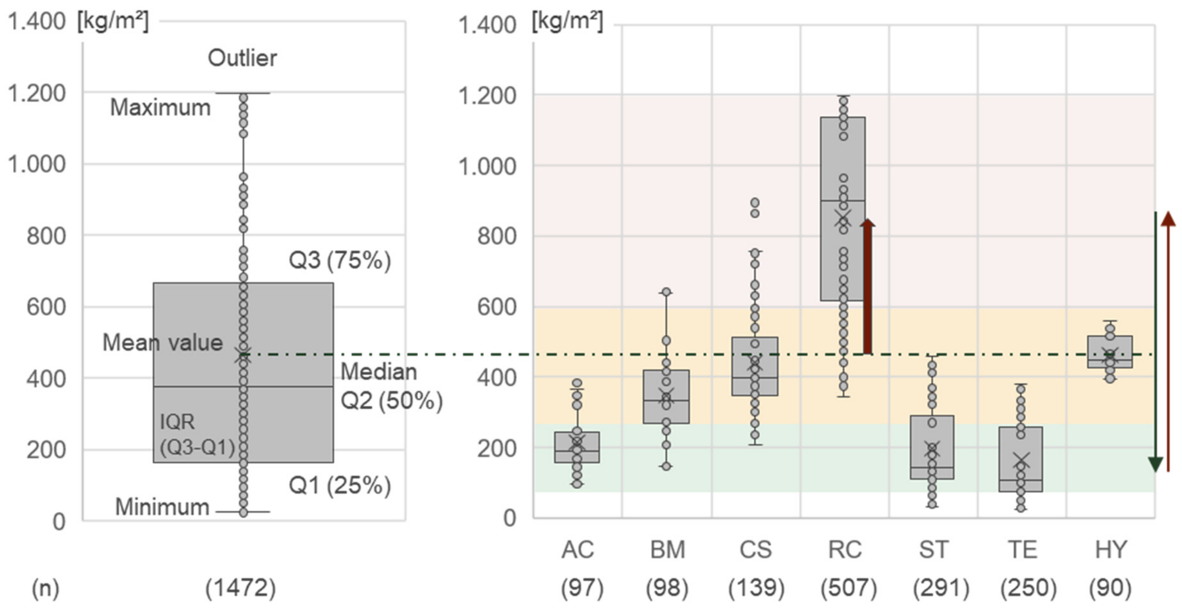


Figure 4-4: Example for the illustration of the results, depicting the mass of the building components, grouped according to the main structural material

The most significant observation here is the "smaller boxes" with therefore smaller discrepancies of data in the different groups. Only the concrete components show a high discrepancy (Foundation elements are only concrete elements) and a +83% (853 kg/m²) higher mean value than the total mean. The components can be put in a general hierarchal order with timber element, solid timer and aerated concrete components as the lightest (green area), brick, calcium silicate and hybrid components in the middle (yellow area) and concrete, especially foundation components, as the heaviest components (red area). As a result, the choice of the main structural material can lead to a total decrease of the mean value of mass of up to 81%, but with foundation components included. This is why an individual investigation of different groups will be necessary for further, more meaningful conclusions.

4.2.2 Outcomes for 'B.1 – Structural Safety'

The results are presented according to the decision factors for the indicator B.1 (cf. 4.1.2):

- DF1.1 Construction: Type of component
- DF2.1 Choice of material: Structural layer
- DF3.1 Choice of geometric design: Structural layer

DF1 Choice of Construction

In the context of structural safety, the investigation is limited to exterior walls (cf. 4.1.2). It is represented by the indicator of the utilization factor to verify the ultimate limit state. In this case, the utilization factor is described by the ratio between the impacting forces (E_d) and the resisting force (R_d). On the one hand, the maximum compressive force of resistance per running meter of wall reflects the maximum load-bearing capacity of the wall. On the other hand, the effect of all actions in the context of the showcase results in a maximum compression force per running meter. The quotient between the compression force resulting from all relevant actions (E_d in kN/m) and the force of resistance (N_{Rd} in kN/m) is expressed as a utilization factor of the wall construction. It is important to mention that the results only reflect the effects of the action according to one very specific and arbitrary showcase and cannot be generalized.

DF2 Choice of Material

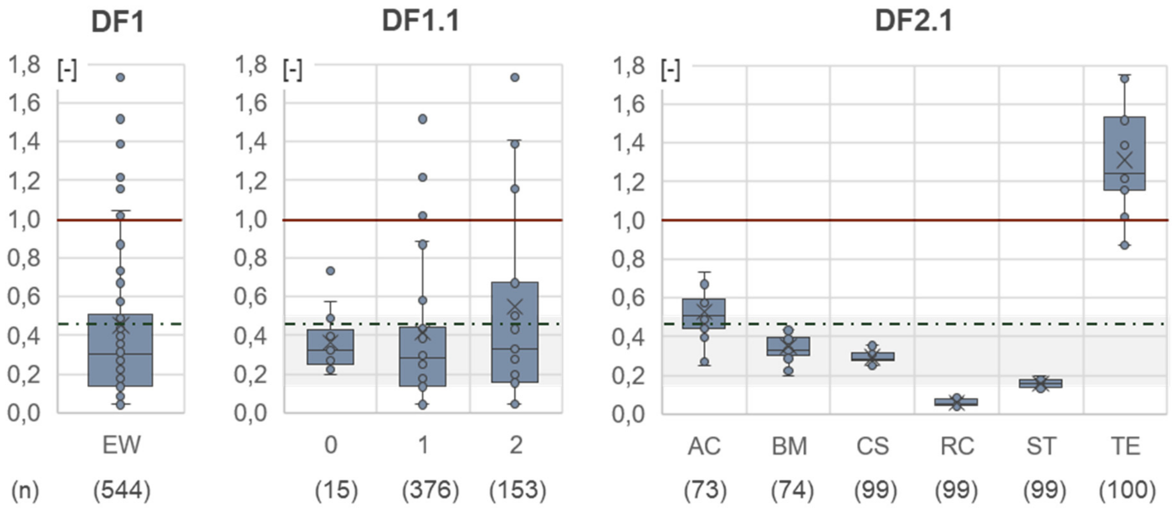


Figure 4-5: Indicator results for the 'utilization factor [-]' (B.1) for all exterior wall components, grouped according to different decision factors (DF)

The results show a high degree of variance and an average utilization of a running meter of exterior wall in the showcase scenario of 0.45 and a median of 0.30. This means that in regard to the value of the results, the utilization of the wall components is almost 50% on average, whereas the majority of the results show a lower utilization of about 30%. However, the overall mix of all wall components (DF1) only offers mediocre possibilities for conclusions. The additional illustration of the type of construction method concerning single- and double-shell or monolithic components does not provide much additional information. The +22% higher mean value (0.55) of utilization factors for double-shell construction is caused by the higher dead load of the components due to the second facing layer. On the other side, the choice of material (DF2.1) shows significant differences in the results. The lowest mean utilization comes with concrete (0.06) and solid timber components (0.16). Brick masonry (0.35) and calcium silicate components (0.29) show a mean utilization close to the total mean value. On the top end lie aerated concrete (0.53) and especially timber element components (1.31). TE components on average exceed the goal of a utilization of 1.0 and are mainly considered as outliers in the consideration of all exterior wall components. This effect is mainly caused by limitations due to the pressure being perpendicular to the grain direction on the top/bottom plate. Of course, during an actual design process, adequate measures (less distance between the studs, stronger top/bottom plate e.g. LVL, or steel reinforcement, etc.) would be taken to meet the goal of verification.

DF3 Choice of Geometric Design

The thickness of the structural layer is varied with each basic version. Therefore, the IQR reflects the range of different results due to the variation of the structural layer's geometry. The higher the IQR, the higher the effect of the choice of geometric design (DF3.1). The results of the basic versions demonstrate that the variation of the structural layer's thickness and quality primarily effects timber panel construction (IQR between 0.50 and 0.56) and monolithic aerated concrete components (IQR of 0.31). On the other side, the choice of the structural layer's thickness is marginal (IQR < 0.17) for the other group of components compared to the effect of the choice of material.

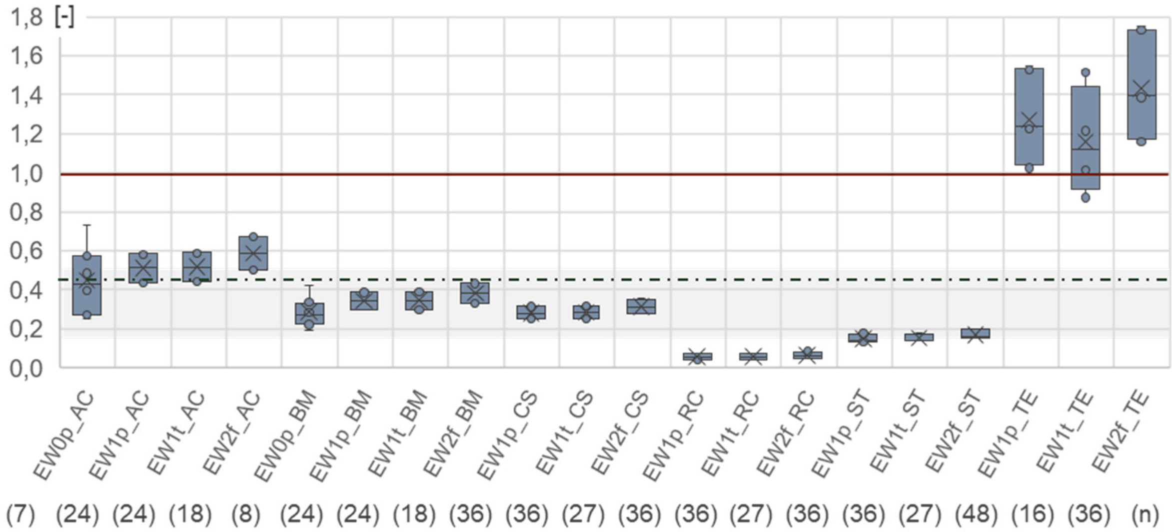


Figure 4-6: Indicator results for the 'utilization factor [-]' (B.1) for all exterior wall components, grouped according to basic versions

The different thickness of the structural layer of the exterior wall components differs in a huge variety, due to material specific design and production issues.

The results for the EW components with different typical thicknesses of the structural layer show that the thickness of the layer becomes more important the higher the total utilization factor is (e.g. AC and TE). The layer's thickness however is by far not the only parameter that influences the results of the utilization factor. The mean results for brick masonry and solid timber components illustrate the difference of the material quality (BM) respectively the material structure (ST). Bricks with a thickness of 365 millimetre and a lower compression strength show more or less the same results as bricks with 240 millimetre and a higher compression strength. On the other side, solid wood panels (CLT) can be composed of different numbers of layers of different thickness. As mentioned before (cf. chapter 4.1.2), a panel with a thickness of 120 millimetre is composed out of three layers of 40 millimetre each (40-40-40), and a panel with 140 millimetre thickness is composed out of five layers of different layer thicknesses (40-20-20-20-40), both showing similar results.

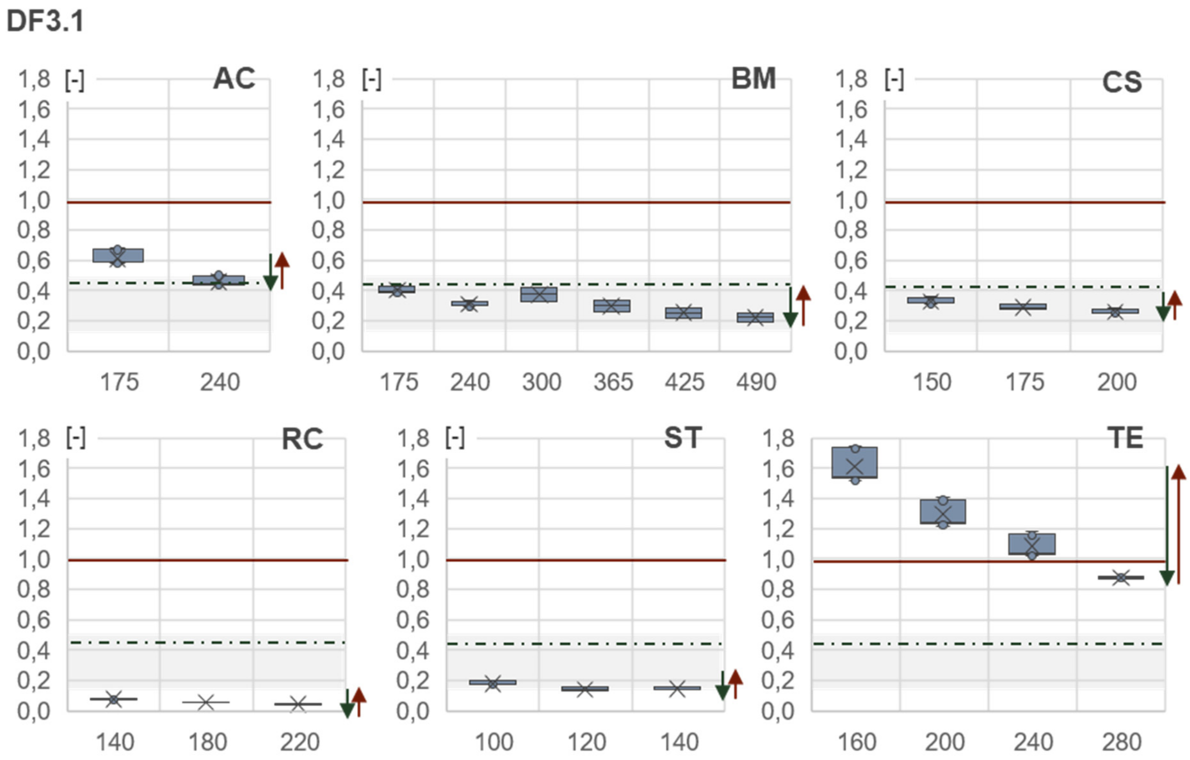


Figure 4-7: Utilization factor results for exterior walls, grouped according to structural material and thickness [mm] of the structural layer (DF3.1)

Next to the choice of construction, the choice of layer thickness is important to reach the goal of sufficient structural stability and load bearing capacity.

Table 4-20: Overview of the variation of the utilization factors for exterior wall components due to the choice of thickness of the structural layer (DF3.1)

Utilization factor [-]	**AC**	**BM**	**CS**
Highest mean value	0.61 (175)	0.40 (175)	0.33 (150)
Decrease / increase	↓-25% | ↑+33%	↓-23% | ↑+29%	↓-21% | ↑+27%
Lowest mean value	0.46 (240)	0.31 (240)	0.26 (200)
Utilization factor [-]	**RC**	**ST**	**TE**
Highest mean value	0.08 (140)	0.18 (100)	1.61 (160)
Decrease / increase	↓-50% | ↑+100%	↓-22% | ↑+29%	↓-45% | ↑+83%
Lowest mean value	0.04 (220)	0.14 (120)	0.88 (280)

In conclusion, the results demonstrate the effect of different design choices. However, the calculation does not cover a general scenario for load bearing exterior walls but a very specific showcase scenario. The goal is not to give a general verification calculation for exterior walls to cover all possible actions and load cases to identify the best solution, but to find effective starting points to influence the outcome and to reach the goal of a structural safety.

4.2.3 Outcomes for 'D.1 – Minimizing Environmental Impacts'

To illustrate the goal of minimizing environmental impacts, more than one indicator is necessary. The fact of having multiple indicators already demonstrates the difficulty of multicriteria decision-making (cf. chapter 5.2). The six indicators for D.1 show different characteristics. The indicators GWP, AP, EP, and POCP have a more or less consistent distribution with the mean value close to the median and an IQR of about 22-28 percent (GWP, AP, EP) and 14 percent (POCP) of the total corridor of results, while there are also some outliers (e.g. EP and POCP). On the other end of the spectrum, the indicators ODP and ADPE show very inconsistent results. The mean values for example do not even come close to 75 percent of the existing data (<Q1 and IQR), due to many very strong outliers. Interpreting the results for ODP and ADPE requires special investigation of the causes and effects, which will have to be put aside in this thesis. This approach however is in line with the current status of the standards, with these indicators still being subject to further scientific research (cf. Table 3-11) (DIN EN 15804, 2014).

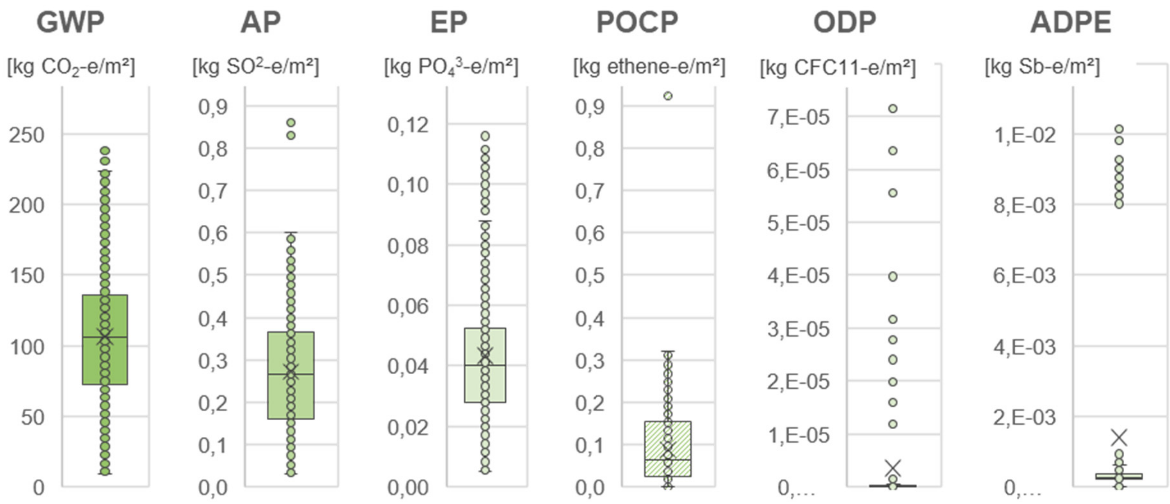


Figure 4-8: Illustration of all different indicator results for the goal D.1 with all building components[23]

The presentation of the results is structured according to the identified decision factors that influence the goal of minimizing environmental impacts (cf. chapter 4.1.3).

From here on out, the level of perspective is increasing in detail through a selection of a group of building components to consider their environmental impact potential. Furthermore, due to the limited extent of this thesis, the presentation and interpretation of the results will be reduced to the indicators GWP, AP, and EP, and if necessary further to only GWP, since this specific environmental issue is currently the biggest task to solve. Additional indicator results, which are not shown here, can be found in the Appendix.

[23] The indicator results are calculated for a lifetime of 50 years including maintenance (B2) and replacement (B4) and depicted as the cumulated value over the life cycle per square meter of component area.

DF1 Choice of Construction

Concerning of the choice of construction method, three possible design choices have to be made:

- DF1.1 Choice of construction: Type of component
- DF1.2 Choice of construction: Exterior finish
- DF1.3 Choice of construction: Interior finish

Starting with the type of construction, a first distinction is made between the different building components. It is important to mention that every type of component has to serve different functions and every component covers different areas. This is why the distribution of impacts between the types of constructions shifts when considering the building as a whole. For multi-storey residential buildings the floor slabs, exterior and interior walls dominate the GWP results especially (Mahler et al., 2019, p.51).

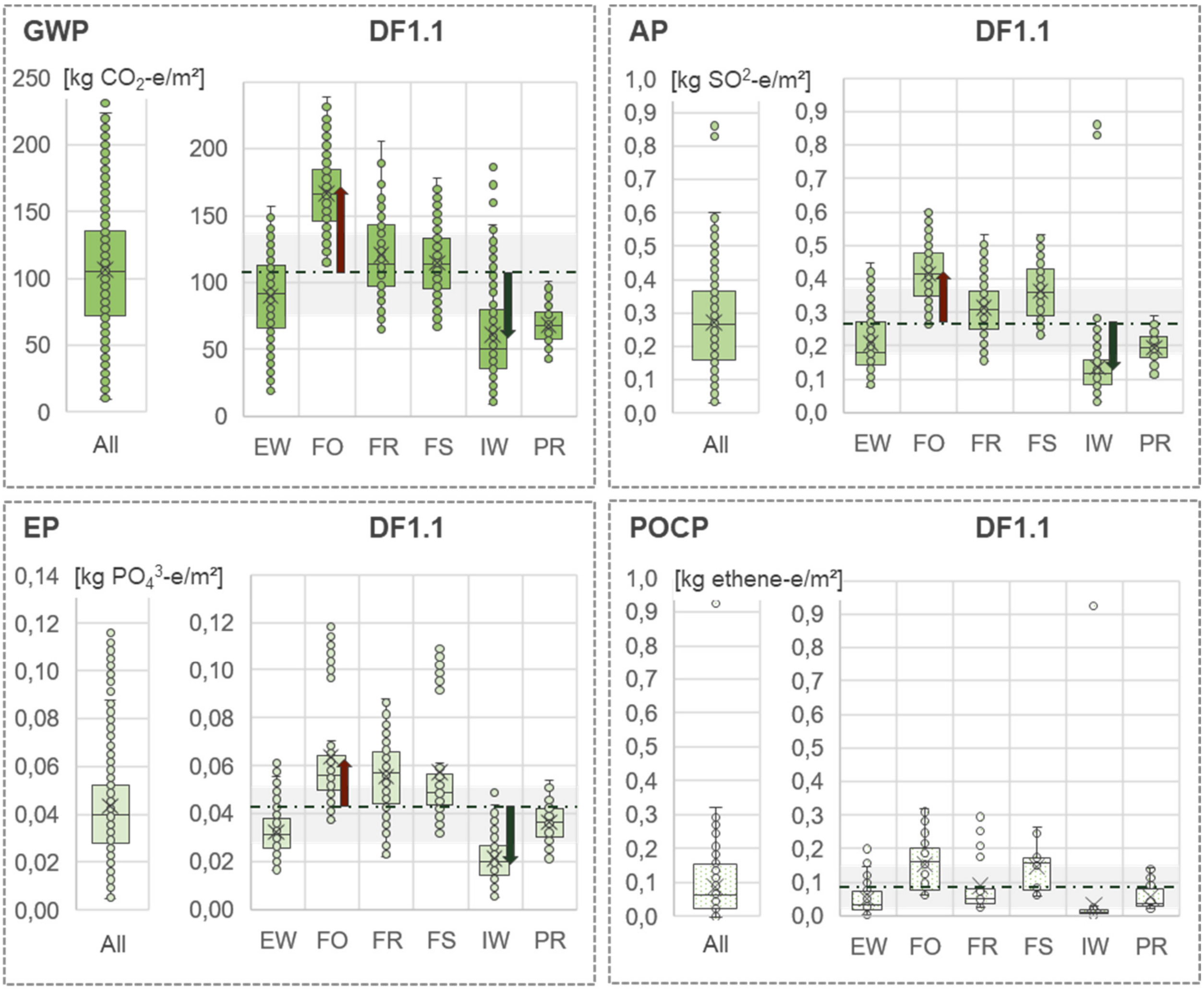


Figure 4-9: Indicator results for GWP, AP and EP (D.1) for all building components, grouped according to the type of building component (DF1.1)

First, the observation of the results (cf. Figure 4-9) for the different indicators reveals a similar distribution, with the pitched roof, exterior and interior wall components in the lower half and the floor slab, flat roof and foundation components in the upper half. The foundation components show the highest overall impact with an average mean value increase of +56% (GWP), +52% (AP) and +47% (EP). On the other side of the spectrum interior walls show an average decrease of the mean value of -45% (GWP), -51% (AP) and -52% (EP). This result implies some correlation between the indicators GWP, AP, and EP, with some significant exceptions (outliers). This result is also part of an ongoing discussion (Marsh, 2016) and will be investigated further (cf. chapter 5.1.3).

The outliers for the GWP results of interior walls can be traced back to double-shell dividing walls made out of aerated concrete, which are also responsible for the AP outliers. The linoleum flooring is responsible for the outliers of the EP results of foundation and floor slab components.

Furthermore, the results are grouped according to the type of exterior finish (DF1.2) for the building envelope, with exterior walls, foundation, pitched and flat roof components. In the second step the results for the interior wall, floor slab and foundation components are grouped according to the interior finish (DF1.3).

The analysis of the effect of the choice of façade design reveals a mean reduction of the GWP results for **exterior walls**, with a reduction for timber cladding of -31% and an increase for the double-shell components with facing layer of +26%. This means that in total the mean potential for decrease can take up to -44%. For the **roof components**, the decrease of 57% of the mean GWP results between flat roof (120.4) and pitched roof components (68.2) is more significant than the variations between the exterior finishes of the two groups. However, the difference between the mean GWP results of the exterior finish can lead to a total decrease of -16% in the case of pitched roof components, or -12% in the case of flat roof components. The choice of construction type as well as the choice of the exterior finish of foundation components show very little effects for decrease (~6%) of the mean GWP results.

Table 4-21: Overview of the variation of the GWP results, based on the choice of exterior finish (DF1.2)

GWP in [kg CO_2-e/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	113.2 (f)	74.3 (m)	130.3 (g)	172.9 (x)
Decrease / increase	↓-45% | ↑+83%	↓-16% | ↑+19%	↓-13% | ↑+14%	↓-6% | ↑+7%
Lowest mean value	61.7 (t)	62.2 (r)	114.0 (s)	162.1 (i)

The choice of construction method concerning the interior finish shows two main results. First, the difference of the mean GWP results between single-shell (42.0) and double-shell interior walls (79.7) show almost a doubling (respectively) in the results. This means that by choosing a single-shell construction where a double-shell separating wall is not necessary, a decrease of the mean GWP result of -47% can be achieved.

Continuing, the choice of the interior wall finish or the ceiling is not as significant as the choice of flooring. The results of the design choices for the interior finish of walls and ceilings lie between the lowest GWP results for visible interior finish (vs) – wherever it is possible – and the highest results for a facing framework interior finish. A double planking finish (pp) is the exception and only used tor timber components. The difference of the interior finish can lead to a maximum decrease of about -19% of interior walls and of about -19% of floor slab ceilings.

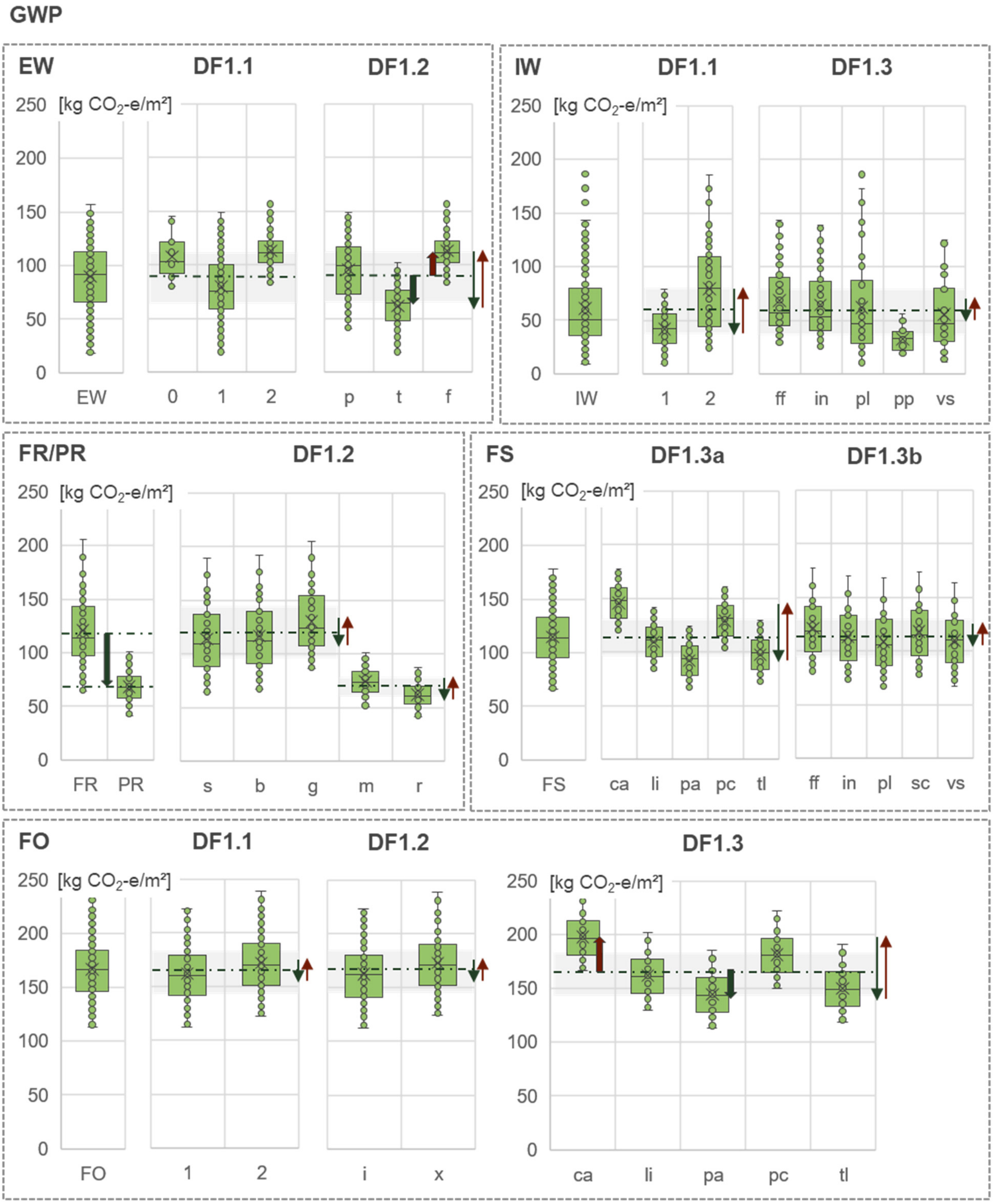


Figure 4-10: GWP results for all components of the building envelop and the interior, grouped according to the exterior (DF1.2) and interior finish (DF1.3)

On the other side, the choice of flooring has the potential to decrease the mean GWP result by up to -37% in the case of foundation components and up to -27% in the case of foundation components. This potential can be achieved by a substitution of carpet flooring with parquet flooring. Carpet flooring components show an increase of the mean GWP results of +27% for floor slab and +19% for foundation components, while the parquet flooring show a decrease of -20% for floor slab and -14% for foundation components.

Table 4-22: Overview of the variation of the GWP results, based on the choice of interior finish (DF1.3)

GWP in [kg CO_2-e/m²]	**IW**	**FS** (ceiling)	**FS** (flooring)	**FO**
Highest mean value	68.3 (ff)	121.6 (ff)	145.7 (ca)	197.6 (ca)
Decrease / increase	↓-19% | ↑+23%	↓-10% | ↑+12%	↓-37% | ↑+58%	↓-27% | ↑+37%
Lowest mean value	55.6 (vs)	109.0 (vs)	92.0 (pa)	144.0 (pa)

These differences primarily arise from a combination of the material basis and the different service life of the flooring options, with the carpet flooring being replaced four times and tiles and parquet flooring zero times during the respected service life of the building component of 50 years.

DF2 Choice of Material

The choice of construction method already covers minor differences of material choices. However, the choice of material can be summarized for the main materials in regard to mass and volume as:

- DF2.1 Choice of material: Structural layer
- DF2.2 Choice of material: Insulation layer

The choice of the structural material of building components is also bound to a number of other goals in the design process; also, not all material possibilities are represented in this study. Nevertheless, the comparison of different structural materials in different types of components offers two major conclusions. First, timber element components always show the lowest mean GWP results, decreasing the mean value of the component group by -19% for flat roof, -13% for pitched roof, -24% for exterior wall, -50% for interior wall and -15% for floor slab components. Secondly, in most cases (except for interior wall components), concrete components show the highest mean GWP results, increasing the mean value of the component group by +31% for flat roof, +20% for exterior wall, +39% for interior wall and +27% for floor slab components. Compared to the mean value of the component group with the highest mean values, the total achievable substitution potentials of timber element components can take up to 66%. Also, the potential for reducing the GWP emissions is higher for vertical wall elements than for horizontal floor slab or roof elements.

Table 4-23: Overview of the variation of the GWP results, based on the choice of structural material (DF2.1)

GWP in [kg CO_2-e/m²]	**FR**	**EW**	**IW**	**FS**
Highest mean value	157.3 (RC)	108.0 (RC)	87.9 (AC)	132.0 (RC)
Decrease / increase	↓-38% | ↑+60%	↓-37% | ↑+59%	↓-66% | ↑+191%	↓-26% | ↑+36%
Lowest mean value	98.1 (TE)	68.1 (TE)	30.2 (TE)	97.1 (TE)

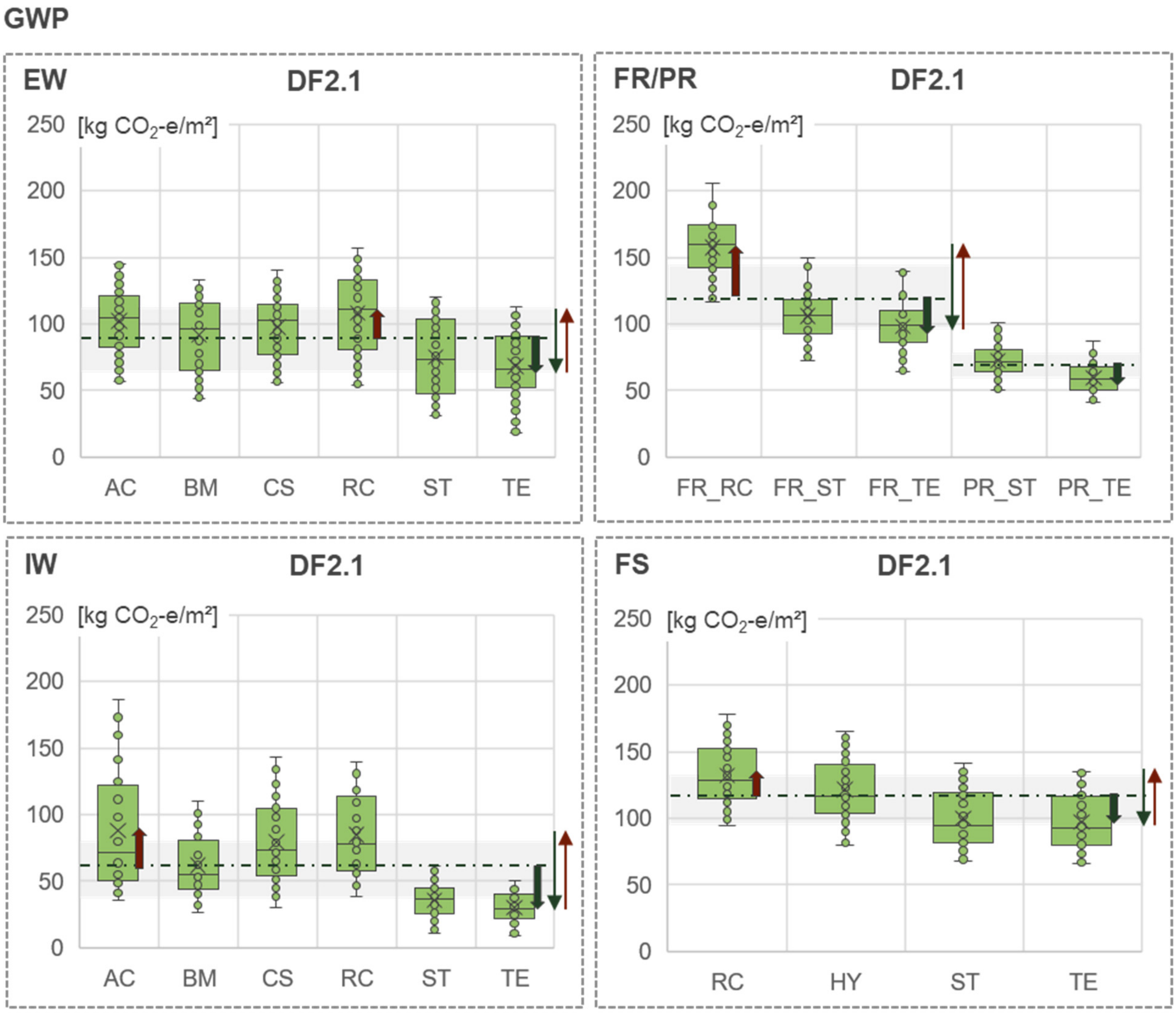


Figure 4-11: GWP results, grouped according to the main structural material (DF2.1)

Next to the structural layer, the thermal insulation layer is dominating the volume distribution of components of the building envelope, in particular roof, exterior wall and foundation components. Interpreting the mean GWP results grouped according to the insulation material shows two insights: On the one hand, the different impacts of the insulation material – and on the other hand, the specific use and resulting construction methods for these materials.

For example, although cellulose and wood fibre insulation need a thicker layer to achieve the same insulating performance, they generally show the lowest mean GWP results. Cellulose however is an insulation material, being installed by being blown into a pre-existing structure.

This method is not suitable for every purpose, which is why it cannot be used for all basic versions, e.g. flat roofs or exterior walls with EWIS (Exterior Wall Insulation System). This is why the construction method and the specific requirements of the insulation layer have to be considered and analysed separately.

In comparison, the effect of the choice of insulation material shows varying potentials for decreasing the mean GWP emissions. For **exterior walls with facing layer** – where the insulation is between the two layers – or for the insulation in **foundation components** (↓-12% | ↑+13%), almost no significant difference can be identified. On the other side of the spectrum, the potential to decrease the mean value of GWP emissions can take up to 35%, e.g. for flat roofs, where most insulation is usually used.

Table 4-24: Overview of the variation of the GWP results, based on the choice of insulation material (DF2.2)

GWP in [kg CO_2-e/m²]	**EWp**	**EWt**	**EWf**
Highest mean value	103.4 (PU)	72.7 (EPS)	81.9 (EPS)
Decrease / increase	↓-24% | ↑+31%	↓-28% | ↑+40%	↓-31% | ↑+45%
Lowest mean value	78.9 (WF)	52.0 (CE)	56.5 (CE)
GWP in [kg CO_2-e/m²]	**PR**	**FR**	**FO**
Highest mean value	81.9 (EPS)	145.9 (CG)	81.9 (EPS)
Decrease / increase	↓-31% | ↑+45%	↓-35% | ↑+54%	↓-31% | ↑+45%
Lowest mean value	56.5 (CE)	94.6 (WF)	56.5 (CE)

The GWP results lead to the conclusion that, considering the choice of material, the choice of main structural material has a higher impact than the choice of insulation material, although the highest impact can be achieved with a combination and optimization of both material choices. Regarding the choice of structural material, the wall components show higher potential for decreasing the mean GWP result (Δ57.7 kg CO_2-e/m², or -66%), whereas regarding the choice of insulation material, the roof, especially flat roof components, offers the highest potential for decrease in absolute numbers (Δ51.3 kg CO_2-e/m²) and in relational numbers (-35%).

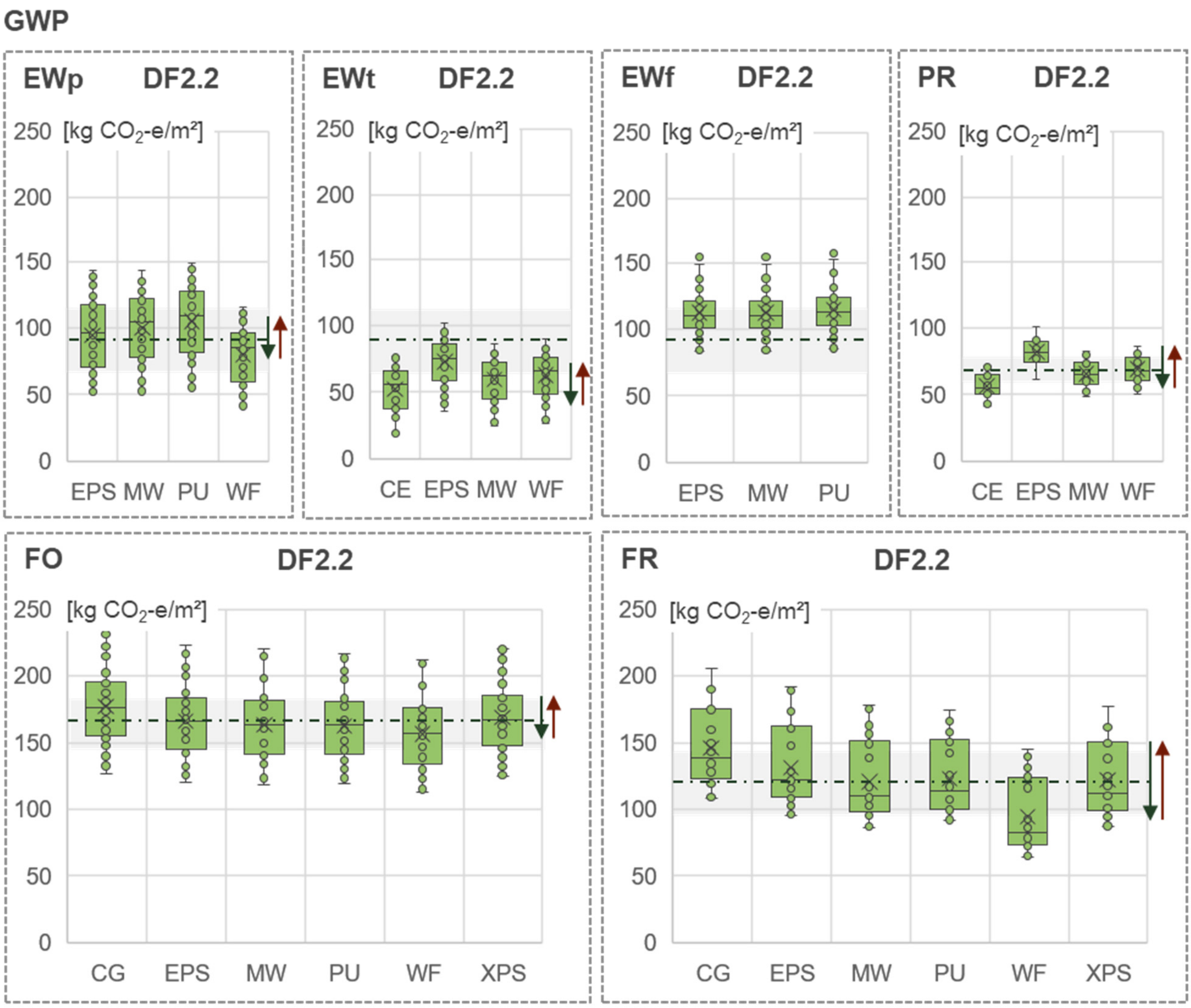


Figure 4-12: GWP results, grouped according to the insulation material (DF2.2)

The choice of material can however have a significant impact on and shift towards other indicators of environmental impacts, since it does not only have a different scaling effect, but changes the product system – here the building material – and therefore the calculation basis. The roof components show a high variety in different insulation materials and offer high variation in the GWP results. The additional consideration of the AP, EP and POCP results delivers additional insights: The different behaviour and the potential for decrease when considering additional indicators reveal significant differences in regard to the choice of material. For example, EPS flat roof insulation shows a mediocre performance concerning the GWP results, yet delivers the best results for AP and EP and by far the highest POCP results. This outlines the problem of multiple indicators and the difficulty to arrive at the ideal choice for the goal of minimizing all environmental impacts in the case of competing options. This problem of multicriteria decision-making will be discussed in more detail in chapter 5.2.

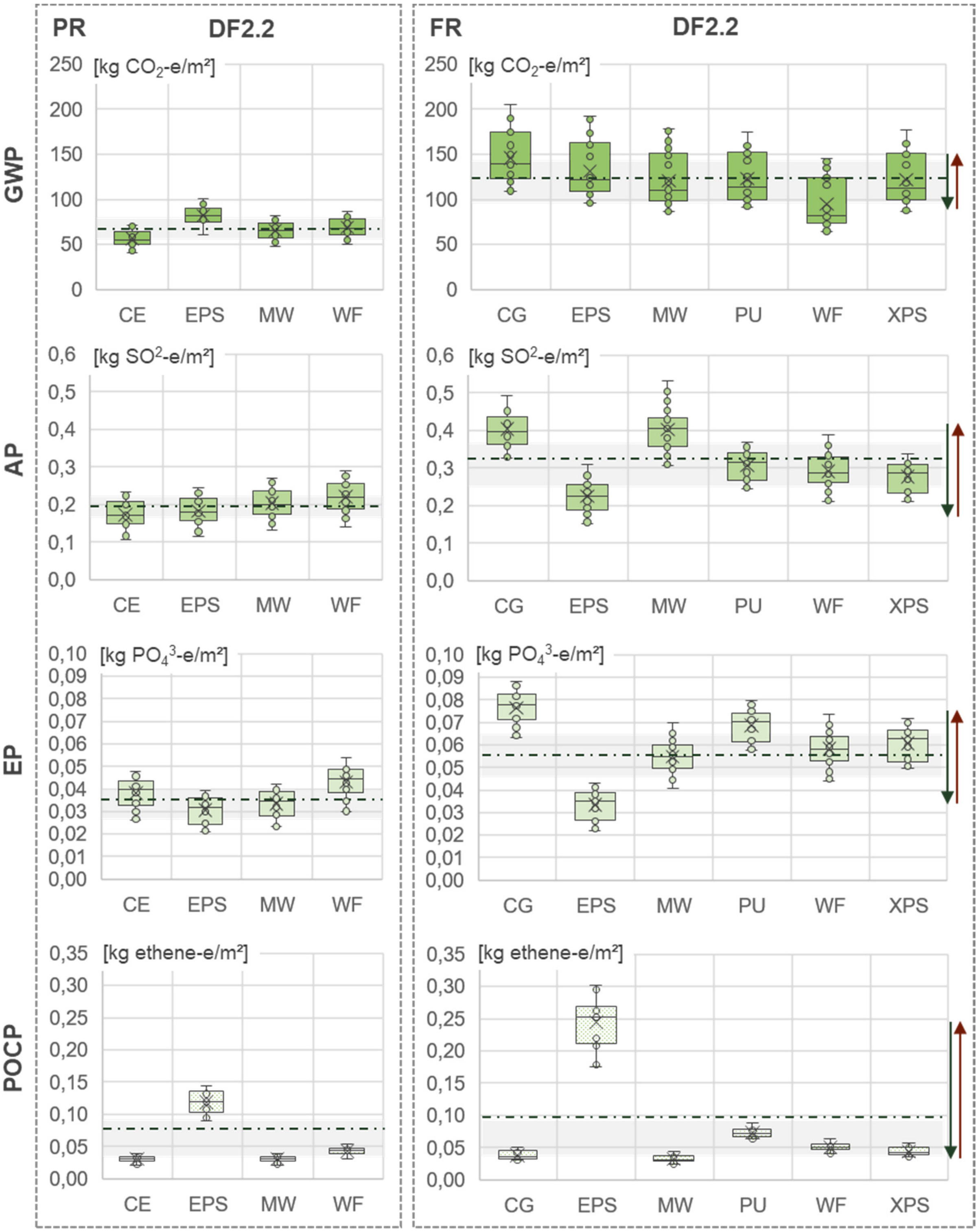


Figure 4-13: Indicator results for GWP, AP, EP and POCP (D.1) for all roof components, grouped according to insulation material (DF2.2)

Table 4-25: Overview of the variation of the results for different indicators for flat roof components, based on the choice of insulation material

(FR) Flat Roof Components	**GWP** [kg CO_2-e/m²]	**AP** [kg SO^2-e/m²]	**EP** [kg $PO_4{}^3$-e/m²]	**POCP** [kg ethene-e/m²]
Highest mean value	145.9 (CG)	0.40 (CG)	0.076 (CG)	0.244 (EPS)
Decrease / increase	↓-35% | ↑+54%	↓-45% | ↑+82%	↓-55% | ↑+124%	↓-86% | ↑+639%
Lowest mean value	94.6 (WF)	0.22 (EPS)	0.034 (EPS)	0.033 (MW)

The results show the differences in the volatility of the indicators, with GWP being the most moderate and POCP revealing high variations.

DF3 Choice of Geometric Design

Finally, the choice of geometric design determining the total mass and volume of the component is also focused on the two main material layers:

- DF3.1 Choice of geometric design: Structural layer
- DF3.2 Choice of geometric design: Insulation layer

The difficulty of showing the impact of the choice of layer thickness lies in the differences of layer thickness according to layer material. This fact accounts for both the structural and the insulation layer. For example, the thickness of the structural layer of an exterior masonry wall will be orientated towards the delivery program of the bricks, while design, reinforcement and formwork issues determine the layer thickness of a concrete wall. Nevertheless, the layer thickness and its impact on the results of environmental impacts is always directly proportional, because the calculation is based on the input of the layer's mass or volume. This only accounts for the layers result however and not for the result of the whole component. This means that a certain increase in thickness does lead to the same increase in the results for the layer, but does not lead to the same increase in the results of the component. For exterior wall components, the increase in layer thickness for the structural layer results in the following mean increase of GWP results:

Table 4-26: Overview of the variation of the GWP results for exterior wall components, based on the choice of thickness of the structural layer

GWP in [kg CO_2-e/m²]	**AC**	**BM**	**CS**
Highest mean value	107.6 (240)	95.9 (240)	103.9 (200)
Decrease / increase	↓-14% | ↑+16%	↓-10% | ↑+11%	↓-12% | ↑+14%
Increase of GWP per mm of thickness	**+0.22/mm**	**+0.14/mm**	**+0.25/mm**
Lowest mean value	93.0 (175)	86.3 (175)	91.4 (150)
GWP in [kg CO_2-e/m²]	**RC**	**ST**	**TE**
Highest mean value	118.6 (220)	78.4 (140)	72.3 (240)
Decrease / increase	↓-18% | ↑+22%	↓-8% | ↑+9%	↓-8% | ↑+8%
Increase of GWP per mm of thickness	**+0.27/mm**	**+0.16/mm**	**+0.07/mm**
Lowest mean value	97.4 (140)	72.0 (100)	66.7 (160)

The mean increase per millimetre can easily be verified in those cases where the structural layer is based on one material dataset only (BM, CS, ST) by calculating one-millimetre thick layers. For example, the total increase of the GWP results (in kg CO2-e/m²) per one millimetre of layer thickness originates from the background data, with 0.14 GWP/mm for clay bricks, 0.25 GWP/mm for calcium silicate bricks and 0.16 GWP/mm for CLT panels. The other values represent the material mix of the structural layer, e.g. additional insulation (TE), steel reinforcement (RC) or different datasets regarding the material's quality (AC).

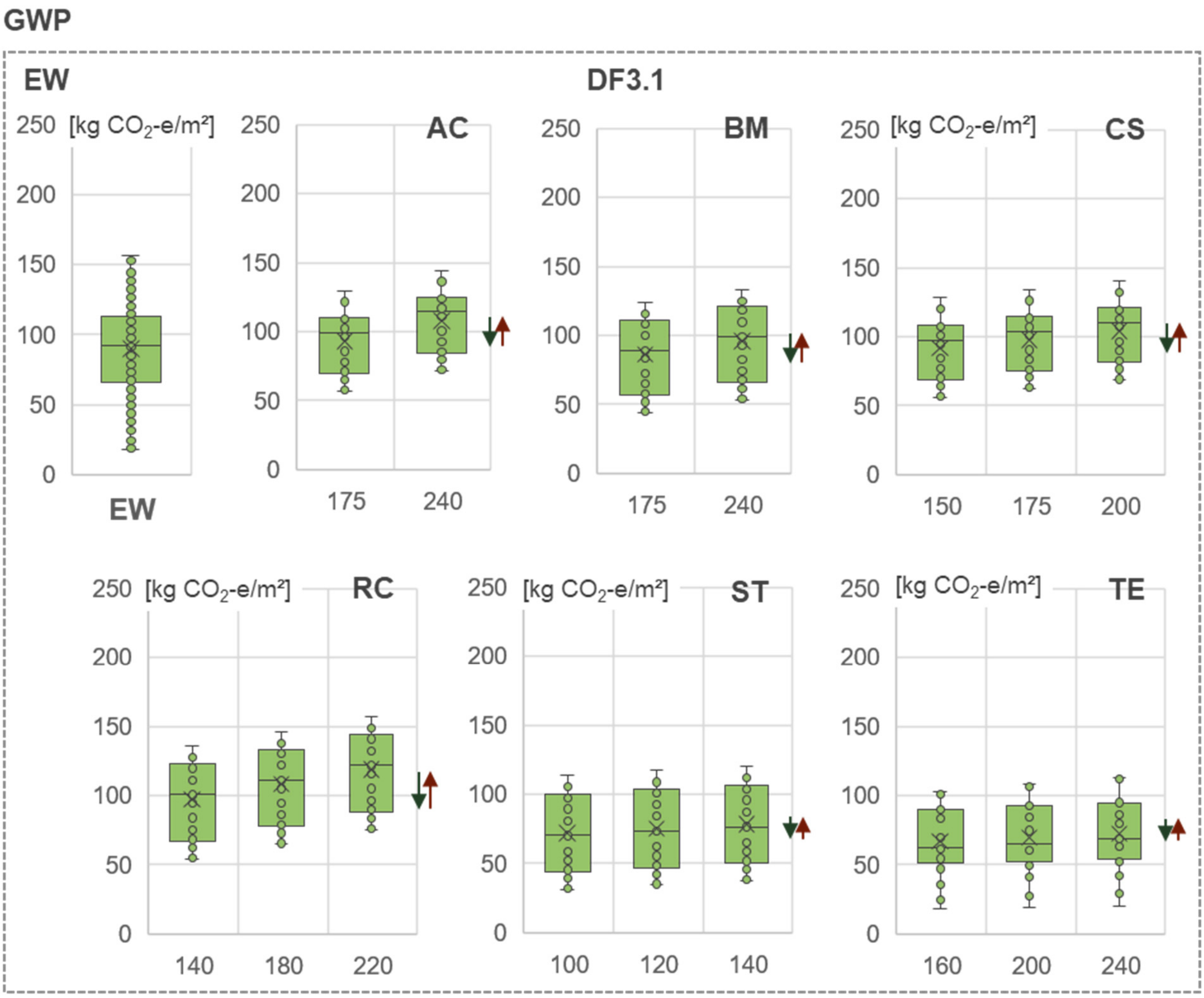


Figure 4-14: GWP results for exterior walls, grouped according to structural material and thickness [mm] of the structural layer (DF3.1)

The illustration (cf. Figure 4-14) of the different structural layers' thicknesses (DF3.1) only considers representative thicknesses and leaves out single components, which cover specific variations of the component group like monolithic constructions. However, the same conclusions apply in that only higher differences between lowest and highest mean values would be displayed. The highest differences can be achieved for concrete components with a net increase of 0.27 GWP/mm. Furthermore, higher differences can also be achieved the thicker the layer becomes. Slab foundation components offer the combination of concrete components with relatively thick structural layers.

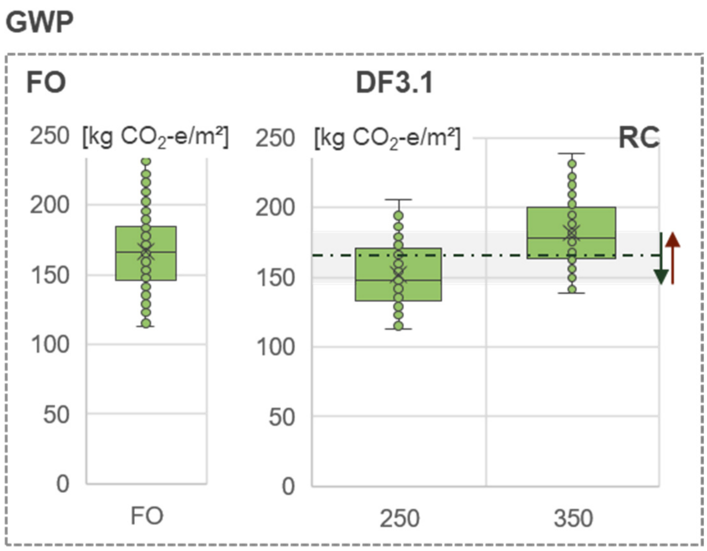


Figure 4-15: GWP results for foundation components, grouped according to thickness [mm] of the structural layer (DF3.1)

The difference of the mean values between either 250 mm (151.9 kg CO_2-e/m²) or 350 mm (181.5 kg CO_2-e/m²) thick concrete slab foundations show a potential to decrease the mean value by 29.6 kg CO_2-e/m², or 0.30 GWP/mm (↓-16% | ↑+19%). This illustrates the fact that when considering the structural layer's thickness, no general answer can be given, because the layer's thickness can vary considerably and depends on the specific case scenario. The results shown only cover a representative but not comprehensive set of different components.

In a similar way, the **thickness of the insulation layer** depends on the delivery program of the insulation materials, the thermal conductivity (λ-value), and the target value of the heat transfer coefficient (U-value). This leads to a variety of different layer thicknesses without any significant statement on the function the thickness tries to achieve. Therefore, the GWP results are already set in relation to the targeted function of thermally insulating the building, expressed by the heat transfer coefficient (U-value) of the component.

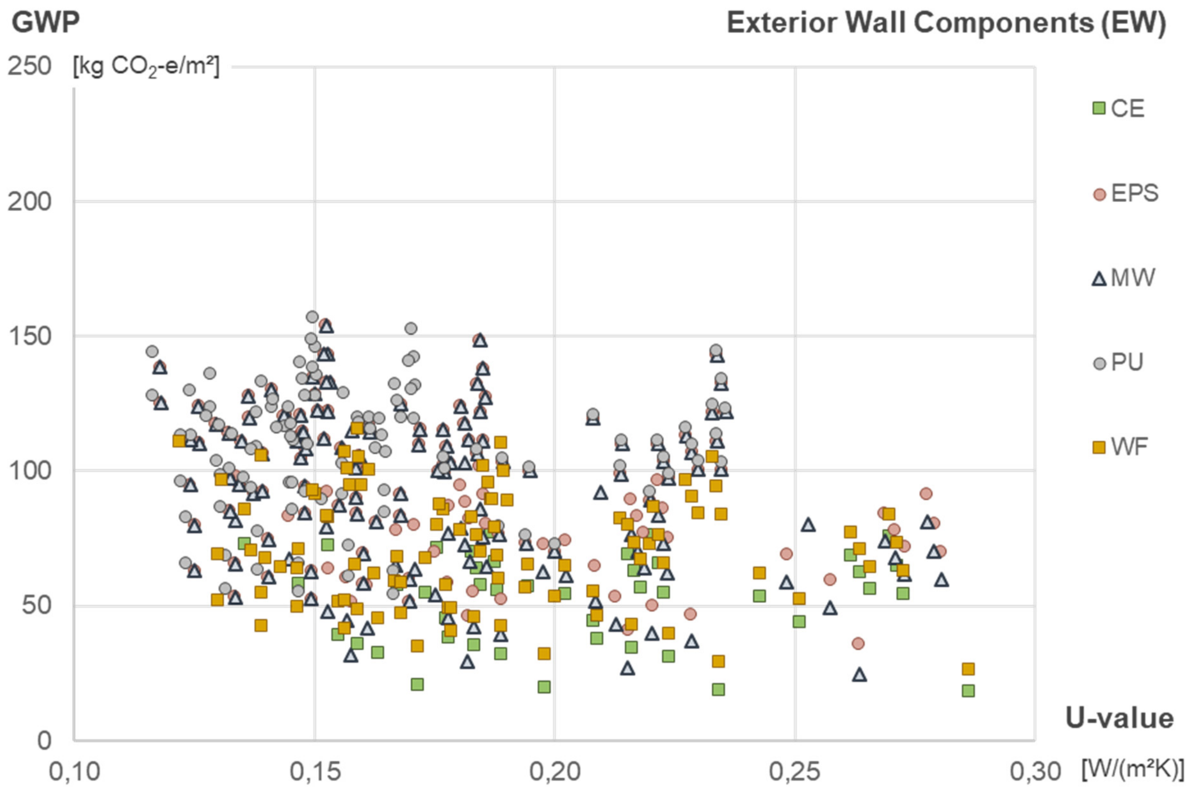


Figure 4-16: GWP results in relation to the U-value (DF3.2) of exterior wall components, grouped according to the insulation material

Comparing the U-value of the exterior wall components and the GWP results illustrates the slightly negative correlation of GWP and U-value. This means that an increase in GWP results goes along with a decrease of the U-value, because of an increase of the thickness of the insulation layer. The U-value itself is also calculated for the entire component, with the insulation layer being the dominating layer but not the only parameter. This increase however is not the same for every insulation material. An individual analysis of the insulation layer itself reveals these differences. In addition, the increase of the GWP results for the thickness of the insulation layer can be shown according to the underlying data.

Table 4-27: Overview of the variation of GWP results for the exterior wall insulation layer (only), based on the choice of thickness of the insulation layer

GWP in [kg CO_2-e/m²]	**CE** (λ=0.040)	**WF** (λ=0.040)	**EPS** (λ=0.035)	**PU** (λ=0.025)	**MW** (λ=0.035)
GWP for R-value ≥ 6	2.0 (240)	16.0 (240)	29.8 (220)	32.7 (160)	12.1 (220)
GWP for R-value ≥ 4	1.3 (160)	10.7 (160)	19.0 (140)	20.4 (100)	7.7 (140)
Increase of GWP per mm of thickness	+0.01/mm	+0.07/mm	+0.14/mm	+0.20/mm	+0.06/mm
Total increase of GWP	**+0.7**	**+5.3**	**+10.8**	**+12.3**	**+4.4**

Singling out the individual performances of each insulation material, it becomes obvious why on the one hand the GWP results for different cellulose insulation thicknesses do not vary a lot. On the other hand, a specific delivery program with 20 mm steps leads to higher volatile results, e.g. for PU insulation panels.

A direct comparison of the thickness would therefore not be expedient. That is why the R-value is chosen for comparative purposes, with the target function depicted by the U-value and the focus on the insulation layer in mind. The additional insight gained from grouping the components according to the R-value of the insulation layer is the overall increase of the GWP results by a general variation of the thickness.

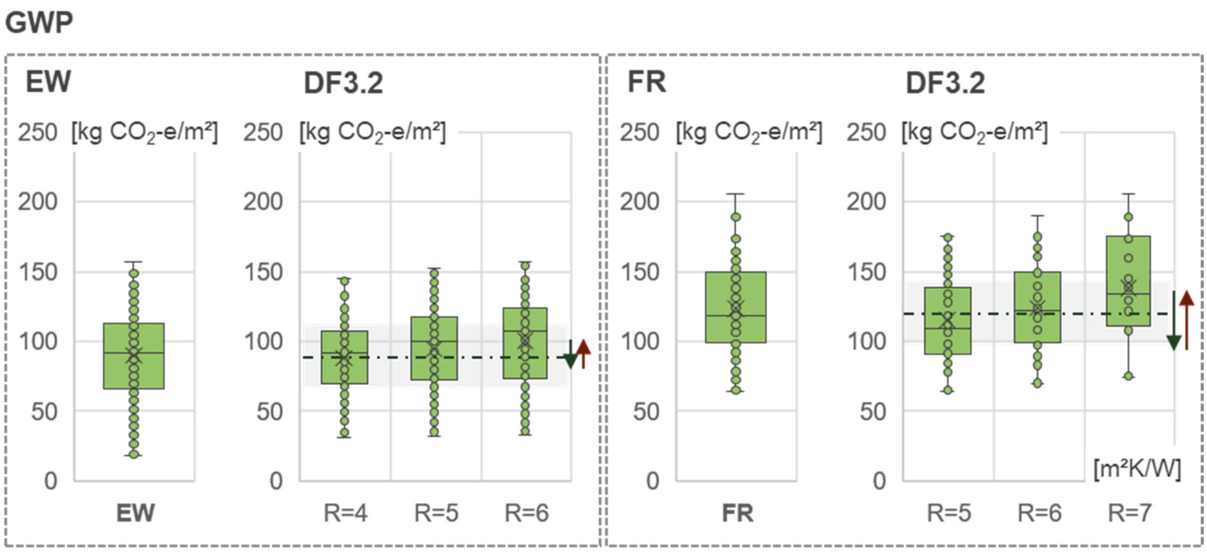


Figure 4-17: GWP results for EW and FR components, grouped according to the R-value of the insulation layer (DF3.2)

Not all exterior wall or flat roof components can be allocated to the grouping method according to the R-value, since the function of insulating is sometimes not achieved by one single insulation layer but by the collaboration of various layers (e.g. timber panel wall or timber beam roof components etc.). In general, the variation of the insulation thickness has a bigger impact on the results of the flat roof components, because the thermal requirements associated with the use as well as the total share of component results of the insulation layer increases.

Table 4-28: Overview of the variation of GWP results for EW, FR and FO components, based on the choice of thickness of the insulation layer

GWP in [kg CO_2-e/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	100.2 (R=6)	71.7 (R=7)	138.2 (R=7)	167.2 (R=3)
Decrease / increase	↓-12% | ↑+14%	↓-10% | ↑+11%	↓-17% | ↑+20%	↓-3% | ↑+3%
Lowest mean value	87.9 (R=4)	64.8 (R=5)	115.2 (R=5)	161.9 (R=2)

The requirements regarding the insulation layer vary regarding flat roof insulation, therefore the characteristics of the insulation materials vary as well.

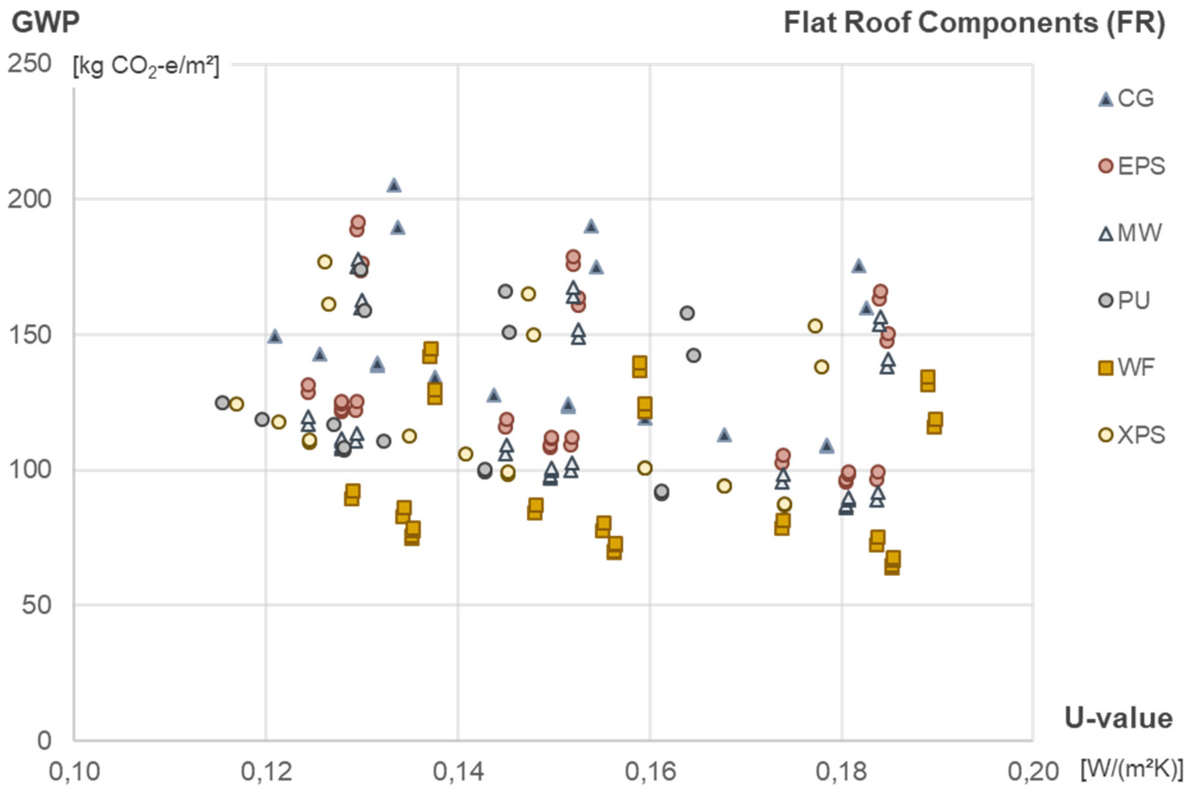


Figure 4-18: GWP results in relation to the U-value (DF3.2) of flat roof components, grouped according to the insulation material

A greater number of requirements for flat roof components in general and the insulation layer of flat roofs in particular result in higher GWP results, next to an increase of the GWP results by a decrease of the U-value – the same trend as seen with the exterior wall components. Analogous to wall insulation materials, observations regarding the insulation layer's thickness can be made according to the underlying data.

Table 4-29: Overview of the variation of GWP results for the flat roof insulation layer (only), based on the choice of thickness of the insulation layer

GWP in [kg CO_2-e/m²]	**WF** (λ=0.040)	**CG** (λ=0.040)	**MW** (λ=0.035)	**EPS** (λ=0.035)	**XPS** (λ=0.035)	**PU** (λ=0.025)
GWP for R-value ≥ 7	18.7 (280)	52.3 (280)	35.3 (260)	42.2 (260)	52.2 (260)	36.8 (180)
GWP for R-value ≥ 5	13.4 (200)	37.3 (200)	24.4 (180)	29.2 (180)	32.5 (180)	28.6 (140)
Increase of GWP per mm of thickness	+0.07/mm	+0.19/mm	+0.14/mm	+0.16/mm	+0.25/mm	+0.20/mm
Total increase (GWP)	**+5.3**	**+15.0**	**+10.9**	**+13.0**	**+19.7**	**+8.2**

The analysis of a variation of the insulation layer's thickness show two main results: on the one hand a general increase of GWP results by increasing the thickness and simultaneously decreasing the U-value, on the other hand a different impact of this increase based on the insulation material used.

Furthermore, focusing merely on the increase of emissions for the building component neglects the effect of improving the thermal envelope of the building as a whole and therefore significantly decreasing the energy demand during the use of the building. Several studies have shown (Mahler et al., 2019; König, 2017) that the additional effort spent on building components pays off during the lifecycle of the building.

4.2.4 Outcomes for 'D.2 – Economic Use of Raw Materials'

The goal 'D.2 Economic use of raw materials' is reflected in a number of indicators (cf. chapter 3.2.5). The indicators can be divided into indicators which display the raw material use for energy and indicators which display the material use of raw materials.

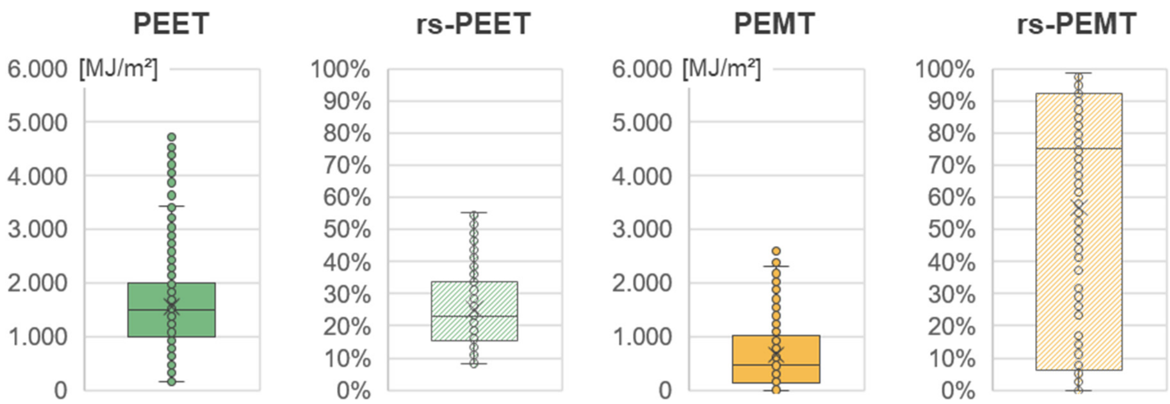


Figure 4-19: Indicator results for an economic energy use of raw materials for all building components

Energy Use | The results for the primary energy use of building components lead to two main conclusions: First, the mean total energy use (PEET) for building components lies at 1559 MJ/m², with a mean share of 25% (with the IQR ranging from 16-34%) of renewable primary energy. The outliers of the PEET results are flat roof components with cellular glass insulation. Secondly, the mean total primary energy content (PEMT) stored within the components is about 663 MJ/m², with its median at 459 MJ/m² and a mean share of 57% (but an IQR range of 6-92%) of renewable primary energy. The outliers of the PEMT results have come from a high content of either timber or wood fibre insulation (mainly roof components). This reveals that the amount of primary energy use and its renewable share can be depicted quite consistently. On the other hand, the primary energy content in general only covers a fraction of the PEET, with its IQR lying in the lower PEET's quartile (between 0% and 42% of the mean PEET). In addition, the IQR of the PEMT's renewable share varies widely between almost all renewable energy (92%) and almost none renewable energy (6%).

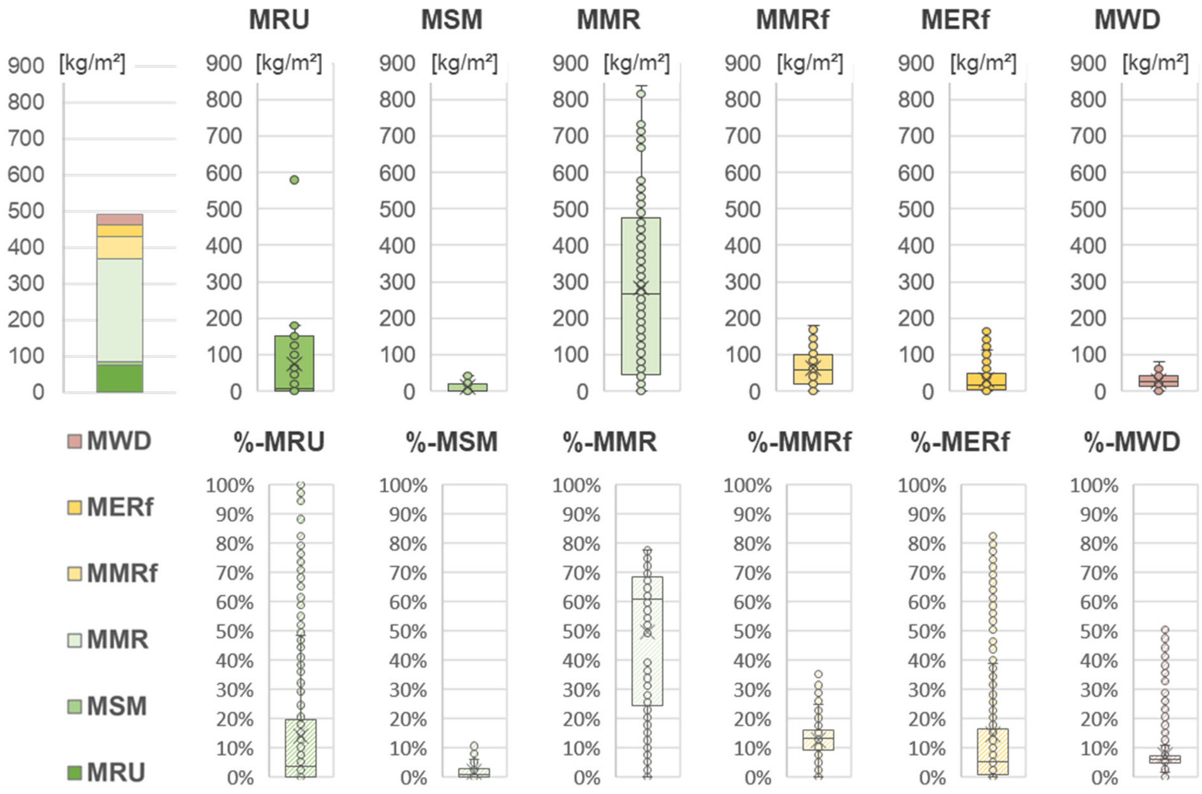


Figure 4-20: Indicator results for an economic material use of raw materials for all building components

Material Use | An analysis of the indicators of the material use of raw materials (MRU, MSM, MMR, MMRf, MERf, MWD) shows first their correlation to the mass results, since the indicators depict mean material flows. The material for reuse (MRU) plays a special role, wherefore the results have to be handled with care. The mean value is a result of a few and partly heavy items or layers of building components, which offer a potential for reuse: e.g. granular subbase for foundations, soil for green roofing etc. The difference between the mean (75 kg/m²) and median (8 kg/m²) values illustrates the fact that materials for reuse do not occur frequently, but when they do, can show high masses. For the overall mean values of all building components, the material for material recycling (MMR) shows the highest mean mass flow (283 kg/m²), with a mean share of 50% of the mass flow of all building components (492 kg/m²). All other indicators show lesser mean material mass flows (<100 kg/m²). A detailed analysis of all indicators would exceed the scope of this thesis. Therefore, the focus of a detailed analysis is put on the following indicators:

- **MWD** | *Material Waste for Disposal*; materials with no recycling potential declared as (non-/hazardous) waste disposed
- **%-MWD** | *Percentage of MWD;* share of material to be disposed compared to the total waste material flows
- **PEET** | *Primary Energy Energy use Total*; total use of non-/renewable primary energy in combination with
- **rs-PEET** | *Renewable share of PEET*

With this selection of indicators, two mayor statements on the use of raw materials are possible: first on the amount of energy resources used, with additional information whether the energy is of renewable or non-renewable origin, and secondly on how much material is taken out of a circular economy by being disposed. Of course, every other indicator will add important information and possibilities for interpretation, but for the scope of this thesis, these two indicators cover the two individual areas of energy and material and are able to generate primary and important conclusions for balancing these two fields.

Concerning the possible differentiation of different decisions, the results are presented according to the decision factors that influence the outcome (cf. chapter 4.1).

DF1 Choice of Construction

In analogy to the goal of minimizing environmental impacts, the goal of an economic use of raw materials is influenced by the choice of construction method, with three further design choices:

- DF1.1 Choice of construction: Type of component
- DF1.2 Choice of construction: Exterior finish
- DF1.3 Choice of construction: Interior finish

Material Use | As a mean average result, 28 kg/m² of a building component have to be disposed. The results for the different types of building components reveal the foundation components as the heaviest in mean value (1033 kg/m²) and with the most material for disposal (51 kg/m²; 4.9%), which constitutes a +82% increase of the mean value. Conversely, pitched roof components have the lowest mean mass results (126 kg/m²) and the lowest mean amount of material to be disposed (2 kg/m²; 2.2%), constituting a decrease of the mean value by -93%. A closer look reveals discrepancies between the results of flat roof components, with a relatively high difference between median and mean value. Additionally, interior wall components display the highest range of results and the highest mean share of disposed material (15.8%) as well as additional outliers. These aspects will be further investigated in the following section.

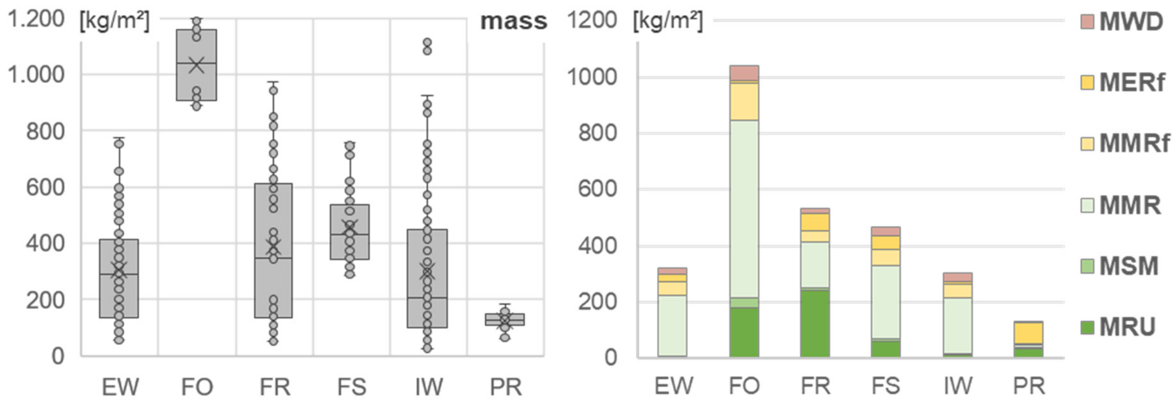


Figure 4-21: Mean mass and distribution of the mean values of the material indicators for all building components, grouped according to the type of building component (DF1.1)

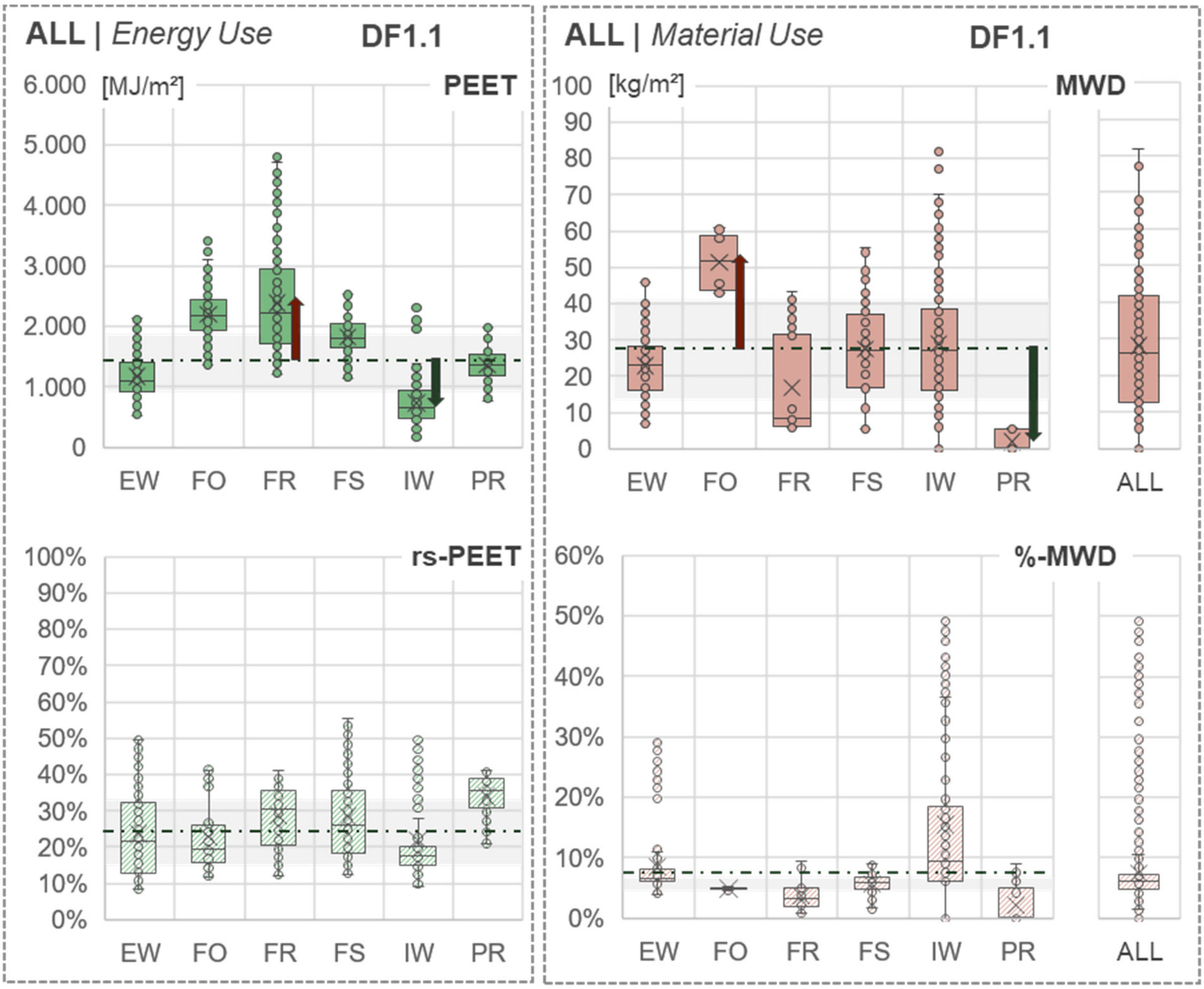


Figure 4-22: Indicator results for energy use (PEET / rs-PEET) and material use (MWD / %-MWD) for all building components, grouped according to the type of building component (DF1.1)

Energy Use | The mean amount of energy used during the life cycle of a building component differs from the type of building component with flat roof components (2384 MJ/m², 29% rs) and foundation components (2202 MJ/m², 23% rs) on top, which implies an increase of the total mean value by +53% or +41%. Interior walls show the lowest mean results (736 MJ/m², 22% rs), which constitutes a decrease of the total mean value by -53%.

However, the choice of building component type is not always a free one, which is why other design choices allow more space for improvement.

The choice of the **exterior finish** of facades (cf. Figure 4-24) shows a variation of potential for decrease for the different façade design options.

Material Use | In regard to the material use of raw materials, a distinction is necessary between the total mean mass of materials for disposal and the relative differences. The option of a facing layer as the exterior finish shows significantly higher overall mean mass results. The highest potential for decrease comes with the choice of the exterior façade finish for exterior wall components. The highest mean value for disposed material comes with a facing façade (28.4 kg/m²), which can be decreased by -33% when using a simple plaster façade. For roof and foundation components, the choice of the exterior finish does not offer a big potential for decrease (<10%).

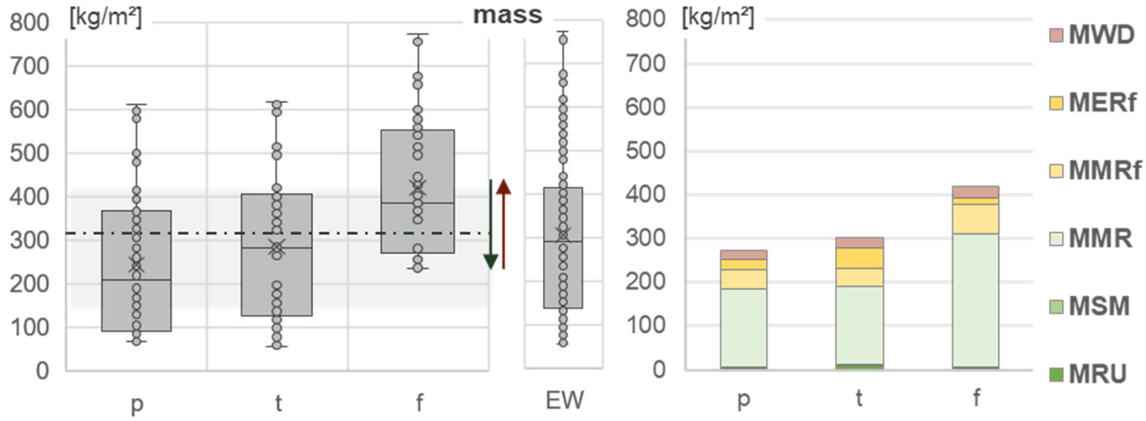


Figure 4-23: Mean mass and distribution of the mean values of the material indicators for exterior wall components, grouped according to the exterior finish (DF1.2)

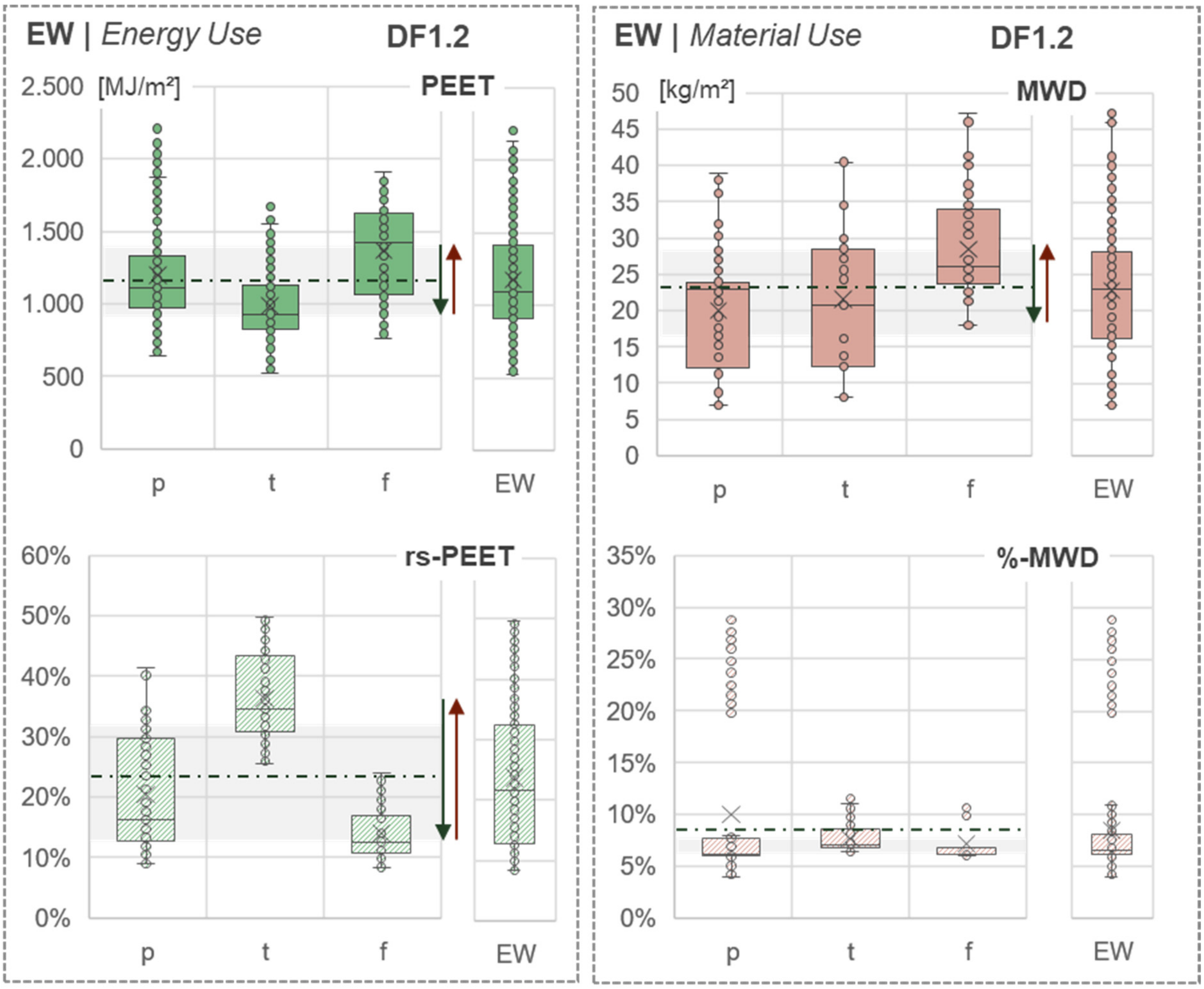


Figure 4-24: Indicator results for energy use (PEET / rs-PEET) and material use (MWD / %-MWD) for exterior wall components, grouped according to the exterior finish (DF1.2)

Energy Use | The timber façade simultaneously has the lowest mean value of energy use (984 MJ/m²) and the highest mean share of renewable energy (36%). This offers a potential to decrease the amount of primary energy use by -28% compared to the option of a facing façade (1366 MJ/m²). With a focus on only the non-renewable primary energy use, the potential for decrease is even higher, at -46%. For other building components, the potential for decrease or increase can be very different. For example, pitched roof and foundation components show little differences between the use of energy (<11%) and their renewable share concerning the choice of exterior finish. Then again, flat roof components show the highest potential of decrease of -45% through the choice between a synthetic sheeting (1870 MJ/m²) or a green roof (3381 MJ/m²). However, in terms of material use the difference between these two options is almost non-existent (~2%).

Table 4-30: Overview of the variation of the results of material and energy use of raw materials, based on the choice of exterior finish (DF1.2)

MWD in [kg/m²]; **[%]**	**EW**	**PR**	**FR**	**FO**
Highest mean value	28.4 [7.2%] (f)	2.1 [2.7%] (m)	17.0 [1.7%] (g)	51.6 [4.9%] (x)
Decrease / increase	↓-30% | ↑+42%	↓-10% | ↑+11%	↓-2% | ↑+2%	↓-1% | ↑+1%
Lowest mean value	20.0 [10.0%] (p)	1.9 [1.7%] (r)	16.6 [5.9%] (s)	51.2 [4.9%] (i)
PEET in [MJ/m²]; **[rs]**	**EW**	**PR**	**FR**	**FO**
Highest mean value	1366 [14%] (f)	1383 [33%] (m)	3381 [35%] (g)	2334 [23%] (x)
Decrease / increase	↓-28% | ↑+39%	↓-3% | ↑+3%	↓-45% | ↑+81%	↓-10% | ↑+11%
Lowest mean value	984 [36%] (t)	1339 [35%] (r)	1870 [26%] (s)	2103 [23%] (i)

The interior wall components illustrate the effects of the choice of the **interior finish** with five different design options (DF1.3).

Material Use | The comparison of the mean mass results of the interior wall components with different interior finishes reveal a significant lower mean mass for wall components with a double planking finish (~100 kg/m²) and a higher mean mass for wall components with a visible surface (~380 kg/m²). This is caused by the fact that the sample of components is limited to the possibility of the individual option of interior finish. For example, a visible surface is only possible for calcium silicate bricks, concrete and solid timber wall components and a double planking finish is normally only used for timber wall elements to increase the fire resistance of the elements. The results of the mean mass distribution show large IQRs due to the grouping of the results according to the interior finish, because all different main materials are mixed.

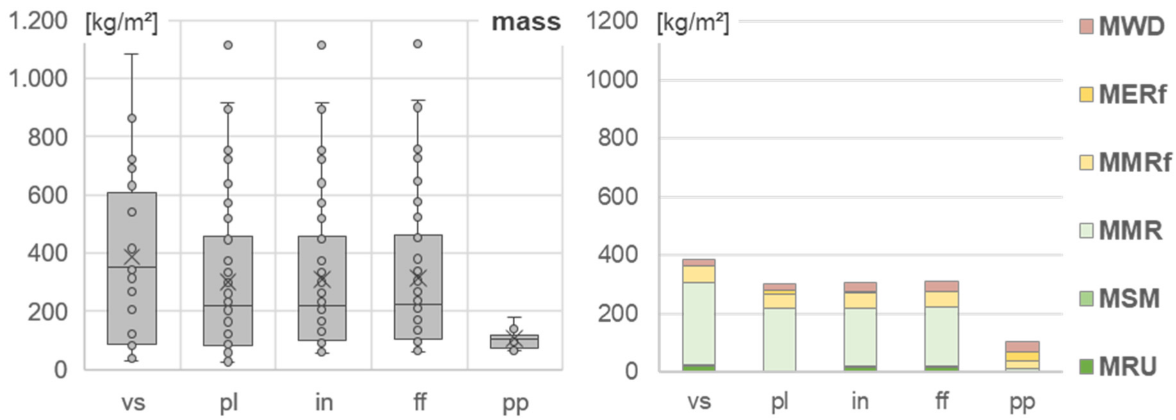


Figure 4-25: Mean mass and distribution of the mean values of the material indicators for interior wall components, grouped according to the interior finish (DF1.3)

The design option of flooring has only little effect on material use (<5%), in contrast to the results for energy use. The choice of ceilings in the context of floor slab components shows similar potential for decrease as the interior finish of interior wall components. A double planking finish, usually with gypsum boards, causes the highest mean mass results for disposal (36.1 kg/m²). The fact that components with a visible surface finish do not show the lowest results is based on the sample of components, since not every interior wall type can make the load-bearing layer visible. However, all interior walls can finish with either a plaster layer or a single planking. This means that the mean mass of material for disposal can be decreased by -37% if replaced by single interior plaster or planking (22.6 kg/m²), or by -54% respectively if only timber wall components (16.5 kg/m²) are considered.

Energy Use | The results for primary energy use show outliers that can be traced back to double-shell interior walls made from aerated concrete. The outliers for the renewable share of primary energy use are the result of solid timber interior wall components. The relatively high number of outliers lead to the conclusion that the high discrepancy of the results is based on their method of grouping, which will be illustrated by grouping them by choice of material. Although the difference is not much, it is obvious that less material for the interior finish leads to a decrease of energy use.

The different flooring options however show a higher potential for decrease. Floor slab components show the highest potential to decrease the energy use by -37%, if carpet flooring (2219 MJ/m²) is being replaced by tile flooring (1404 MJ/m²). If only non-renewable primary energy were regarded, the decrease would rise to -41%. A similar effect can be seen for foundation slab components. Carpet flooring shows owes its high energy use to the fact that it is exchanged four times during a lifetime of 50 years.

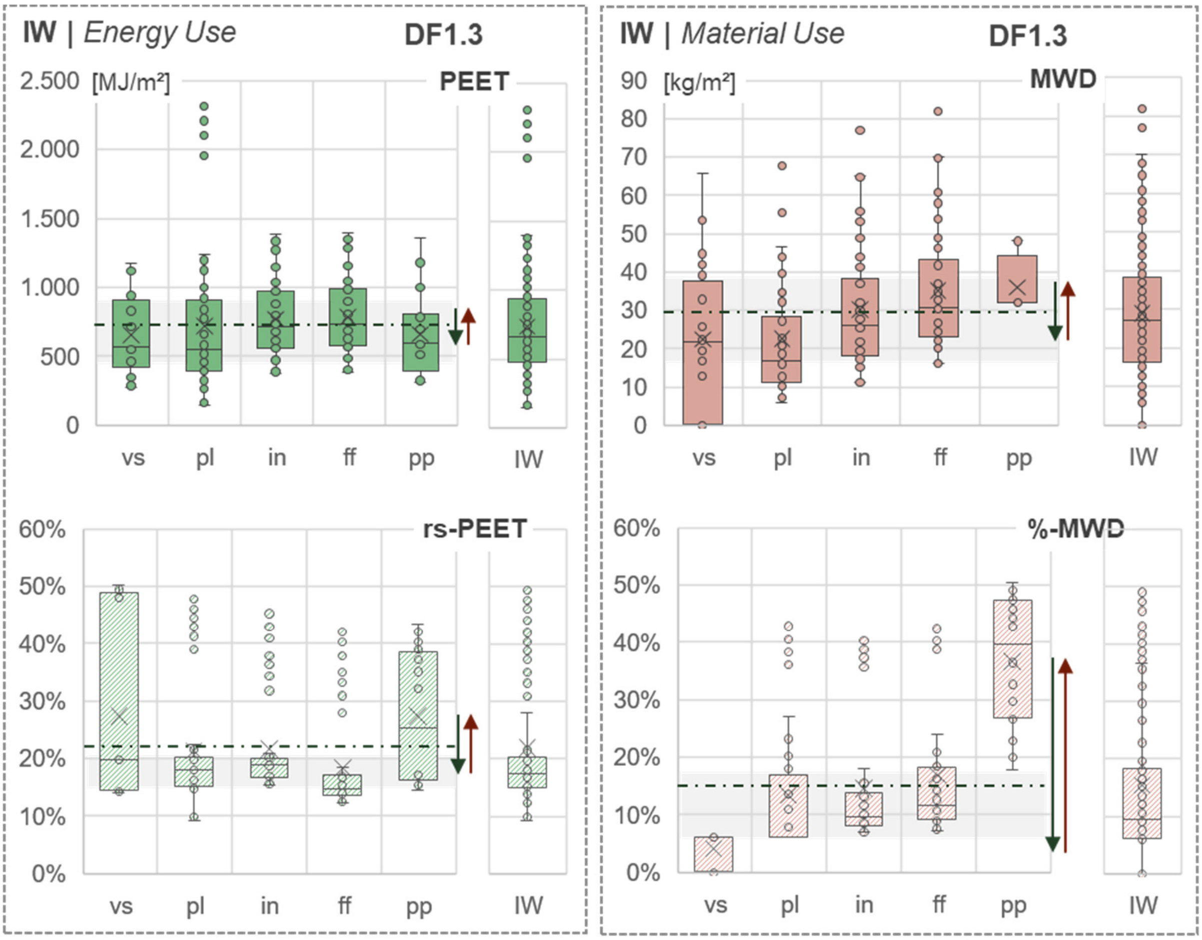


Figure 4-26: Indicator results for energy use (PEET / rs-PEET) and material use (MWD / %-MWD) for interior wall components, grouped according to the interior finish (DF1.3)

The relatively high mean results for interior walls in general are caused by the combination of both single shell and double shell separating wall components. This means that a relative comparison would lead to higher results of relative increase or decrease for single shell wall components and lower results of relative increase or decrease for double shell wall components.

Table 4-31: Overview of the variation of the results of material and energy use of raw materials, based on the choice of interior finish (DF1.3)

MWD in [kg/m²]; **[%]**	**IW**	**FS** (ceiling)	**FS** (flooring)	**FO**
Highest mean value	36.1 [37%] (pp)	33.4 [7.0%] (sc)	28.3 [5.8%] (tl)	52.2 [5.0%] (tl)
Decrease / increase	↓-37% | ↑+60%	↓-30% | ↑+43%	↓-5% | ↑+5%	↓-3% | ↑+3%
Lowest mean value	22.6 [13%] (pl)	23.3 [4.3%] (vs)	27.0 [5.6%] (li)	50.8 [4.9%] (li)
PEET in [MJ/m²]; **[rs]**	**IW**	**FS** (ceiling)	**FS** (flooring)	**FO**
Highest mean value	783 [18%] (ff)	1882 [27%] (ff)	2219 [18%] (ca)	2599 [15%] (ca)
Decrease / increase	↓-16% | ↑+20%	↓-7% | ↑+8%	↓-37% | ↑+58%	↓-31% | ↑+46%
Lowest mean value	654 [27%] (vs)	1748 [29%] (pl)	1404 [24%] (tl)	1783 [18%] (tl)

The detailed design choices of the exterior and interior finish show the problem of concurrent behaviour in the results. An economic use of raw materials when used as energy resources does not automatically imply an economic use of raw materials when used as building material. Furthermore, the distribution of the data leads to the conclusion that different decision factors play a more decisive role in influencing the results (cf. Figure 4-26).

DF2 Choice of Material

In addition to the choice of construction method, the different main materials are analysed individually and grouped according to:

- DF2.1 Choice of material: Structural layer
- DF2.2 Choice of material: Insulation layer

In general, the two chosen layers show the highest results regarding use of material either by mass (structural layer) or by volume (insulation layer). This is why the choice of material for these two layers often has a significant impact on the results of the energy and material use.

Material Use | Grouping the mass results according to the main material of the *structural layer,* the distribution of the mean mass values shows a significantly better fit.

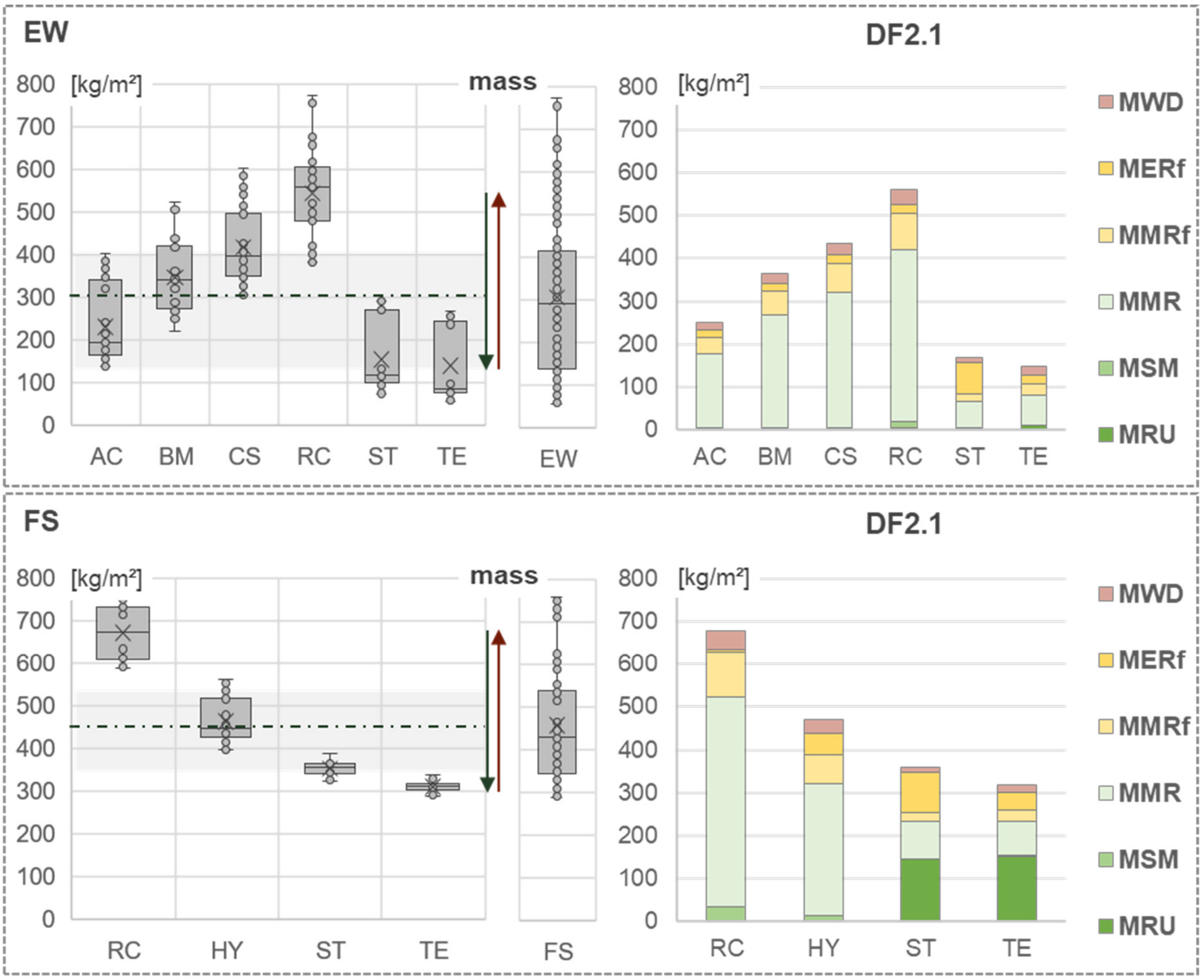


Figure 4-27: Mean mass and distribution of the mean values of the material indicators for exterior wall and floor slab components, grouped according the structural material (DF2.1)

The exemplary illustrations for both exterior wall and floor slab components show relatively compact IQR (<~150 kg/m²) and a potential to decrease the mean mass of an exterior wall component by -75% by choosing timber frame elements (138.3 kg/m²) instead of concrete (542.7 kg/m²). Floor slab components are generally heavier, but timber beam slabs (97.1 kg/m²) can still decrease the mean mass per square meter by -26% compared to concrete floor slabs (132.0 kg/m²). The high mass fraction of reusable material for timber floor slabs is caused by a loose filling of gravel which is necessary to reasons of sound insulation.

Concerning the results for the material to be disposed (MWD), a clear correlation between the weight of a component and its share of MWD becomes apparent. One exception can be observed for timber element components. Due to the typically used gypsum boards for fire safety reasons, the total mean amount of disposable waste increases – especially the share of MWD (17.0%) rises significantly to about +100% compared to the total mean value for exterior walls (8.5%). Compared with flat roof, floor slab, exterior and interior wall components, concrete components always show the highest amount of MWD. The use of solid timber components reduces the amount of material to be disposed by -81% for flat roof, -74% for floor slab, -65% for exterior and -66% for interior walls components.

Energy Use | The amount of primary energy used in the whole lifecycle is not equally influenced by the choice of main structural material compared to material use. Solid timber components show high mean values in the total primary energy use and simultaneously the highest mean share of renewable energy. For exterior wall components, this results in a potential to decrease the total mean primary energy use by -26% when comparing solid timber wall components (1369 MJ/m²; 34%) with aerated concrete wall components (1019 MJ/m²; 22%). With a focus on the non-renewable primary energy use of solid timber wall components (917 MJ/m²), this decrease potential shrinks to -14%, -11% lower than the non-renewable primary energy use of concrete wall components (1295 MJ/m²; 22%).

Table 4-32: Overview of the variation of the results of material and energy use of raw materials, based on the choice of structural material (DF2.1)

MWD in [kg/m²]; **[%]**	**FR**	**EW**	**IW**	**FS**
Highest mean value	36.1 [4.5%] (RC)	34.8 [6.2%] (RC)	47.7 [7%] (RC)	44.4 [6.6%] (RC)
Decrease / increase	↓-81% | ↑+423%	↓-65% | ↑+185%	↓-66% | ↑+194%	↓-74% | ↑+279%
Lowest mean value	6.9 [2.7%] (ST)	12.2 [7.5%] (ST)	16.2 [16%] (ST)	11.7 [3.2%] (ST)
PEET in [MJ/m²]; **[rs]**	**FR**	**EW**	**IW**	**FS**
Highest mean value	2536 [24%] (RC)	1369 [34%] (ST)	890 [16%] (AC)	1976 [36%] (ST)
Decrease / increase	↓-17% | ↑+20%	↓-26% | ↑+34%	↓-50% | ↑+100%	↓-14% | ↑+16%
Lowest mean value	2114 [28%] (TE)	1019 [22%] (AC)	446 [18%] (TE)	1698 [27%] (TE)

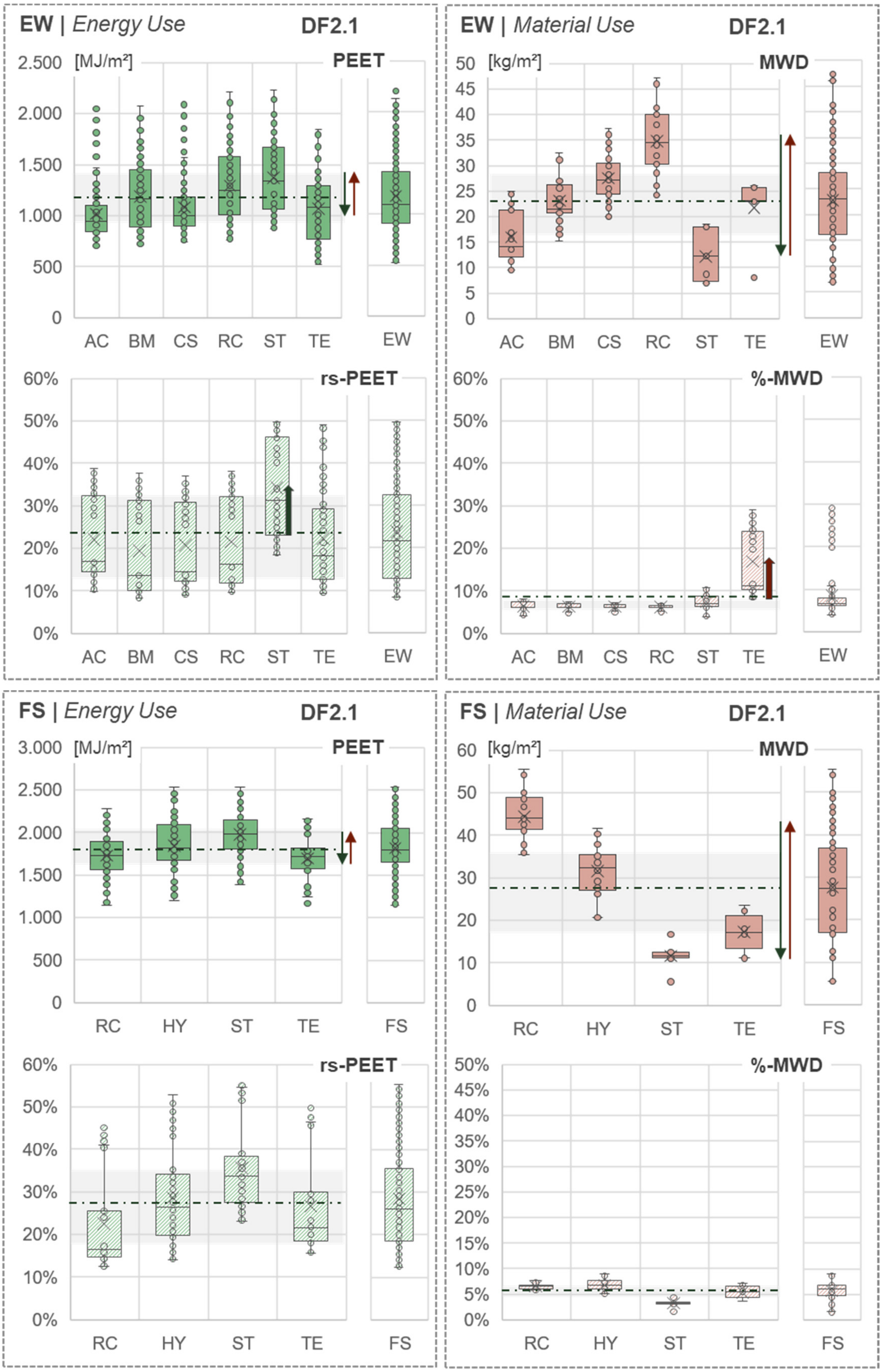


Figure 4-28: Indicator results for energy use (PEET / rs-PEET) and material use (MWD / %-MWD) for exterior wall and floor slab components, grouped according to the structural material (DF2.1)

Insulation material is not very heavy by nature but due to its thermal function, the share of volume can be quite high.

Material Use | The large IQR of the MWD results underlines the fact that grouping according to the main structural material has a large effect on the range of the mass results in general as well as for MWD. The variation between the mean values of MWD of flat roof components with different insulation material shows little potential for decrease (<18%). The share of the material to be deposed in general is less than 5% of the total mass.

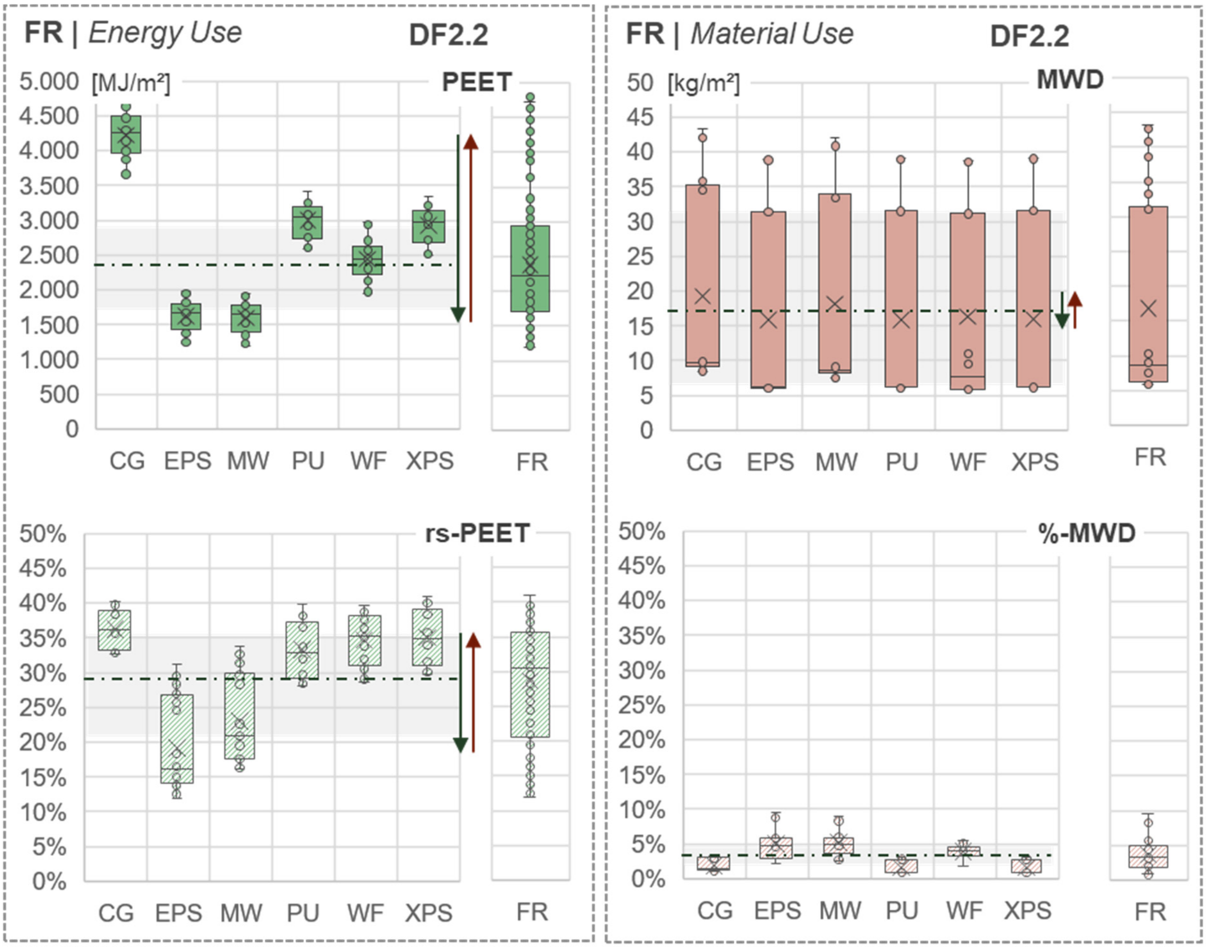


Figure 4-29: Indicator results for energy use (PEET / rs-PEET) and material use (MWD / %-MWD) for flat roof components, grouped according the insulation material (DF2.2)

Energy Use | The results of the use of primary energy, however, show completely different effects. First of all, the grouping according to insulation material shows relatively small IQR, meaning the differences for all roof components with the same insulation material do not differ substantially. For the total primary energy use, two groups of insulation materials show deviations from the mean value. Between the insulation materials for non-used flat roofs, EPS and MW (~1600 MJ/m²) show significant lower results than WF insulation (2436 MJ/m²), and for the insulation of usable flat roofs, with higher requirements, the results for CG (4223 MJ/m²) break out compared to PU and XPS insulation (~3000 MJ/m²). This leads to a decrease potential between CG and MW of -62%. Within the two groups of insulation with foot traffic (CG, PU, XPS) and without foot traffic (EPS, MW, WF), the decrease potential is -31% for flat roof constructions with foot traffic (CG → XPS) and -34% for flat roof components with no traffic (WF → MW). For insulation materials of other building components, the potential for decrease shows similar results ranging from -33% for pitched roof components to -42% for the insulation of EWIS of exterior wall components with plaster finish.

Table 4-33: Overview of the variation of the results of material and energy use of raw materials, based on the choice of insulation material (DF2.2)

MWD in [kg/m²]; **[%]**	**EWp**	**EWt**	**PR**	**FR**
Highest mean value	21.5 [10.1%] (MW)	21.6 [7.9%] (MW)	2.0 [2.4] (EPS)	19.3 [1.9%] (CG)
Decrease / increase	↓-9% | ↑+10%	↓-1% | ↑+1%	↓-0% | ↑+0%	↓-18% | ↑+21%
Lowest mean value	19.5 [9.0%] (WF)	21.5 [7.4%] (CE)	2.0 [2.0%] (WF)	15.9 [1.6%] (PU)
PEET in [MJ/m²]; **[rs]**	**EWp**	**EWt**	**PR**	**FR**
Highest mean value	1669 [33%] (WF)	1315 [39%] (WF)	1746 [37%] (WF)	4223 [36%] (CG)
Decrease / increase	↓-42% | ↑+74%	↓-37% | ↑+58%	↓-33% | ↑+48%	↓-62% | ↑165%
Lowest mean value	960 [16%] (EPS)	832 [38%] (CE)	1178 [35%] (CE)	1596 [23%] (MW)

The results grouped according to the structural or insulation material show two major trends: Due to its high mass input, the choice of structural layer is decisive for the material use and the resulting material for disposal. Due to its high volume fraction, the insulation layer on the other hand becomes crucial for the amount of primary energy used.

DF3 Choice of Geometric Design

- DF3.1 Choice of geometric design: Structural layer
- DF3.2 Choice of geometric design: Insulation layer

Since the choice of the structural material influences the indicators of material use the most, the variation of the **structural layer's thickness** is grouped according to the different structural main materials of the exterior wall components.

Table 4-34: Overview of the variation of the MWD results for exterior wall components, based on the choice of thickness of the structural layer

MWD in [kg/m²]; **[%]**	**AC**	**BM**	**CS**
Highest mean value	16.9 [6.6%] (240)	25.9 [6.4%] (240)	30.3 [6.4%] (200)
Decrease / increase	↓-14% | ↑+16%	↓-19% | ↑+23%	↓-18% | ↑+22%
Increase per mm	**+0.04/mm**	**+0.07/mm**	**+0.11/mm**
Lowest mean value	14.6 [6.5%] (175)	21.0 [6.4%] (175)	24.8 [6.3%] (150)
MWD in [kg/m²]; **[%]**	**RC**	**ST**	**TE**
Highest mean value	40.8 [6.2%] (220)	12.2 [7.0%] (140)	22.3 [16.6%] (240)
Decrease / increase	↓-29% | ↑+42%	↓-0% | ↑+0%	↓-0% | ↑+0%
Increase per mm	**+0.15/mm**	**+0.00/mm**	**+0.00/mm**
Lowest mean value	28.8 [6.2%] (140)	12.2 [8.0%] (100)	22.3 [18.0%] (160)

The data for the structural material of exterior wall components shows two main results. First, increasing the thickness results in a moderate increase of the material for disposal. Secondly, depending on the material of the structural layer, the increase varies from 0.04 to 0.15 kg/m² of MWD per extra millimetre of thickness. Especially timber wall components show no increase of MWD at all, since the structural layer does not contribute to the material for disposal.

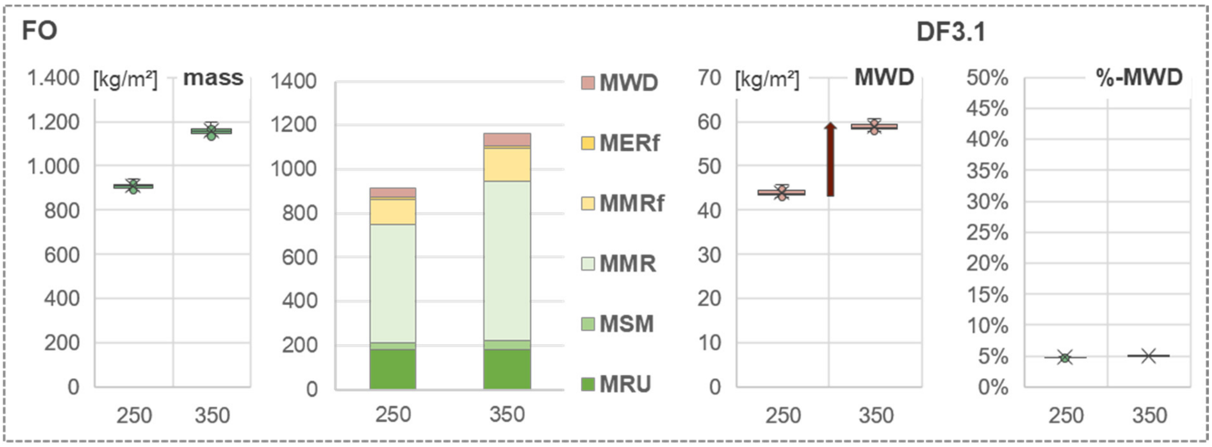


Figure 4-30: Mean mass and material indicators (MWD and %MWD) for foundation components, grouped according to the thickness of the structural layer (DF3.1)

The thicker the structural layer is, the more dominant the choice of thickness of the structural layer becomes. For example, a ten centimetre increase from 250 mm (43.9 kg/m²) to 350 mm (58.8 kg/m²) of the structural concrete layer of foundation slab components results in a +34% mean increase of the material for disposal, although the mean share of MWD is only about 5% of the total mass of the component.

The prior results of DF2 show that a variation of the insulation layer in case of insulation material has only minimum effect on the results of the indicators for material use, due to the low material density. This is why now the effect of the choice of the **thickness of the insulation layer** is considered in regard to the indicators of energy use.

Comparing the U-value of the exterior wall components with the PEET results reveals the obvious correlation of an increase in PEET results by a decrease of the U-value because of an increase of the thickness of the insulation layer. The U-value itself is also calculated for the entire component, with the insulation layer as the dominating layer but not the only parameter.

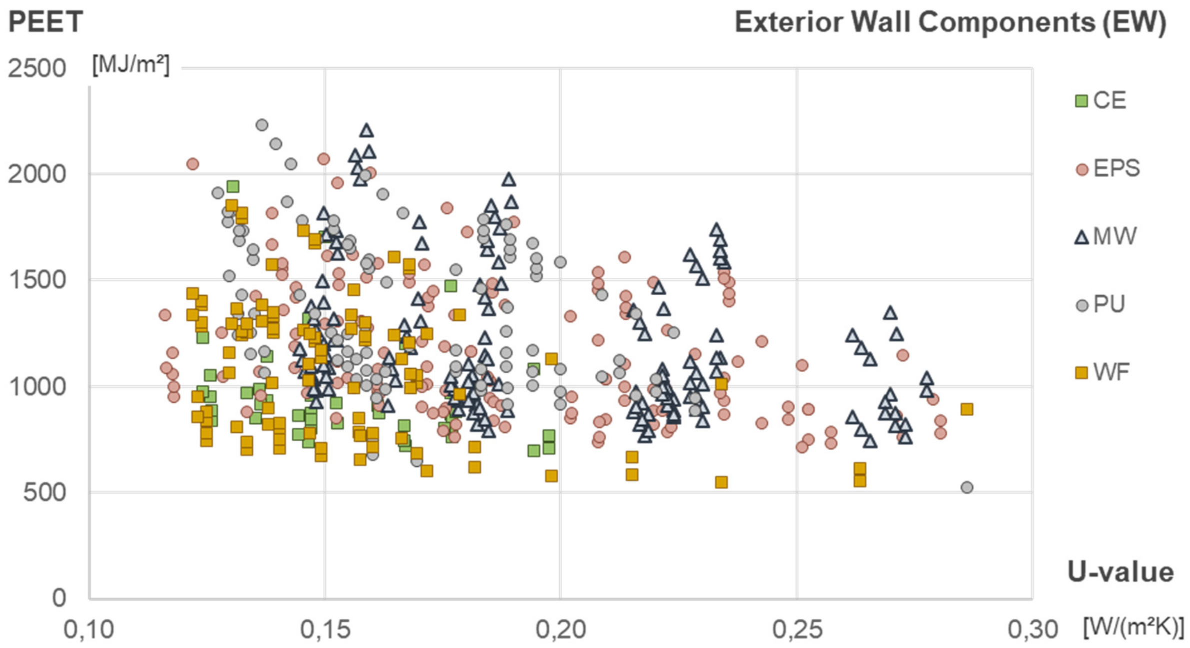


Figure 4-31: PEET results in relation to the U-value (DF3.2) of exterior wall components, grouped according to the insulation material

This increase, however, is not the same for every insulation material. An individual analysis of the insulation layer itself reveals the differences. Focusing only on the insulation layer and its individual thickness according to the thermal conductivity and the standard delivery program, a look at the minimum thickness (R ≥ 4 Km²/W) cellulose insulation shows the least primary energy (41 MJ/m²) and also the least relational increase per millimetre (+0.26 MJ/m² per mm) as well as total increase (+21 MJ/m²). Biologically based insulation materials like wood fibre and cellulose both show high shares of renewable energy use (~40%). Contrasting with this, wood fibre insulation shows approximately ten times the results as cellulose. Other insulation materials fall between cellulose and wood fibre (cf. Table 4-35). Although, it has to be mentioned that, depending on the requirements for the insulation layer, not every insulation material shows the same properties – e.g. cellulose insulation is primarily used as cavity insulation.

Table 4-35: Overview of the variation of PEET results for the exterior wall insulation layer (only), based on the choice of thickness of the insulation layer

PEET in [MJ/m²]	**CE** (λ=0.040)	**WF** (λ=0.040)	**EPS** (λ=0.035)	**PU** (λ=0.025)	**MW** (λ=0.035)
R-value ≥ 6 (mm)	62 (240)	699 (240)	205 (220)	344 (160)	104 (220)
R-value ≥ 4 (mm)	41 (160)	466 (160)	131 (140)	215 (100)	66 (140)
rs-PEET	39.6%	40.9%	2.3%	6.8%	14.0%
Increase per mm of thickness	+0.26/mm	+2.91/mm	+0.93/mm	+2.15/mm	+0.47/mm
Total increase	**+21**	**+233**	**+75**	**+129**	**+38**

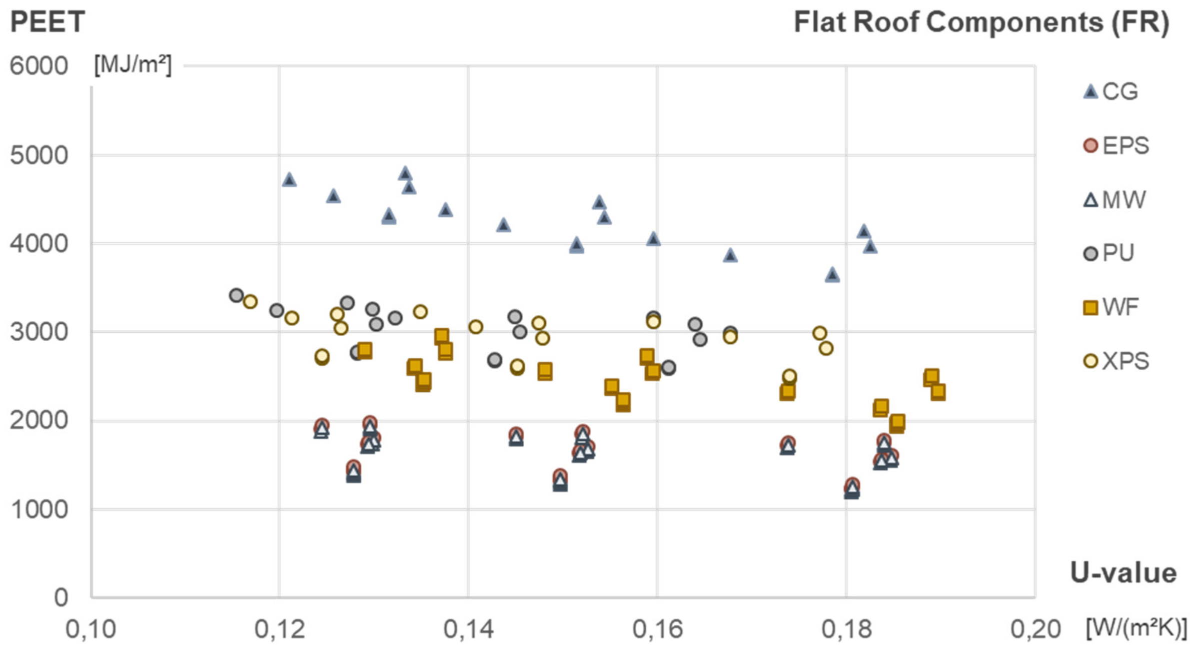


Figure 4-32: PEET results in relation to the U-value (DF3.2) of flat roof components, grouped according to the insulation material

Putting the PEET results in relation with the U-value of the flat roof components, the correlation of an increase of PEET with an increase of the U-value becomes clearly visible. For flat roof components, the choice of insulation material "sets" the line of flat roof components on different levels in the chart (cf. DF2). The incline of the components with the same insulation material is caused by the increasing thickness of the insulation layer. For a more detailed analysis, the insulation layer of flat roof components is considered individually. In general, the insulation layers behave similarly to the exterior wall insulation, with deviations for some insulation materials (MW, EPS) due to the higher requirements of flat roof insulation (cf. Table 4-36). With no cavity insulation, mineral wool insulation shows the lowest results (209 MJ/m²) and also the least increase (+1.16 MJ/m² per mm and +93 MJ/m² in total). On the other side of the spectrum, cellular glass shows the highest total results (827 MJ/m²) and the highest results in relation to an increase of thickness (+4.14 MJ/m² per mm; +331 MJ/m² in total).

Table 4-36: Overview of the variation of PEET results for the flat roof insulation layer (only), based on the choice of thickness of the insulation layer

PEET in [MJ/m²]	**WF** (λ=0.040)	**MW** (λ=0.035)	**EPS** (λ=0.035)	**CG** (λ=0.040)	**XPS** (λ=0.035)	**PU** (λ=0.025)
R-value ≥ 7 (mm)	816 (280)	302 (260)	320 (260)	1158 (280)	365 (260)	387 (180)
R-value ≥ 5 (mm)	583 (200)	209 (180)	222 (180)	827 (200)	253 (180)	301 (140)
rs-PEET	40.9%	14.0%	2.2%	30.5%	12.1%	6.8%
Increase per mm of thickness	+2.91/mm	+1.16/mm	+1.23/mm	+4.14 /mm	+1.40/mm	+2.15/mm
Total increase	**+233**	**+93**	**+99**	**+331**	**+112**	**+86**

Considering the building component as a whole compared to the insulation layer alone, the results become more moderate and show a potential to increase the mean use of primary energy by +2% (FR) or +15% (EW) by increasing the insulation thickness. Especially for flat roof components it can be stated that a general increase of the insulation layers thickness has little effect on the overall PEET results. However, as seen before, certain insulation materials come with a higher energy use, and an increase of thickness can lead to an increase of the components' PEET results of between 10-15%.

Table 4-37: Overview of the variation of PEET results for EW, PR, FR, and FO components, based on the choice of thickness of the insulation layer

PEET in [MJ/m²]; **(rs-PEET)** in [%]	**EW**	**PR**	**FR**	**FO**
Highest mean value	1286 [24.1%] (R=6)	1431 [34.3%] (R=7)	2412 [28.7%] (R=7)	2201 [22.8%] (R=3)
De- / increase	↓-13% | ↑+15%	↓-10% | ↑+11%	↓-2% | ↑+2%	↓-4% | ↑+4%
Lowest mean value	1123 [24.5%] (R=4)	1292 [33.7%] (R=5)	2371 [31.5%] (R=5)	2123 [22.8%] (R=2)

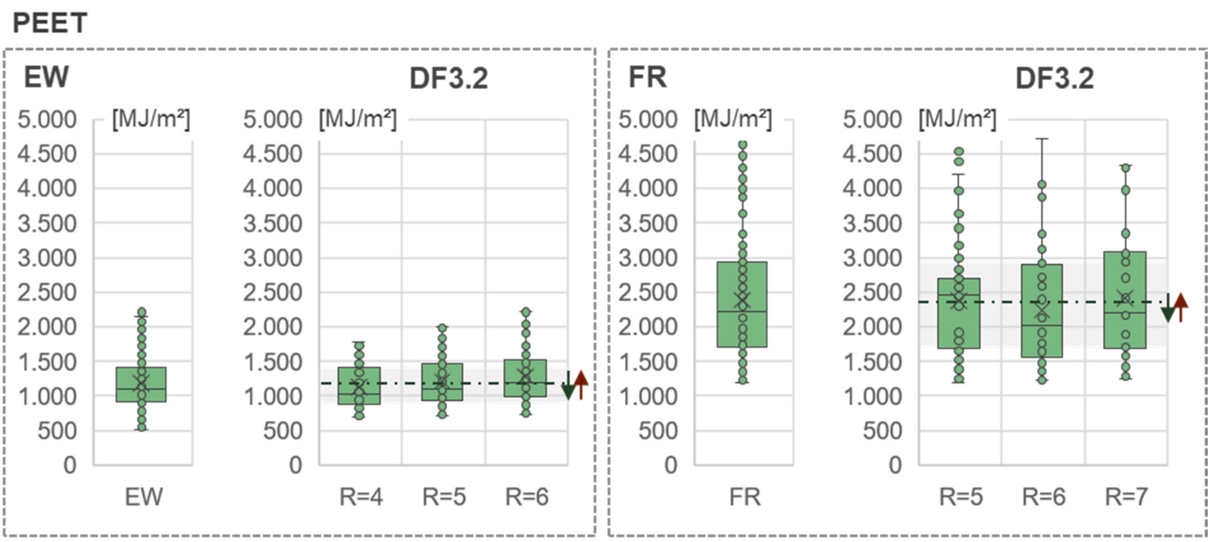


Figure 4-33: PEET results for EW and FR components, grouped according to the R-value of the insulation layer (DF3.2)

In summary the choice of thickness of the insulation layer does not show the same impact on the PEET results as the choice of insulation materials (cf. DF2.2) in the first place.

4.2.5 Outcomes for 'E.1 – Economic Use of Financial Resources'

The goal of an economic use of financial resources is illustrated by costs and life cycle costs (LCC) in particular. All results represent gross life cycle costs calculated with the BKI database retrieved in the first quarter of the year 2019.

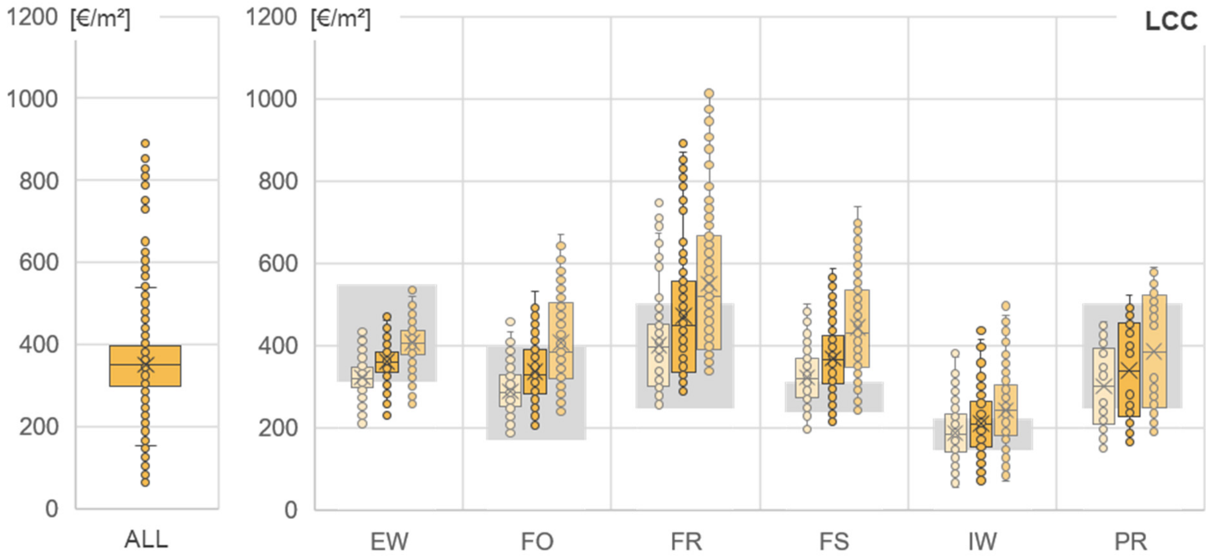


Figure 4-34: 'From' (left column), 'average' (middle column) and 'to' (right column) LCC results for all building components with mean lower and higher costs for multi-story residential buildings for comparison (grey area)[24]

Comparing the LCC results of different component types with the mean values of the second level of cost structure for multi-storey residential buildings (BKI, 2019a, p.121) shows that the results do not always fit properly. There are different reasons for this. In order to put the results in relation to comparative cost values of BKI cost groups, the boundary conditions of the calculations have to be considered. On the one hand, BKI cost groups cover more than the square metre of a building component, including extras like windows, openings, supports, and others. On the other hand, the calculation of life cycle costs includes maintenance (B2) and replacement (B4) of certain parts of the component. Therefore, especially elements with different kinds of flooring (FO and FS) show higher results.

A better comparison (cf. Figure 4-35) can be done when looking at the costs of elements that include only the elements of the third level of cost structure (BKI, 2019a, p.216ff) for multi-storey residential buildings (with <6 to >20 dwelling units) that are included in the LCC calculation as well (cf. chapter 4.1.3 and 4.1.4). Comparing the mean 'from' and 'to' range of the cost of building components of multi-story residential buildings shows higher results for four

[24] The LCC indicator results are calculated for a lifetime of 50 years including maintenance (B2) and replacement (B4) and are depicted as the cumulated value over the life cycle per square meter of component area.

component groups. In general, these higher results are caused by considering maintenance and replacement, which is part of the scope of the calculation.

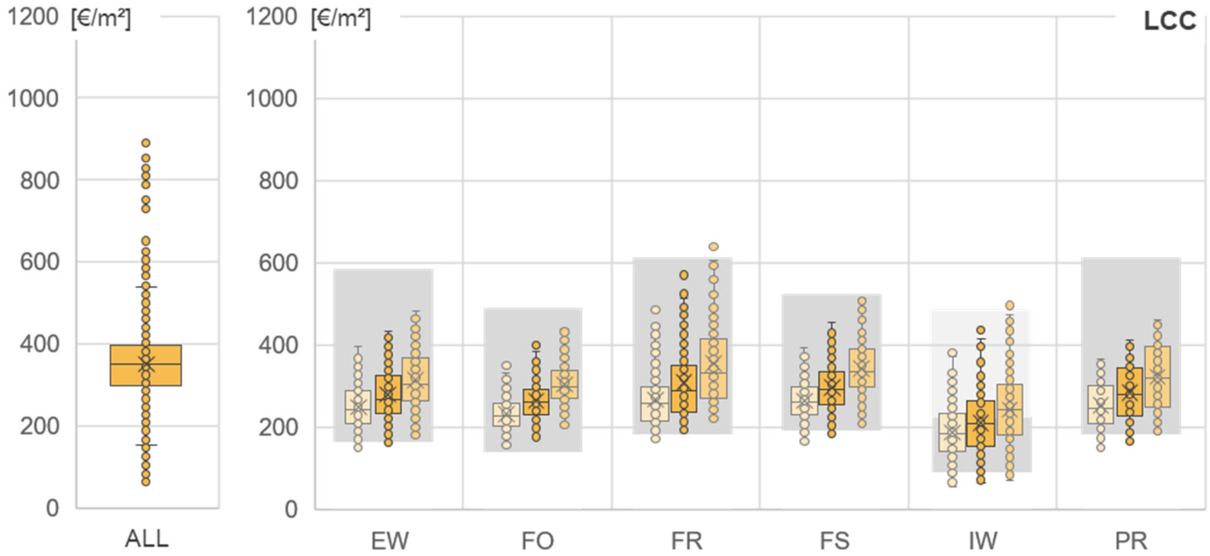


Figure 4-35: 'From' (left column), 'average' (middle column) and 'to' (right column) LCC results for all building components with mean adapted lower and higher costs for multi-story residential buildings for comparison (grey area)

The higher results and outliers for foundation and floor slab components are therefore caused by the replacement of the flooring layer. The high cost results for interior walls are partly caused by the sample of both single- and double-shell (separating) interior walls. Single limit values in the comparative costs for interior wall elements (light grey area) show the potential range for separating walls as well. For the comparison of flat and pitched roof components, only mean costs for roof elements in general exist. Pitched roof components fit in the lower part of this comparative range, while flat roof components are allocated in the higher part of the range, with outliers resulting from the replacement of the roofing layer.

In the following presentation of the LCC results, only the mean average costs are analysed and structured according to the decision factors identified, which influence the goal of an economic use of financial resources (cf. chapter 4.1.5).

DF1 Choice of Construction

- DF1.1 Choice of construction: Type of component
- DF1.2 Choice of construction: Exterior finish
- DF1.3 Choice of construction: Interior finish

The LCC results for the different types of construction have already been discussed previously. The choice of finish (interior and exterior) becomes especially relevant for costs considering the life cycle (and not only construction), due to the necessity of replacement, since finishing layers are exposed to a multitude of impacts.

In regard to the **exterior finish**, the LCC results show large differences between the mean values of exterior wall, roof and foundation components on the one side, and how strong the different exterior finish options impact the results on the other side.

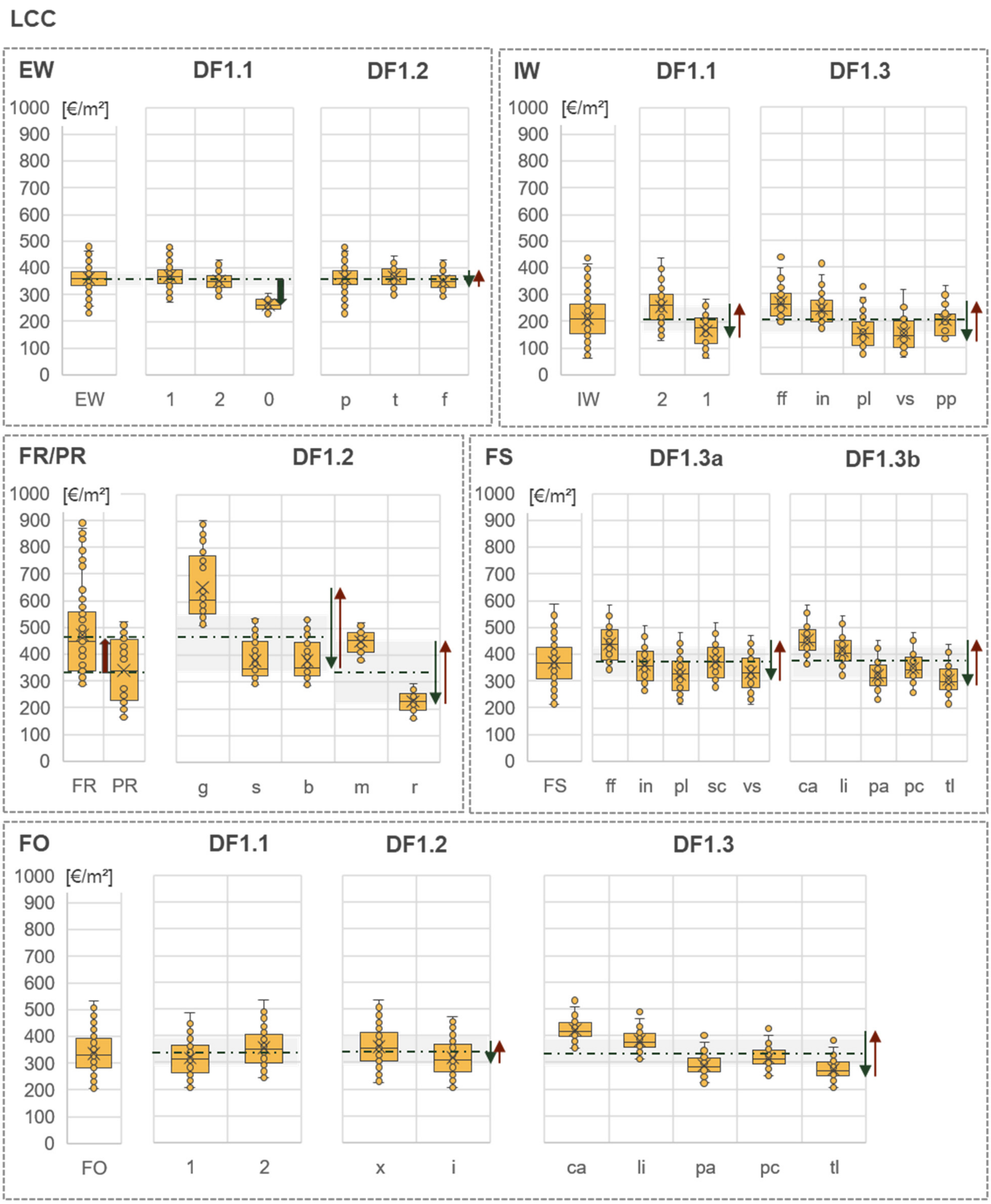


Figure 4-36: LCC results for all components of the building envelop and the interior, grouped according to the exterior (DF1.2) and interior finish (DF1.3)

For exterior wall components, the mean LCC of monolithic construction type (263 €/m²) with plaster finish (0; p) is -27% lower than the mean value for exterior walls. It is also interesting to see that although the exterior wall components with facing layer show the highest mean construction costs (350 €/m²), the mean LCC results over the life cycle of 50 years are even lower than for single-shell wall types with plaster finish (EWp: 362 €/m²) or timber cladding (EWt: 368 €/m²), because no replacement is necessary. The roof components show the highest variations in LCC results. On the one side, the mean LCC results for flat roof components (472 €/m²) are +39% higher than the mean value of pitched roof components (340 €/m²). On the other side, the difference between the roofing layer options reveals itself large differences. For pitched roof components, the mean value for metal roofing (452 €/m²) is +100% higher than for roofing tiles (228 (€/m²), because, first, the construction costs are already ~50% higher, and, secondly, the replacement of metal roofing is a major cost factor. A similar effect can be observed for flat roof components, with mean LCC results of the green roofing option already showing higher construction costs, which, including replacement (654 €/m²), results in a potential for decrease of -42% compared to a bituminous roofing finish (380 €/m³). Foundation components only show relatively little potential for decrease with -13% when perimeter insulation (313 €/m²) is replaced by interior insulation (271 €/m²).

Table 4-38: Overview of the variation of LCC results, based on the choice of exterior finish (DF1.2)

LCC in [€/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	368 (t)	452 (m)	654 (g)	313 (x)
Decrease / increase	↓-5% | ↑+5%	↓-50% | ↑+100%	↓-42% | ↑+72%	↓-13% | ↑+15%
Lowest mean value	350 (f)	228 (r)	380 (b)	271 (i)

The results of the choice of **interior finish** also reveal two important aspects: the construction costs of the option and the impact of replacement. Interior wall finishes and ceilings are almost not replaced at all but show a potential to decrease the mean LCC results from -43% (IW) to -50% (FS) in the case of only choosing a single plaster or planking layer instead of a facing framework layer. Furthermore, the difference between single- and double-shell constructions for interior walls becomes apparent. The mean average results for single-shell interior walls (166 €/m²) come closer to the comparative values, and a double-shell separating interior wall (256 €/m²) goes along with an increase of the mean LCC results by +54%. The different flooring options illustrate the effect of replacement. The mean LCC results of the choice of carpet flooring, which has to be replaced four times during the reference study period of 50 years, show a +48% (FS) to +50% (FO) increase compared to a tile flooring which does not have to be replaced at all. With a mere focus on the construction costs, this effect is not visible, and the mean average construction costs for tile flooring are +9% higher than the mean construction costs for carpet flooring.

Table 4-39: Overview of the variation of LCC results, based on the choice of interior finish (DF1.3)

LCC in [€/m²]	**IW**	**FS** (ceiling)	**FS** (flooring)	**FO**
Highest mean value	267 (ff)	452 (ff)	454 (ca)	421 (ca)
Decrease / increase	↓-43% | ↑+75%	↓-50% | ↑+98%	↓-33% | ↑+48%	↓-35% | ↑+54%
Lowest mean value	153 (pl)	228 (pl)	306 (tl)	273 (tl)

DF2 Choice of Material

In addition to the choice of construction, the different main materials are analysed individually and grouped according to:

- DF2.1 Choice of material: Structural layer
- DF2.2 Choice of material: Insulation layer

The choice of material of the **structural layer** does not show the most significant effect.

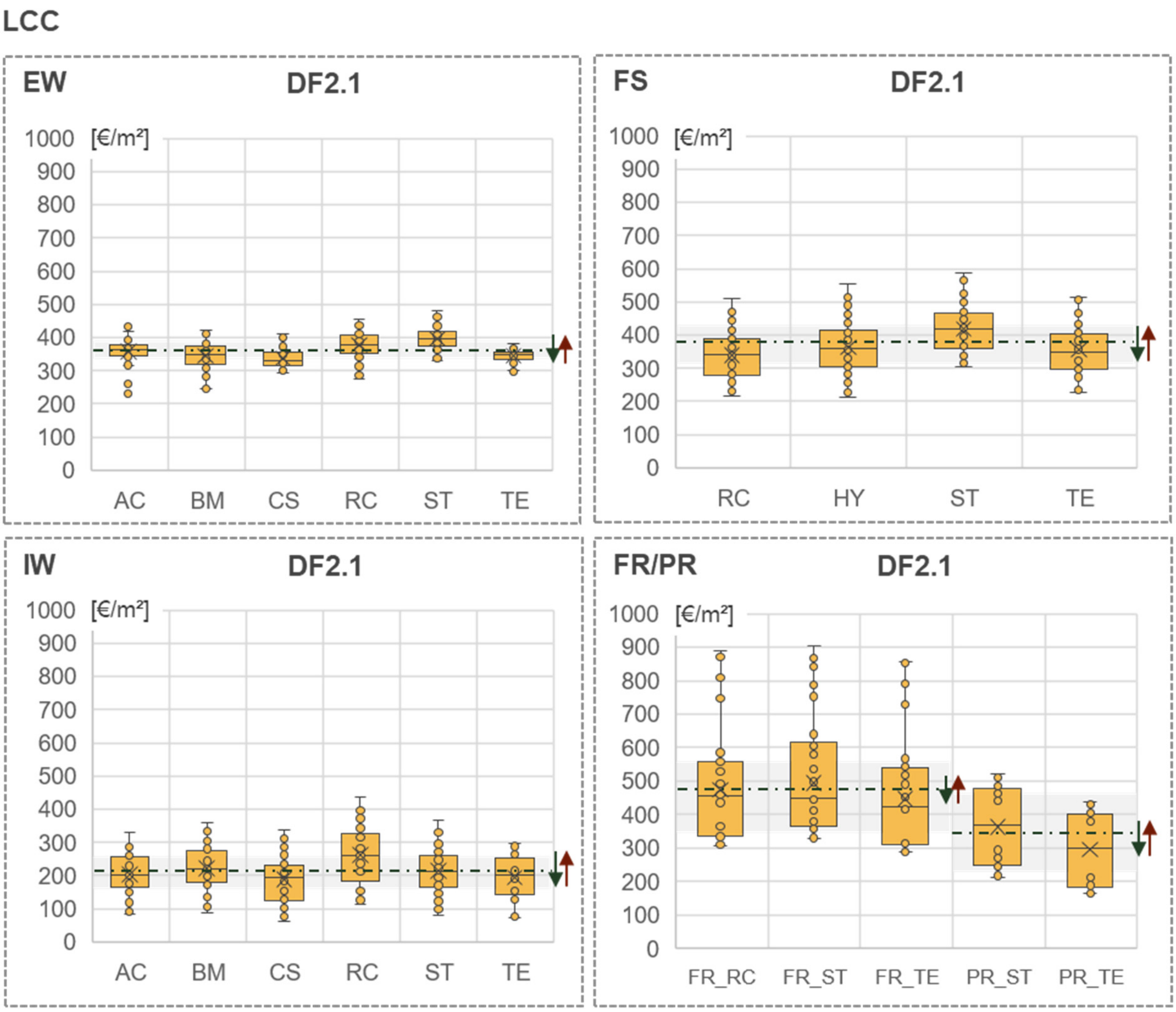


Figure 4-37: LCC results for all EW, IW, FS and FR/PR components, grouped according to the main structural material (DF2.1)

For exterior and interior wall components, the mean LCC results for calcium silicate components show the lowest results and represent a maximum potential for decrease of -15% compared to solid timber exterior walls and -28% compared to reinforced concrete interior wall components. Similar effects can be observed for horizontal building components, where the maximum decrease potential is less than -19% for floor slab and pitched roof components and only -10% for flat roof components, since the mean average LCC result for flat roof components is quite high in general.

Table 4-40: Overview of the variation of LCC results, based on the material choice of the structural layer (DF2.1)

LCC in [€/m²]	**EW**	**IW**	**FS**	**FR**	**PR**
Highest mean value	397 (ST)	262 (RC)	418 (ST)	495 (ST)	362 (ST)
Decrease / increase	↓-15% | ↑+17%	↓-28% | ↑+39%	↓-19% | ↑+23%	↓-10% | ↑+11%	↓-19% | ↑+23%
Lowest mean value	338 (CS)	189 (CS)	339 (RC)	447 (TE)	295 (TE)

Since the structural layer is not part of any replacement effort, the only difference in the mean costs is caused by different material and construction costs, which seem to show lesser general variation. In addition, with the exception of interior wall components, solid timber components show the highest mean average results, which can be related to the assumptions made regarding to underlying missing data (cf. chapter 4.1.5).

The LCC results for the choice of **insulation material** show similarities to the choice of structural material, with some exceptions.

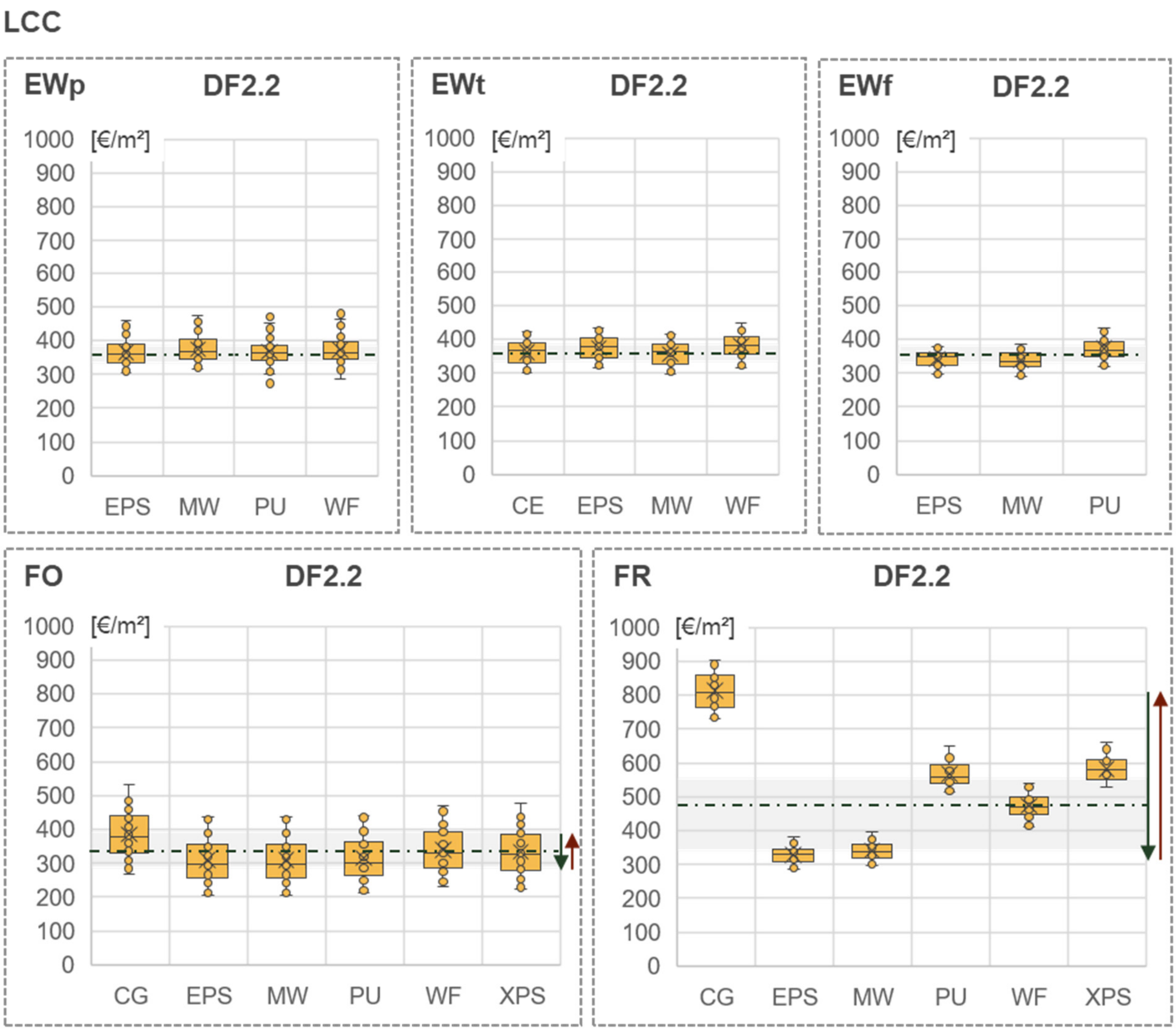


Figure 4-38: LCC results for all EW, FO and FR components, grouped according to the insulation material (DF2.2)

The difference in the material and construction costs for the insulation layer of exterior wall components seems to be very small, with a potential for decrease below -9%. The necessary replacement of the insulation layer levels the differences between the types of construction (EWp, EWt, EWf), as already mentioned, but also does not have any multiplying effect on the mean LCC results of different insulation materials. Though the mean LCC results of pitched roof components behave similarly to exterior wall components, flat roof components reveal a different situation.

Table 4-41: Overview of the variation of the GWP results, based on the material choice of the insulation layer (DF2.2)

LCC in [€/m²]	**EWp**	**EWt**	**EWf**
Highest mean value	372 (WF)	381 (WF)	371 (PU)
Decrease / increase	↓-3% | ↑+3%	↓-7% | ↑+7%	↓-9% | ↑+10%
Lowest mean value	364 (EPS)	356 (MW)	337 (MW)
LCC in [€/m²]	**PR**	**FR**	**FO**
Highest mean value	356 (WF)	813 (CG)	385 (CG)
Decrease / increase	↓-8% | ↑+8%	↓-60% | ↑+147%	↓-19% | ↑+24%
Lowest mean value	329 (CE)	329 (EPS)	310 (MW)

The choice of cellular glass as an insulation material either for foundation or flat roof components comes with higher mean LCC results in general. In the case of flat roof insulation and the necessity for replacement, this effect is amplified. The difference between the mean LCC results of flat roof components with cellular glass and EPS insulation shows a potential for a -60% decrease. Even compared to XPS insulation, which would be an alternative choice due to the requirements needed, the potential for decrease would still be -28%.

DF3 Choice of Geometric Design

- DF3.1 Choice of geometric design: Structural layer
- DF3.2 Choice of geometric design: Insulation layer

Finally, the differences in the LCC results in regard to the thickness of the structural and insulation layer will be presented.

Since the impact of the choice of material on the LCC results is significant only in specific cases (like CG insulation; see above), the impact of the choice of thickness of these layers is only moderate, too.

Table 4-42: Overview of the variation of the LCC results for exterior wall components, based on the choice of thickness of the structural layer (DF3.1)

LCC in [€/m²]	**AC**	**BM**	**CS**
Highest mean value	378 (240)	368 (240)	350 (200)
Decrease / increase	↓-5% | ↑+5%	↓-8% | ↑+8%	↓-6% | ↑+7%
Lowest mean value	359 (175)	340 (175)	328 (150)

LCC in [€/m²]	**RC**	**ST**	**TE**
Highest mean value	400 (220)	414 (140)	355 (240)
Decrease / increase	↓-12% | ↑+14%	↓-8% | ↑+9%	↓-5% | ↑+6%
Lowest mean value	352 (140)	379 (100)	336 (160)

For typical differences in the thickness of the structural layer, the increase of the mean average LCC results is less than +14% for concrete layers and less than +9% for brickwork and timber components in general.

Looking at the insulation layer with a thickness variation depending on the thermal conductivity of each material, the overall mean average of LCC results for exterior walls is similar to the choice of material in the first place, whereas the results for the variation of thickness of flat roof insulation layers are distinctly lower.

Table 4-43: Overview of the variation of LCC results for EW, PR, FR, and FO components, based on the choice of thickness of the insulation layer (DF3.2)

LCC in [€/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	384 (R=6)	350 (R=7)	479 (R=7)	405 (R=3)
Decrease / increase	↓-9% | ↑+9%	↓-5% | ↑+6%	↓-5% | ↑+5%	↓-3% | ↑+3%
Lowest mean value	351 (R=4)	331 (R=5)	455 (R=5)	394 (R=2)

Compared to the previously mentioned decision factors of choice of construction and material, the choice of the layer thickness does not have the same impact on mean LCC results.

Although the presentation of the different outcomes for each goal cannot depict every single detail, it can give an idea of the overall performance in regard to each indicator, with characteristic values for top and bottom limits, the mean values and the mean distribution. This information can be used to compare and classify the results for a single building component. Furthermore, these results can be used for benchmarking, depending on scope and context. Yet, to derive appropriate conclusions for decision-making, a deeper analysis is necessary.

5 Analysis for Value-Based Decision Making

5.1 Interpretation of Individual Indicator Results of the Parameter Variation

5.1.1 Scope of the Interpretation and Sensitivity Analysis

The extensive amount of data and results for 1472 building components and its versions offers the opportunity of interpretation an evaluation from many different perspectives. The presentation of the outcomes already illustrated the fact that every grouping option covers a variety of individual results. Obviously then, almost every arbitrary conclusion can be derived by picking individual datasets as long as the context is ignored. The goal of this chapter is to derive conclusions regarding effectiveness (*How a goal can be best accomplished?*) and interrelations (*What are the correlations between achieving different goals?*) within the scope of the parameter variation. The following chapter 5.2 will then direct its focus on how to deal with these interrelations between goal achievements by evaluation. The following interpretation and analysis seek to derive an initial and basic, yet general approach that can be further used in additional parameter variations and expanded through other indicators and goals.

Before going into an in-depth interpretation of the outcomes, it is important to note that the validity of the interpretation and the evaluation is limited to the scope of the parameter variation in the first place. Although the parameter variation already covers many standard construction types and variations of building components, it can still be extended by even more specific and special construction types. This is why the following analysis seeks to identify how sensitive the outcomes of the parameter variation are towards certain pre-choices considering the study design.

Study Design Options for B.1 Structural Safety

There are various assumptions and boundary conditions (cf. chapter 4.1.2) made in regard to verifying the ultimate limit state and the calculation of the utilization factor (B.1). Through different variations regarding the structural layer's thickness (DF3.1) or the quality of the structural material (e.g. BM, AC), plenty of additional options become able to influence the results of the utilization factor. For example, the setting, defined in the case of the parameter variation by a specific showcase, provides adjusting aspects like geometric aspects, joining techniques, etc. To keep the same boundary conditions for all wall elements, only design options specific to material constructive form are analysed. For the construction of timber panel wall elements (TE) especially, where the results show the highest values, additional typical design options can be resorted to. The critical aspect of the verification of the ultimate limit state for the original timber element components is the pressure perpendicular to the grain direction on the top/bottom plate. To reduce the pressure, the force on the top/bottom plate and in every stud has to be reduced. Three of these study design options (SDO) and their effect on the results of the utilization factor will be analysed in detail:

- **SDO1** | Number and distance between studs
  - *Original*: Studs with construction timber KVH C24, width of 80 mm, e = 625mm
  - *Option*: Studs with construction timber KVH C24, width of 80 mm, e = 312.5mm
- **SDO2** | Quality and material for the top and bottom plate
  - *Original*: Top/bottom plate with construction timber KVH C24, width of 80 mm
  - *Option*: Top/bottom plate with glue-laminated timber GL28h, width of 80 mm
- **SDO3** | Combination of SDO1 and SDO2
  - *Option*: Top/bottom plate with GL28h, width of 80 mm, studs with KVH C24, width of 80 mm, e = 312.5mm

The effect these changes in the study design have on the UF results for timber panel wall components can be seen in the following comparison between the original calculation and the results for the three options (SDO1, SDO2 and SDO3) mentioned above.

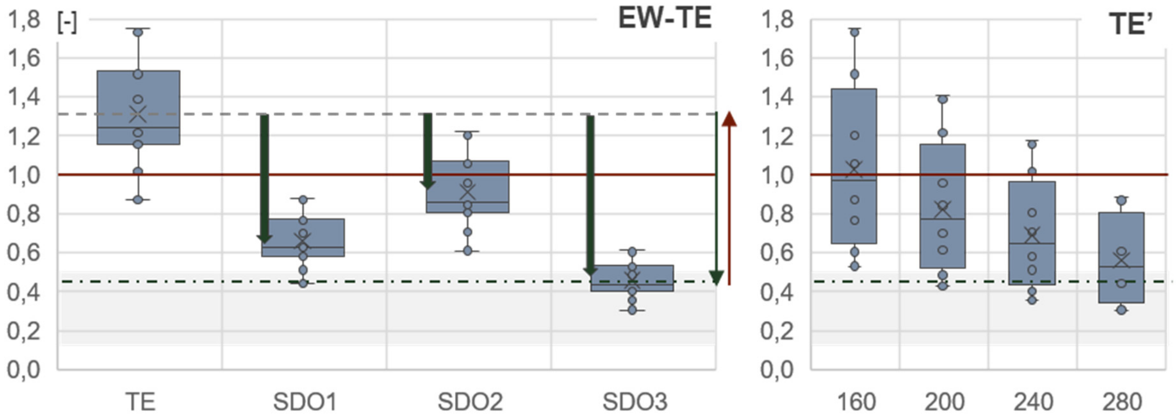


Figure 5-1: Effect of SDO1-SDO3 on the UF results of TE exterior wall components with different wall thickness in [mm]

The results reveal a significant effect of the variations made by the study design options. The variation of the number and distance between the timber studs (SDO1) decreases the mean results of all timber element wall components by -50%, whereas the variation of the top and bottom plate's quality (SDO2) leads to a decrease of the mean value by -31%. A combination of both variations (SDO3) results in a further decrease of the mean values by -65%. The results, according to the thickness of the timber element wall components, show – in a descending order – distinct lower mean values if the component options of the SDOs are included.

Table 5-1: Overview of the effect of the study design options considering the utilization factors for exterior wall components (SDO1, SDO2, and SDO3)

Utilization factor [-]	**SDO1**	**SDO2**	**SDO3**
Original mean value (TE)		*1,31*	
SDO mean value	0.66	0.91	0.46
ΔUF (utilization factor: E_d/R_d) of the mean values [-]	**Δ -0.65**	**Δ -0.40**	**Δ -0.85**
Decrease / increase	↓**-50%** | ↑+94%	↓**-31%** | ↑+44%	↓**-65%** | ↑+185%

With these variations the relatively high results of timber element components in the parameter variation fall amongst the results of other wall components. The analysis reveals the sensitivity of the UF results for TE wall components regarding additional decision factors. The conclusion is that the calculation of the utilization factor is influenced by a various number of design choices, which emphasizes the earlier statement (cf. chapter 4.1.2) that additional decision factors have to be considered carefully.

Study Design Options for D.1 Minimizing Environmental Impacts

The results of the indicators for goal D.1 (GWP, AP, EP, POCP, and ODP) and also for the indicators of energy use in goal D.2 (PEET, rs-PEET) are based on the background database ÖKOBAUDAT. Though the use of this database is common practice for LCA studies in Germany, sometimes different design options are chosen, e.g. which dataset is to be used or which material density to calculate with. With the insulation material having a decisive effect on the result of the D.1 indicators, different data options will be analysed:

- **SDO4** | Variation of the underlying data (ÖKOBAUDAT):
  - *Original*: EPS wall insulation (ID: c5edec42-1921-46c6-a3aa-5cbd27685a74)
  - *Option*: EPS grey insulation (ID: eca9691f-06d7-48a7-94a9-ea808e2d67e8)
- **SDO5** | Variation of the underlying data (ÖKOBAUDAT):
  - *Original*: WF insulation (ID: d601d54e-a2eb-42bb-b32b-c59d1b2332a9)
  - *Option*: WF panel insulation (ID: 40b5bfc6-83b6-43e3-8852-567822c56729)
- **SDO6** | Variation of the underlying data (ÖKOBAUDAT):
  - *Original*: MW with low density (ID: ec17f51c-27ff-4729-977e-cd0e273c2ee3)
  - *Option*: MW w. middle density (ID: eca9691f-06d7-48a7-94a9-ea808e2d67e8)
- **SDO7** | Variation of the underlying data (ÖKOBAUDAT):
  - *Original*: MW with low density (ID: ec17f51c-27ff-4729-977e-cd0e273c2ee3)
  - *Option*: MW w. high density (ID: b0e3aedd-a5e2-4b97-b0f3-e51548912687)

The effects these changes in the study design have on the GWP results for wall insulation materials can be seen in the following comparison between the original calculation and the results for options (SDO4, SDO5, SDO6 and SDO7).

The results show a significant effect, ranging from an improvement of -21% (SDO5) to a decrease of the GWO results of almost +300% (SDO7) just for the choice of specific datasets for insulation materials. The analysis focuses on the effect of different data for just the insulation layer as one part of a building component. The consequences for the entire component can only be estimated, with the insulation material's share ranging from 10-50% (Schwede and Störl, 2018) for the insulation layer in EW wall components depending on the type of component and the indicator in consideration, and about 6% (e.g. for GWP) in the context of a multi-storey residential building (Mahler et al., 2019, p.51). This leads to an estimated total decrease of about -1.3% or an increase of about +17.9% for a building and a decrease of about -2 to -10% or an increase of about +30 to +150% for the exterior wall component.

Table 5-2: Overview of the effect of SDO4-SDO7 considering GWP results for the exterior wall insulation layer, based (only) on the choice of thickness of the insulation layer

GWP in [kg CO_2-e/m²]	R-value ≥ 6	R-value ≥ 4	Total increase	Increase / mm
WF (λ=0.040)	**SDO4**			
Original mean value	*16.0 (240)*	*10.7 (160)*	*+5.3*	*+0.07/mm*
SDO mean value	25.7 (240)	17.1 (160)	+8.6	+0.11/mm
ΔGWP in [kg CO_2-e/m²]	**Δ +9.7**	**Δ +6.4**	**Δ +3.3**	**Δ +0.04/mm**
Decrease / increase	↓-38% | ↑**+62%**			
EPS (λ=0.035)	**SDO5**			
Original mean value	*29.8 (220)*	*19.0 (140)*	*+10.8*	*+0.14/mm*
SDO mean value	23.3 (220)	14.9 (140)	+8.5	+0.11/mm
ΔGWP in [kg CO_2-e/m²]	**Δ -6.5**	**Δ -4.1**	**Δ -2.3**	**Δ -0.03/mm**
Decrease / increase	↓**-22%** | ↑+28%			
MW (λ=0.035)	**SDO6**			
Original mean value	*12.1 (220)*	*7.7 (140)*	*+4.4*	*+0.06/mm*
SDO mean value	29.9 (220)	19.1 (140)	+10.9	+0.14/mm
ΔGWP in [kg CO_2-e/m²]	**Δ +17.8**	**Δ +11.4**	**Δ +6.5**	**Δ +0.08/mm**
Decrease / increase	↓-60% | ↑**+147%**			
MW (λ=0.035)	**SDO7**			
Original mean value	*12.1 (220)*	*7.7 (140)*	*+4.4*	*+0.06/mm*
SDO mean value	48.2 (220)	30.7 (140)	+17.5	+0.22/mm
ΔGWP in [kg CO_2-e/m²]	**Δ +36.1**	**23.0**	**Δ +13.1**	**Δ +0.16/mm**
Decrease / increase	↓-75% | ↑**+299%**			

The results stress the importance of data selection, since the choice of datasets has a significant effect on the results of the LCA indicators. It is worth mentioning that not every choice of dataset has such a variety of options and thus a similar effect on the results, furthermore, the different datasets compared cover different specifics of the insulation material. For example, SDO7 describes a mineral wool insulation material with almost four times the mean density, which is used in situations where high compression strength is required. However, these effects can influence the final result in many ways and might even counterbalance themselves, with one choice increasing and another choice decreasing the final result. The necessary conclusion therefore is that the underlying data has to be chosen thoroughly and the choice of data has to be made transparent (cf. principles of LCA, chapter 4.1.3).

Study Design Options for D.2 Economic Use of Raw Materials

Due to the use of the same calculation method, the indicators for the goal of an economic use of raw materials for energy use (PEET, PEMT, and their renewable share) show the same issue of data selection as other LCA indicators. Referring to the study design options described above (SDO4-7), the effect on the PEET and rs-PEET shows similar results.

Table 5-3: Overview of the effect of SDO4-SDO7 considering PEET results for the exterior wall insulation layer, based (only) on the choice of thickness of the insulation layer

PEET in [MJ/m²]	R-value ≥ 6	R-value ≥ 4	Total increase	Increase / mm	**rs-PEET** [%]
WF (λ=0.040)			**SDO4**		
Original mean value	*699 (240)*	*466 (160)*	*+233*	*+2.91/mm*	*40.9%*
SDO mean value	531 (240)	354 (160)	+177	+2.21/mm	17.3%
Δ PEET in [MJ/m²]	**Δ -168**	**Δ -112**	**Δ -56**	**Δ -0.70/mm**	**Δ -23.6**
Decrease / increase			↓**-24%** | ↑+32%		↓**-58%**
EPS (λ=0.035)			**SDO5**		
Original mean value	*205 (220)*	*131 (140)*	*+75*	*+0.94/mm*	*2.3%*
SDO mean value	173 (220)	110 (140)	+63	+0.79/mm	2.8%
Δ PEET in [MJ/m²]	**Δ -32**	**Δ -21**	**Δ -12**	**Δ -0.03/mm**	**Δ +0.3**
Decrease / increase			↓**-16%** | ↑+19%		↑**+13%**
MW (λ=0.035)			**SDO6**		
Original mean value	*104 (220)*	*66 (140)*	*+38*	*+0.48/mm*	*14.0%*
SDO mean value	256 (220)	163 (140)	+93	+1.16/mm	14.0%
Δ PEET in [MJ/m²]	**Δ +152**	**Δ +97**	**Δ +55**	**Δ +0.68/mm**	**Δ 0.0**
Decrease / increase			↓-59% | ↑**+146%**		-
MW (λ=0.035)			**SDO7**		
Original mean value	*104 (220)*	*66 (140)*	*+38*	*+0.48/mm*	*14.0%*
SDO mean value	413 (220)	263 (140)	+150	+1.89/mm	14.0%
Δ PEET in [MJ/m²]	**Δ +309**	**Δ +197**	**Δ +122**	**Δ +1.41/mm**	**Δ 0.0**
Decrease / increase			↓-75% | ↑**+298%**		-

Comparing different datasets reveals that results can and do vary between different indicators and can even behave in opposite ways. Whereas the GWP results increase when using the SDO4 alternative, the primary energy use (PEET) declines, and with it the share of renewable energy. This also explains why the result of 439 MJ/m² of non-renewable primary energy (PENRE, which is mainly responsible for GWP emissions), for the 240 mm thick insulation option (SDO4) is still higher than the 413 MJ/m² of PENRE of the 240mm thick original option[25].

For the results for raw material use (MRU, MSM, MMR, MMRf, MERf, MWD), the outcome is not controlled by the underlying datasets in the same way as it is for the LCA results. However,

[25] Which is calculated as follows: PENRE = PEET · (1 – rs-PEET)

the share of different material waste and recycling flows in the results reveal two major influencing quantities. On the one hand, the results for material for reuse (MRU) are strongly depended on the decision whether the material or component may or may not have the possibility to be reused. In addition to this preliminary decision, the method of joining then becomes crucial for whether this potential for reuse can actually be exploited in the end (cf. chapter 4.1.4).

	AC	BM	CC	CS	ST
MWD	6.2%	6.2%	6.2%	6.2%	0.0%
MERf	0.0%	0.0%	0.0%	0.0%	88.5%
MMRf	16.1%	16.1%	16.1%	16.1%	0.0%
MMR	77.7%	77.7%	77.7%	77.7%	11.5%
MSM	0.0%	0.0%	0.0%	0.0%	0.0%
MRU	tbd	tbd	tbd	tbd	tbd

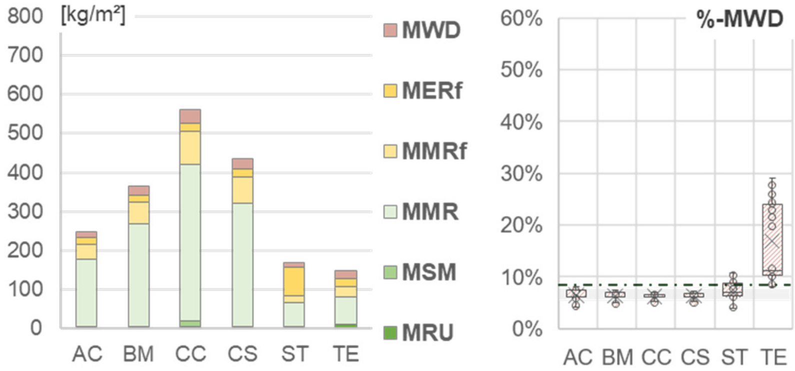


Figure 5-2: Comparison of the statistical background data (left) with the outcome for the indicators of material use (idle) and the share of MWD (right) for EW components, grouped according to the main structural material

On the other side the distribution of the additional material flows (MSM, MMR, MMRf, MERf, MWD) is highly dependent on the statistical data being used (cf. Table 4-9). It is also marginally influenced by the method of joining. For example, the results for the exterior wall components, grouped according to the main structural material, mirror the statistical distribution (e.g. with their mean value of %MWD of 6.5% [AC], 6.4% [BM], 6.2% [RC], 6.4% [CS]). Two major statements for optimization can be concluded:

- It is necessary to develop a **guideline of reuse**: Identifying an extensive list of materials and components that offer a realistic potential for reuse, including technical and market boundary conditions.
- It is necessary to expand and **optimise the statistical background** data of the model, based on consistent statistical data that can provide a well-defined scope (e.g. on a national level for Germany).

Study Design Options for E.1 Economic Use of Financial Resources

The calculation of the indicator results for an economic use of financial resources (LCC) reveals the dependence of valid results on reliable data. The inherent problem of varying reliability of cost data, due to many fluctuating influences on prices and the market, aggravates this further. The approach of the BKI database is to accumulate long-term cost data and combine it with comparison data as well as a big library of buildings. However, not every construction technique and modality are covered by the database.

As a consequence, the impact of alternative assumptions regarding the missing data for cross laminated timber panels in the sample of solid timber EW components is investigated (SDO8).

The analysis of the outcome of the indicators reveals another major influence regarding the scope of the cost calculation: The inclusion of the use phase leads to a shift in results. The effect and difference between the mere construction costs and the life cycle costs is the object of investigation in SDO9.

- **SDO8** | Variation of the underlying data (BKI)
  - *Original*: Cost data for GLT timber, GL24h, industrial quality (361.16.P06)
  - *Option*: Variation of the cost assumption by +/- 10.0%
- **SDO9** | Variation of the life cycle scope (B4)
  - *Original*: Consideration of LCC for EW wall components
  - *Option*: Consideration of construction costs (CC) for EW wall components

The effect of the variation of one single dataset (SDO8) on the LCC results in the case of CLT solid timber components can be seen below.

Table 5-4: Overview of the effect of the study design options considering PEET results for the exterior wall insulation layer, based (only) on the choice of thickness of the insulation layer

LCC in [€/m²]	**SDO8**	
Original mean value (ST)	*397*	
SDO mean value	386	407
Δ costs in [€/m²]	**Δ -11**	**Δ +10**
Lowest mean value	↓**-2.8%** | ↑+2.8%	↓-2.5% | ↑**+2.5%**

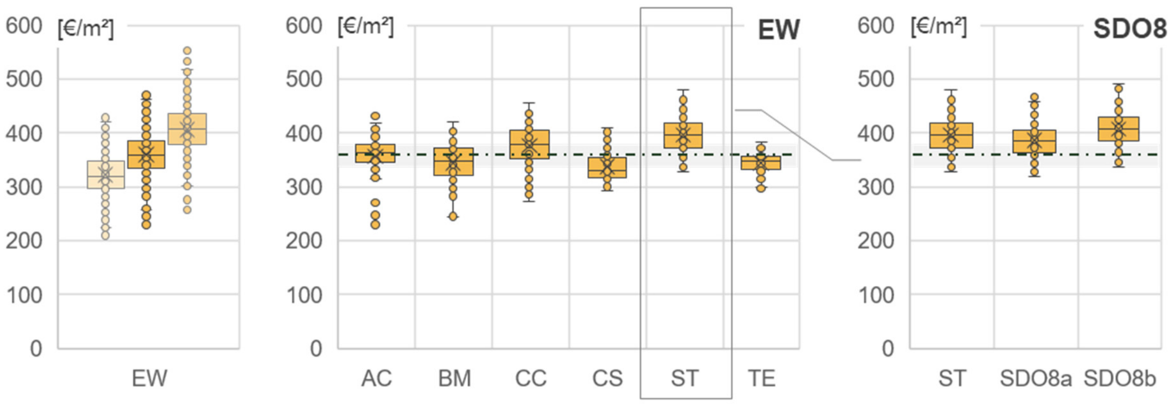


Figure 5-3: Overview of the effect of the study design option SDO8 of a variation of the underlying data for CLT in the context of EW components

This variation reveals that changing the underlying data for one single dataset does not have a very high effect on the LCC result of the whole component. A 10% variation of cost of the structural layer only leads to a 2.5- 2.8% variation of the overall costs of the entire solid timber EW component. Consequently, the importance of a single assumption is relatively low compared to other study design choices. Ye it needs to be remembered that a combination of various assumptions and choices of data can still easily affect the results.

One of the other study design choices mentioned prior is the design of the scope of the calculation, concerning for example the exchange of materials and components during the life cycle of a building or component (SDO9).

Table 5-5: Overview of the effect of SDO9 considering LCC and CC results for the exterior wall components, grouped according to the exterior finish

	SDO9		
LCC in [€/m²]	**EWp**	**EWt**	**EWf**
Original mean value (LCC)	*361*	*368*	*350*
SDO mean value (CC)	233	275	350
Δ costs in [€/m²]	**Δ +128**	**Δ +93**	**Δ 0**
Lowest mean value	↓**-35%** | ↑+55%	↓**-25%** | ↑+34%	-

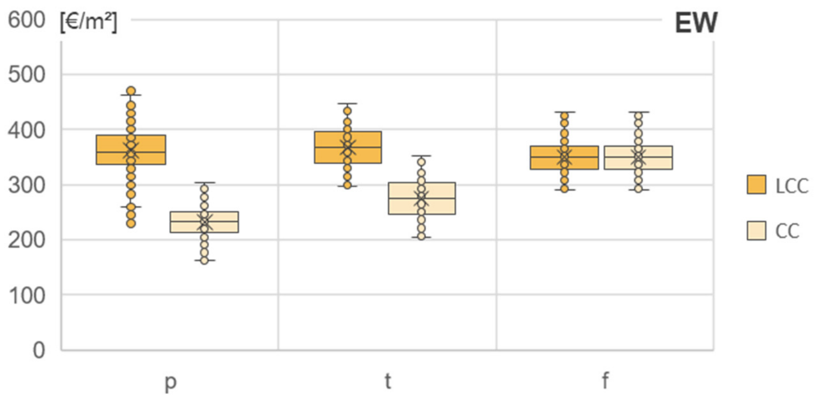


Figure 5-4: Overview of the effect of the study design option SDO9 between construction costs (CC) and life cycle costs (LCC) in the context of EW components

This comparison quite vividly illustrates the effect of exchanging materials regarding the extent of the materials needing to be exchanged. Since the exchange of materials in the context of exterior walls mainly effects the exterior finish, the different options for exterior finish best illustrate this effect. For exterior walls with plaster finish, especially with EWIS, the whole EWIS, including the insulation, has to be exchanged once during the reference study period of 50 years, leading to the highest difference of +55% in regard to the LCC. For exterior walls with a timber cladding, the insulation layer lies behind the vapour barrier, whereas only the timber cladding and the substructure have to be exchanged, leading to a +34% increase of costs over 50 years. Last but not least, a façade finish with a facing brick façade does not have to be exchanged at all, which is why no additional costs or differences between CC and LCC can be observed. This SDO illustrates the importance of a clearly defined scope of a study and the importance to keep the big picture (meaning the whole life cycle) in mind. Decision-making in planning should not rely on a (short-sighted) focus on construction costs.

5.1.2 Effectivity Analysis – How to Achieve the Best Result per Indicator

The objective of the effectivity analysis is to identify the effectiveness of every decision factor and to arrive at a suitable hierarchy and order for effective decision-making. Therefore, each decision that has an influence on the indicator under consideration is analysed according to the absolute amount of and the relational differences this decision implies regarding the results. The absolute amount of differences in the indicators' results of mean values is portrayed as delta of the Indicator (e.g. ΔGWP, ΔMWD, ΔLCC, etc.). The advantage of looking at the absolute differences between the mean values of the differently grouped data of building components lies in its equalizing effect, since outliers and other choices of the study design are equally represented in every group of data, and the values of the delta of the Indicator only show the respective differences.

Table 5-6: Total differences between the mean values of the GWP (ΔGWP) results, grouped according to the type of building component (DF1.1)

ΔGWP	DF1.1	EW	IW	FR	PR	FS	FO	[kg CO_2-e.]
DF1.1	**mean v.**	89.8	60.8	120.4	68.2	114.8	166.7	**Ø**
EW	89.8		29.0	-30.6	21.6	-25.0	-76.9	**-16.4**
IW	60.8	-29.0		-59.6	-7.4	-53.9	**-105.9**	**-51.1**
FR	120.4	30.6	59.6		52.2	**5.6**	-46.3	**20.3**
PR	68.24	-21.6	7.4	-52.2		-46.5	-98.5	**-42.3**
FS	114.8	25.0	53.9	**-5.6**	46.5		-51.9	**13.6**
FO	166.7	76.9	**105.9**	46.3	98.5	51.9		**75.9**

Annotations:
- Each coloured parcel is the result of the subtraction of the mean value in the column minus the mean value in the upper row, showing the difference between mean values.
- The parcel's result can be read as: "Potential for decrease (-) or increase (+) of GWP of the option in the first column (going left) in comparison with the option of the first line (going up)".
- The last column shows the mean value of all mean differences of the option in the first column (going left) in comparison with each option of the first line (going up).

Although the choice of building component is limited to the overall building design, the differences between the mean values of the indicator results (here: GWP as ΔGWP) of the building components (see Table 5-6) confirm and complement the outcome portrayed earlier (cf. chapter 4.2.3). On the one hand, the table illustrates that comparing interior wall with foundation components leads to the highest difference (ΔGWP: 105.9 kg CO_2-e.), while on the other hand, floor slab components compared to flat roof components show the lowest difference between mean values (ΔGWP: 5.6 kg CO_2-e.). These results can be found for all indicators and illustrate the potential effect of the design choice to decrease the mean value of the group of results in comparison. The bigger the difference, the bigger the potential for decrease and therefore the bigger the potential effectiveness.

A comparison of the differences of GWP results for all different decision factors (DF) offers the chance to arrive at another conclusion concerning the overall effectiveness of the different design choices.

Table 5-7: Display of the difference in GWP results (ΔGWP) for different decision factors (DF) as well as the difference between options for each DF, covering all building components

DF & Choices			**ΔGWP** of the mean values [kg CO_2-e.]	**De-/increase** [%]
DF1.1	highest Δ	FO-IW	**105.9**	↓-64% | ↑+174%
	lowest Δ	FS-FR	5.6	↓-5% | ↑+5%
DF1.2	highest Δ	EW: t-f	**51.5**	↓-45% | ↑+83%
	lowest Δ	FO: i-x	10.8	↓-6% | ↑+7%
DF1.3	highest Δ	FS: pa-ca	**53.7**	↓-37% | ↑+58%
	lowest Δ	FS: vs-ff	12.6	↓-10% | ↑+12%
DF2.1	highest Δ	FR: TE-RC	**59.1**	↓-38% | ↑+60%
	lowest Δ	FS: TE-RC	34.9	↓-26% | ↑+36%
DF2.2	highest Δ	FR: WF-CG	**51.3**	↓-35% | ↑+54%
	lowest Δ	EWt: CE-EPS	20.7	↓-28% | ↑+40%
DF3.1	highest Δ	RC: 140-220	**21.2**	↓-18% | ↑+22%
	lowest Δ	TE: 160-240	5.6	↓-8% | ↑+8%
DF3.2	highest Δ	FR: R=5-7	**23.0**	↓-17% | ↑+20%
	lowest Δ	FO: R=2-3	5.3	↓-3% | ↑+3%

In the context of the different groups of building components, the maximum difference between component types exceeds all other design choices. In addition, the analysis of the differences cannot merely consider the overall difference (e.g. DF2.2 Choice of insulation material), because not all insulation materials can be exchanged freely due to different requirements concerning the intended use and construction (cavity insulation, EWIS, flat roof insulation, etc.). This is why the comparison is consistently limited to the spectrum of equally possible design choices (e.g. all different façade finishes, all different flooring options, all different flat EWIS insulation materials, etc.).

The relation of the results for each decision factor to the other decision factors allows the conclusion about the priority of design choices according to how effective they are in achieving a low GWP result:

(1) DF1.1 Choice of construction: Type of component
(2) DF2.1 Choice of material: Structural layer
(3) DF1.3 Choice of construction: Interior finish
(4) DF1.2 Choice of construction: Exterior finish
(5) DF2.2 Choice of material: Insulation layer
(6) DF3.2 Choice of geometric design: Insulation layer
(7) DF3.1 Choice of geometric design: Structural layer

Of course, this order is not a universal statement about expected results of a building component. But it can be a helpful orientation at a general and early design stage. The user has to bear in mind that this priority derives from the extensive parameter variation, which is neither complete nor uses a distribution according to real occurrences (as discussed in chapter 4.2.1).

So, for better accuracy, this approach is extended to the other indicators and translated for the scope of specific groups of building components, since the need and the possibilities for different design options also differ depending on which components are under consideration (e.g. interior wall or floor slab components lack the choice of thickness of the insulation material at all). The following effectivity analysis is done only for exterior wall components in order to showcase the approach. This approach can simultaneously be transferred to other building components or even other indicators and their underlying goals.

Effectivity of Structural Safety (B.1)

Starting with the first goal of structural safety (B.1), three decision factors in the parameter variation on the component level are considered that influence the indicator of the utilization factor and that have to be put in a hierarchical order.

Table 5-8: Display of the differences in B.1 results (ΔUF) of different decision factors (DF), with the highest and lowest options for each DF covering exterior wall components

DF & Choices		**Option** with its mean value	**ΔUF** (utilization factor: E_d/R_d) of the mean values [-]	**De-/increase** [%]
DF1.1	highest Δ	0.55 (2)	**0.19** (2-0)	↓-35% | ↑+53%
		0.36 (0)		
	lowest Δ	0.42 (1)	0.05 (1-0)	↓-11% | ↑+14%
		0.36 (0)		
DF2.1	highest Δ	1.31 (TE)	**1.25** (TE-RC)	↓-95% | ↑+208%
		0.06 (RC)		
	lowest Δ	0.35 (BM)	0.06 (BM-CS)	↓-17% | ↑+21%
		0.29 (CS)		
DF3.1	highest Δ	1.61 (TE: 160)	**0.73** (TE: 160-240)	↓-45% | ↑+83%
		0.88 (TE: 240)		
	lowest Δ	0.18 (ST: 100)	0.04 (ST: 100-120)	↓-22% | ↑+29%
		0.14 (ST:120)		

Every construction engineer will find the results of the effectivity analysis in the case of structural safety (B.1) to be quite obvious – starting with the choice of structural material showing the highest difference, followed by the choice of geometric design of the structural layer and ending with the choice of construction (monolithic, single- or double-shell), which only influences the weight of the construction component. Therefore, a simple priority of decision factors within the possible options for the indicator ‘utilization factor’ can be concluded:

(1) **DF2.1** Choice of **material**: Structural layer
(RC → ST → CS → BM → AC → TE)
(2) **DF3.1** Choice of **geometric design**: Structural layer
("as thick as needed")
(3) **DF1.1** Choice of construction: **Type** of component
(0 → 1 → 2)

This priority can be shown by looking at the top and lowest ten datasets, if they are structured and ordered in an ascending order of the UF indicator result. On the other end of the spectrum, the lowest differences (see Table 5-9) show the minimum effect an alternative decision can have. The results for the indicator B.1 reveal that for every decision the effect is, at minimum, more than a -11% decrease or a +14% increase (DF1.1). However, the validity of this priority is limited to the specific showcase and load case described earlier (cf. chapter 4.1.2). It can be verified by the top and bottom ten results of the EW components, sorted by UF result in ascending order.

Table 5-9: Overview of the top and bottom ten EW component versions, sorted by the indicator UF result in an ascending order

Top ten EW component versions sorted by **UF** results in an ascending order	**Bottom ten** EW component versions sorted by **UF** results in an ascending order
EW1p-pl_RC22_EPS14a	…
EW1p-pl_RC22_PU10a	EW2f-pl_TE16_EPS8-MW
EW1p-pl_RC22_EPS18b	EW2f-pl_TE16_PU6-MW
EW1p-pl_RC22_EPS22c	EW2f-pl_TE16_EPS8-CE
EW1p-pl_RC22_PU14b	EW2f-pl_TE16_MW8-EPS
EW1p-pl_RC22_PU16c	EW2f-pl_TE16_PU6-CE
EW1p-pl_RC22_MW14a	EW2f-pl_TE16_MW8-MW
EW1p-pl_RC22_MW18b	EW2f-pl_TE16_EPS8-WF
EW1t-pl_RC22_EPS14a	EW2f-pl_TE16_PU6-WF
EW1t-pl_RC22_EPS18b	EW2f-pl_TE16_MW8-CE
…	EW2f-pl_TE16_MW8-WF

The priority list only considers a limited amount of decision factors within the level of building components. For an integral assessment of the load bearing capacity in general, several load cases have to be analysed, and the respective data of the performance of the building components has to be used to derive a more general priority of decision factors.

However, the sensitivity analysis already revealed the effect and importance of several design options within the design of the component, and additionally of the bigger context and the design options within the design of the whole building. The options that were considered show similar effects on the results and reveal the importance of extending the priority list with additional decision factors when calculating the indicator of the utilization factor within and beyond the level of the building component.

Effectivity of Minimising Environmental Impacts (D.1)

Regarding the goal of minimising environmental impacts (D.1), an effectivity analysis for four of the seven indicators is presented according to the outcome and consistency of the results (cf. chapter 4.2.3). The results reveal a different potential of the decision factors and the possible options to achieve the highest difference according to the indicator under consideration. Deriving one single order of priority for these decision factors will always end in a compromise for any single indicator. Therefore, four priority lists are derived for each indicator in particular.

Two decision factors are limited in their explanatory power: the choice of the construction type (DF1.1) and the choice of the interior finish (DF1.3). The choice of construction type is clustered in three different options, whereby the option '0' only contains 15 datasets and has therefore limited significance. Furthermore, the same dataset for the option '2' is covered by the option 'f' of the decision factor DF1.2. Within the scope of the parameter variation, the interior finish of the exterior wall components was not part of the variation. The variation of the interior wall components according to the interior finish is used in this interpretation for comparative reasons. For the interpretation of environmental impacts, the option of double planking 'pp', which only covers timber components, was neglected due to the underrepresentation of other component versions.

Table 5-10: Display of the differences in D.1 results (ΔGWP, ΔAP, ΔEP, ΔPOCP) of different decision factors (DF), with the highest and lowest options for each DF covering exterior wall components.

Choice / option		**ΔGWP** of the mean value [kg CO_2-e/m²]	**ΔAP** of the mean values [g SO^2-e/m²]	**ΔEP** of the mean values [g $PO_4{}^3$-e/m²]	**ΔPOCP** of the mean values [g ethene-e/m²]
DF1.1	highest Δ	**33.5** (2-1)	**91.6** (2-0)	**4.6** (2-0)	**47.0** (1-0)
	lowest Δ	5.6 (2-0)	0.9 (1-0)	0.4 (2-1)	2.6 (1-2)
DF1.2	highest Δ	**51.5** (f-t)	**128.8** (f-t)	**5.8** (p-t)	**25.1** (p-t)
	lowest Δ	17.5 (f-p)	60.8 (f-p)	2.0 (p-f)	11.8 (p-f)
DF1.3	highest Δ	**12.7** (IW: ff-vs)	**58.1** (IW: pl-vs)	**6.0** (IW: ff-vs)	**85,5** (IW: pl-in)
	lowest Δ	2.6 (IW: in-pl)	6.1 (IW: ff-in)	0.1 (IW: ff-in)	0.3 (IW: ff-in)
DF2.1	highest Δ	**39.9** (RC-TE)	**93.0** (CS-RC)	**11.0** (CS-RC)	**18.9** (ST-BM)
	lowest Δ	4.4 (AC-CS)	6.6 (BM-ST)	0.6 (AC-CS)	0.7 (AC-BM)
DF2.2	highest Δ	**24.5** (e: PU-WF)	**145.8** (e: EPS-MW)	**19.7** (e: EPS-WF)	**130.4** (e:EPS-MW)
	lowest Δ	0.0 (f: MW-EPS)	7.1 (t: CE-EPS)	2.7 (e: WF-MW)	0.3 (f: MW-CE)
DF3.1	highest Δ	**21.2** (RC:220-140)	**38.7** (RC:220-140)	**6.9** (RC:220-140)	**10.4** (TE:240-160)
	lowest Δ	5.6 (CS:200-150)	10.2 (CS:200-150)	2.0 (CS:200-150)	0.1 (BM:240-175)
DF3.2	highest Δ	**12.3** (R=6-4)	**32.4** (R=6-4)	**5.1** (R=6-4)	**17.8** (R=6-4)
	lowest Δ	5.6 (R=5-4)	15.3 (R=6-5)	2.4 (R=6-5)	8.5 (R=6-5)
Annotations: For EW components, the interior finish (DF1.3) was not varied.					

The differences between the mean values of the GWP results reveal three decision factors with higher values: the choice of exterior facade (highest difference between the EW with timber cladding and the wall components with a facing façade) at the top, followed by the choice of structural material (highest difference between TE and RC components) and the choice of construction type (with the biggest difference between single- and double-shell components). The mean differences between the choice of insulation material (DF2.2) or the choice of structural layer's thickness (DF3.1) show mediocre potential for lowering GWP results. The remaining decision factors (DF1.3 and DF 3.2) show only minimal influence on GWP results. A priority list for achieving the lowest **GWP** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF1.2** Choice of construction: Exterior finish
(2) **DF2.1** Choice of material: Structural layer
(3) **DF1.1** Choice of construction: Type of component
(4) **DF2.2** Choice of material: Insulation layer
(5) **DF3.1** Choice of geometric design: Structural layer
(6) **DF1.3** Choice of construction: Interior finish
(7) **DF3.2** Choice of geometric design: Insulation layer

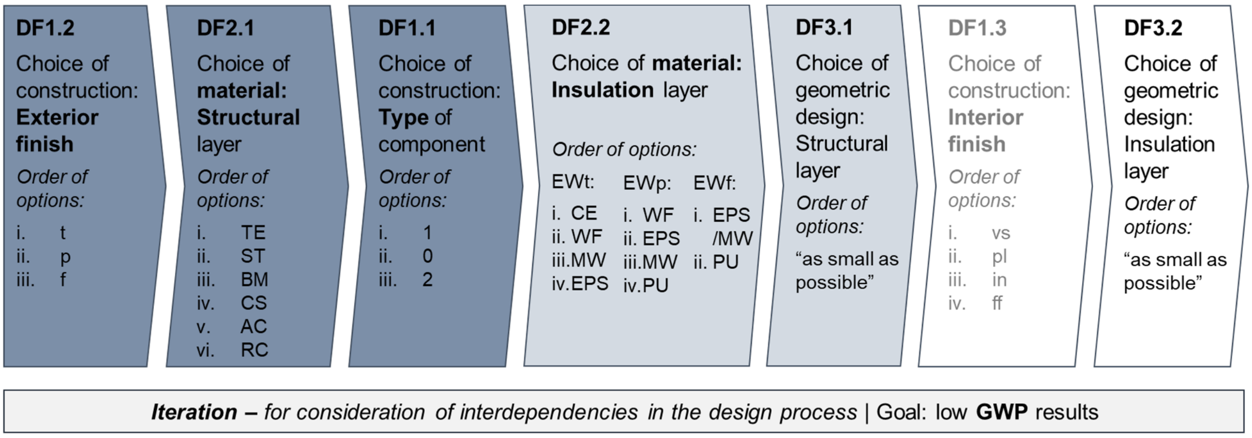


Figure 5-5: Flowchart of an effective decision procedure of EW components for low GWP results

The differences in the AP results can be clustered in three groups. The choice of insulation material (DF2.2) and the choice of exterior façade (DF1.2) show the highest potential for different results by far. A mediocre potential for different results is offered by the choice of structural material (DF2.1) and the choice of construction type (DF1.1). The other decision factors show only minimal possibilities for influencing the indicator results. A priority list for achieving the lowest **AP** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF2.2** Choice of material: Insulation layer
(2) **DF1.2** Choice of construction: Exterior finish
(3) **DF2.1** Choice of material: Structural layer
(4) **DF1.1** Choice of construction: Type of component
(5) **DF1.3** Choice of construction: Interior finish
(6) **DF3.1** Choice of geometric design: Structural layer
(7) **DF3.2** Choice of geometric design: Insulation layer

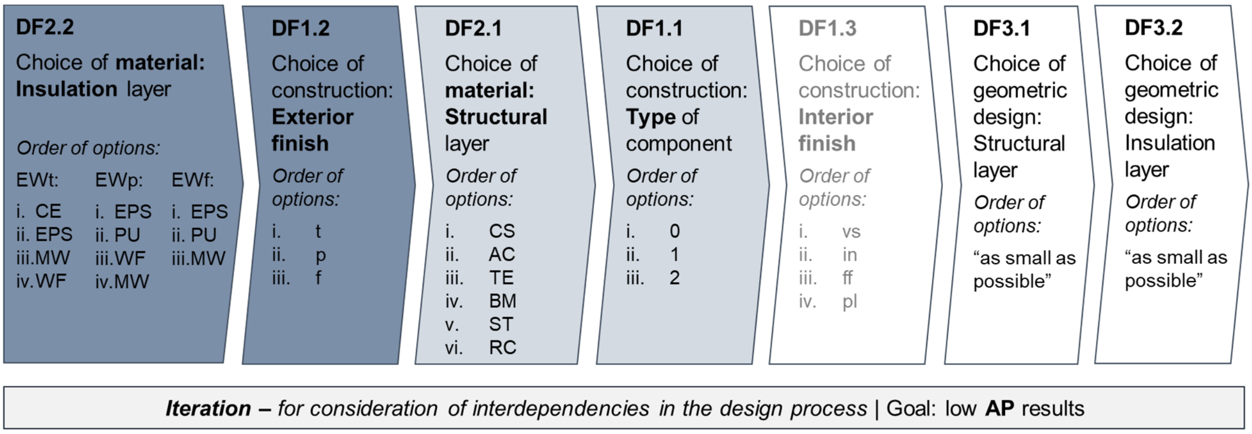


Figure 5-6: Flowchart of an effective decision procedure of EW components for low AP results

The results for the differences between the mean values of the indicator EP reveal one decisive factor: the choice of insulation material (DF2.2). It has the highest potential to influence the EP results, while the choice of structural material (DF2.1) shows less yet still significant potential to lower the mean value of EP results. The remaining decision factors and their different options only have minor impacts on the EP results. A priority list for achieving the lowest **EP** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF2.2** Choice of material: Insulation layer
(2) **DF2.1** Choice of material: Structural layer
(3) **DF3.1** Choice of geometric design: Structural layer
(4) **DF1.3** Choice of construction: Interior finish
(5) **DF1.2** Choice of construction: Exterior finish
(6) **DF3.2** Choice of geometric design: Insulation layer
(7) **DF1.1** Choice of construction: Type of component

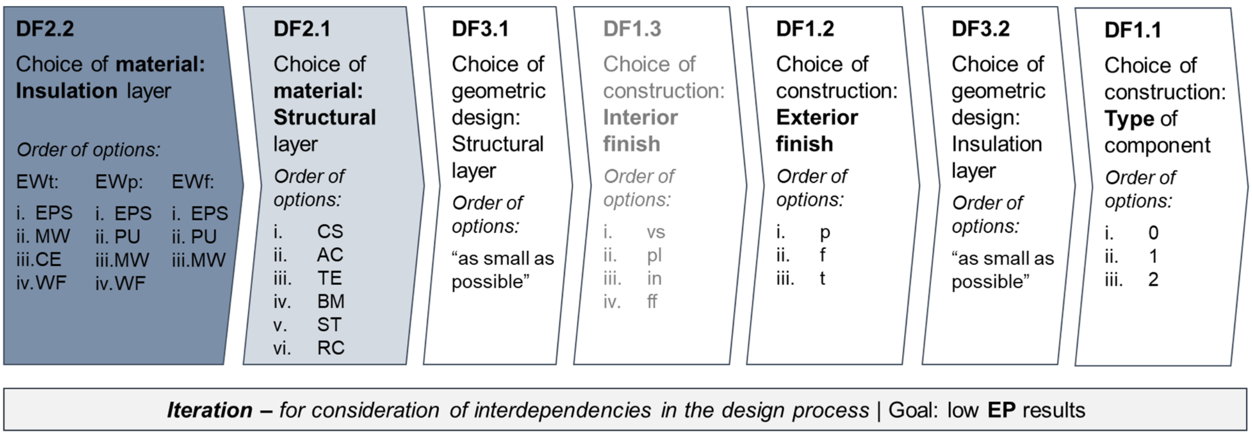


Figure 5-7: Flowchart of an effective decision procedure of EW components for low EP results

Similar to the EP results, the POCP results are mainly influenced by the choice of insulation material, but with a very concurrent order of the possible options. Whereas EPS has the lowest results for optimal EP results, it has the highest POCP results (cf. Figure 4-13). The choice of construction (DF1), including exterior and interior finish as well as the type of component, has also a significant impact on the POCP results. The choice of structural material and the choice of a layer's thickness shows only minor potential for lower POCP results. A priority list for achieving the lowest **POCP** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF2.2** Choice of material: Insulation layer
(2) **DF1.3** Choice of construction: Interior finish
(3) **DF1.1** Choice of construction: Type of component
(4) **DF1.2** Choice of construction: Exterior finish
(5) **DF2.1** Choice of material: Structural layer
(6) **DF3.2** Choice of geometric design: Insulation layer
(7) **DF3.1** Choice of geometric design: Structural layer

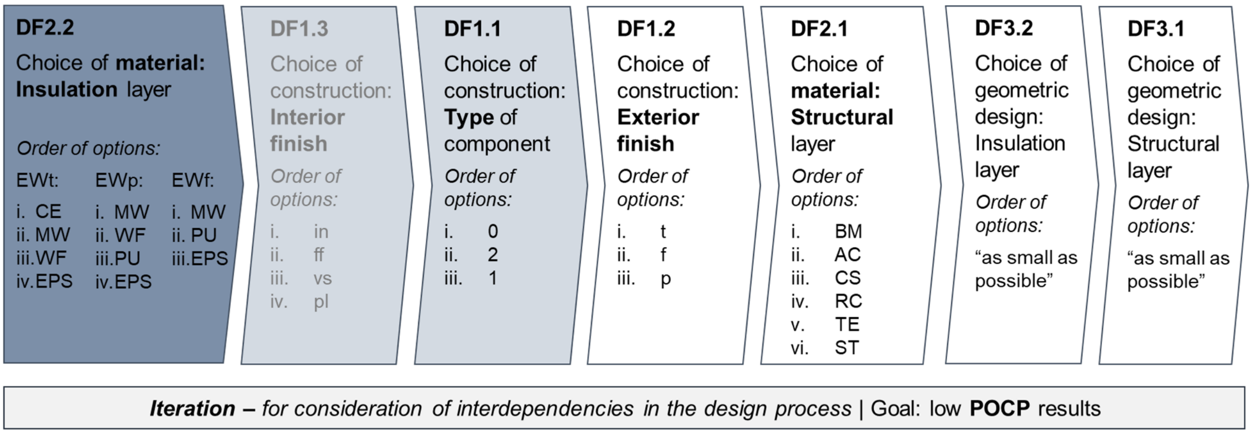


Figure 5-8: Flowchart of an effective decision procedure of EW components for low POCP results

Generally, it can be observed that while no effective decision procedure is the same, the choice of insulation material is the dominating factor for the results of the EP, AP and POCP indicators, and that the choice of the insulation or structural layers thickness has rather little effect on the indicator results. The validity of these priority lists is underlined by the top ten and bottom ten datasets of exterior wall components, sorted according to the respective indicator results in ascending order and showing the influence of the decision factors.

Table 5-11: Overview of the top and bottom ten EW component versions (of 544), sorted by the GWP, AP, EP and POCP indicator results in an ascending order

EW component versions sorted by **GWP** results in an ascending order	**EW component versions** sorted by **AP** results in an ascending order	**EW component versions** sorted by **EP** results in an ascending order	**EW component versions** sorted by **POCP** results in an ascending order
Top ten results			
EW1t-pl_TE16_CE	EW1t-pl_TE16_CE	EW2f-pl_CS15_EPS14a	EW0p-pl_BM30a_MW
EW1t-pl_TE20_CE	EW1t-pl_TE20_CE	EW1t-pl_TE16_EPS	EW0p-pl_BM30b_HS
EW1t-pl_TE24_CE	EW1t-pl_TE16_EPS	EW2f-pl_CS15_EPS18b	EW0p-pl_BM36,5a_MW
EW1t-pl_TE28_CE	EW1t-pl_TE24_CE	EW2f-pl_CS17.5_EPS14	EW0p-pl_BM36,5b_HS
EW1t-pl_TE16_MW	EW1t-pl_TE20_EPS	EW2f-pl_CS15_EPS22c	EW0p-pl_AC30_HS

EW1t-pl_TE16_WF	EW1t-pl_TE28_CE	EW1t-pl_TE20_EPS	EW0p-pl_BM42,5a_MW
EW1t-pl_TE20_MW	EW1t-pl_CS15_CE16a	EW2f-pl_CS17.5_EPS18b	EW0p-pl_BM42,5b_HS
EW1t-pl_TE20_WF	EW1t-pl_AC17.5_CE16a	EW1p-pl_AC17.5_EPS14a	EW0p-pl_AC36,5_HS
EW1t-pl_TE24_MW	EW1t-pl_TE16_MW	EW1p-pl_TE16_EPS8-EPS	EW0p-pl_BM49a_MW
EW1t-pl_ST10_CE16a	EW2f-pl_CS15_EPS14a	EW2f-pl_CS20_EPS14a	EW0p-pl_BM49b_HS
…	…	…	…
EW2f-pl_RC22_PU10a	EW2f-pl_BM24_MW22c	EW1p-pl_ST10_WF24c	EW1p-pl_CS17.5_EPS22c
EW0p-pl_AC50b_HS	EW2f-pl_RC18_MW18b	EW1p-pl_RC18_MW22c	EW1p-pl_CS20_EPS22c
EW2f-pl_RC18_PU16c	EW2f-pl_RC14_MW22c	EW1p-pl_RC14_WF24c	EW1p-pl_AC17.5_EPS22c
EW2f-pl_RC22_EPS18b	EW2f-pl_ST12_MW22c	EW1p-pl_ST14_MW22c	EW1p-pl_AC24_EPS22c
EW2f-pl_RC22_MW18b	EW1p-pl_RC18_MW22c	EW1p-pl_ST12_WF24c	EW1p-pl_RC14_EPS22c
EW1p-pl_RC22_PU16c	EW2f-pl_ST14_MW22c	EW1p-pl_RC22_WF20b	EW1p-pl_RC18_EPS22c
EW2f-pl_RC22_PU14b	EW2f-pl_RC22_MW18b	EW1p-pl_RC22_MW22c	EW1p-pl_RC22_EPS22c
EW2f-pl_RC22_EPS22c	EW2f-pl_RC18_MW22c	EW1p-pl_RC18_WF24c	EW1p-pl_ST10_EPS22c
EW2f-pl_RC22_MW22c	EW1p-pl_RC22_MW22c	EW1p-pl_ST14_WF24c	EW1p-pl_ST12_EPS22c
EW2f-pl_RC22_PU16c	EW2f-pl_RC22_MW22c	EW1p-pl_RC22_WF24c	EW1p-pl_ST14_EPS22c
Bottom ten results			

The **GWP** results show the dominance of the decision factors for the exterior finish (DF1.2), with timber cladding showing the lowest results, and of the DF for the main structural material (DF2.1), with timber element components showing the lowest results. The components with the highest GWP results respectively are also dominated by the same options, e.g. exterior finish (DF1.2) with a facing facade as well as concrete as the main structural material (DF2.1). The other decision factors like insulation material (DF2.2) or the thickness of the structural layer (DF3.1) play only minor parts in ordering the top and bottom ten options.

In regard to the **AP** results, the dominant decision factors – choice of insulation material (DF2.2) and exterior finish (DF1.2) – are portrayed simultaneously by the top performing options. The option with timber cladding (no exchange of the insulation) and the two options of CE and EPS insulation, showing minimal differences between them (cf. Table 5-10), are both represented in the top list. This dominance is also reflected in the bottom list as the other side of the option's spectrum, with MW insulation in all components and with a facing layer façade. The choice of structural material (DF2.1) and other DF reveal its secondary priority by being represented in both top and bottom lists with different kinds of material for the structural layer.

The dominance of the material decision (DF2) for the outcome of the **EP** results can be seen in the top component versions all including EPS as insulation material (best option of DF2.2) and having either calcium silicate, timber elements or aerated concrete as their structural layer's material (the best option being DF2.1). In the bottom results a similar observation can be made, with all versions of components including wood fibre or mineral wool insulation, since the difference between these two options is marginal (cf. Table 5-10).

The **POCP** show a combination of the choice of insulation material (DF2.2) – with monolithic brick constructions (0 and p) as the top-ranking components with either no insulation (HS) or filled with mineral wool (MW). The dominance of the decision factors DF2.2, DF1.1/DF1.2 is accordingly portrayed by single-shell (1) components with EPS insulation in the bottom list, since the interior finish was not analysed within the context of exterior wall components.

Effectivity of Achieving an Economic Use of Raw Materials (D.2)

In order to derive a priority of the decision factors for effective decision-making in regard to the goal of an economic use of raw materials, the same approach as in the previous section can be adapted to the results. The possibility to achieve the highest difference with different options and decision factors varies according to the indicator under consideration. Deriving one single order of priority for the decision factors will always end in a compromise for a single indicator. Therefore, four priority lists are derived for each indicator in particular.

Table 5-12: Display of the differences in D.2 results (ΔMWD, Δ%MWD, ΔPEET, Δrs-PEET) of different decision factors (DF), with the highest and lowest options for each DF covering exterior wall components.

Choice / option		**ΔMWD** of the mean value [kg/m²]	**Δ%MWD** of the mean values [M-%/m²]	**ΔPEET** of the mean values [MJ/m²]	**Δrs-PEET** of the mean values [PEET-%/m²]
DF1.1	highest Δ	**9.3** (2-1)	**2.9** (1-0)	**326.4** (2-0)	**13.8** (1-2)
	lowest Δ	1.6 (1-0)	1.0 (2-1)	65.2 (1-0)	1.2 (0-2)
DF1.2	highest Δ	**8.5** (f-p)	**2.8** (p-f)	**382.1** (f-t)	**22.2** (t-f)
	lowest Δ	1.6 (t-p)	0.5 (t-f)	55.7 (p-t)	6.4 (p-f)
DF1.3	highest Δ	**13.4** (IW: pp-pl)	**31.8** (IW: pp-vs)	**129.7** (IW: ff-vs)	**9.1** (IW: vs-ff)
	lowest Δ	0.9 (IW: pp-ff)	1.14 (IW: in-pl)	6.7 (IW: pp-vs)	0.0 (IW: pp-vs)
DF2.1	highest Δ	**22.6** (RC-ST)	**10.7** (TE-RC)	**349.7** (ST-AC)	**14.7** (ST-BM)
	lowest Δ	1.4 (BM-TE)	0.0 (BM-CS)	15.7 (CS-TE)	0.7 (AC-BM)
DF2.2	highest Δ	**1.9** (e: MW-WF)	**2.0** (e: EPS-WF)	**709.0** (e: WF-EPS)	**17.5** (e: WF-PU)
	lowest Δ	0.0 (t: CE-EPS)	0.2 (t: MW-CE)	25.4 (t: CE-MW)	0.0 (f: EPS-PU)
DF3.1	highest Δ	**11.9** (RC:220-140)	**1.4** (TE:160-240)	**204** (RC:220-140)	**2.2** (ST:140-100)
	lowest Δ	0.0 (ST/TE)	0.0 (BM:175-240)	109 (AC:240-175)	0.4 (RC:140-220)
DF3.2	highest Δ	**0.15** (R=6-4)	**0.2** (R=6-4)	**162.9** (R=6-4)	**0.4** (R=6-4)
	lowest Δ	0.7 (R=5-4)	0.1 (R=6-5)	75.6 (R=6-5)	0.2 (R=6-5)

Annotations: For EW components, the interior finish (DF1.3) was not varied. The results from the IW components variation were used for comparative reason.

The results in Table 5-12 show the differences between the highest and lowest values. However, the goal cannot always be described as “the lower the value the better” as it was for the goal D.1. Since the topic of evaluation (cf. chapter 5.2) should not be anticipated here, it should only be mentioned that regarding the indicator of the renewable share of primary energy (rs-PEET), a higher value means less non-renewable primary energy, therefore the goal is to achieve the highest value possible. The limitation of the decision factors on the choice of construction type (DF1.1) and the choice of the interior finish (DF1.3) remains. However, since the results for the option with double planking ‘pp’ are detached from the indicator PEET and rs-

PEET and show significant results for the indicator MWD and %MWD, the option is discussed accordingly, even though it only covers timber components.

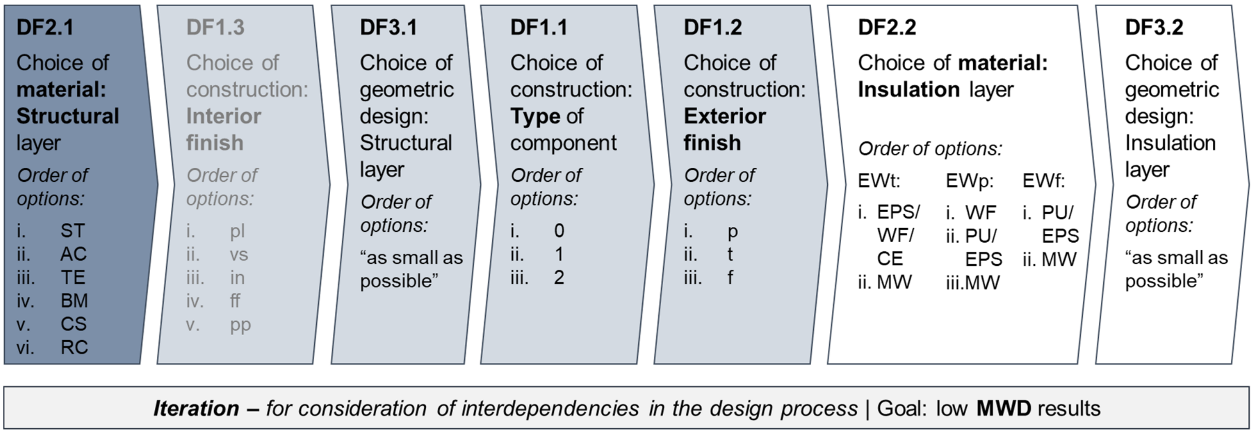


Figure 5-9: Flowchart of an effective decision procedure of EW components for low MWD results

For the indicator of MWD, the differences between the mean values of different design options and between the decision factors themselves show the highest difference between the choices of main structural materials (DF2.1) in addition to the choice of the layer’s thickness (DF3.1). The difference in MWD results that can be achieved based on the choice of construction show a high potential for the interior finish (DF1.3), due to the intense use of gypsum (pp), but also in regard to the choice of exterior façade (DF1.2 in combination with DF1.1). The insulation layer has – due to its light weight – no significant or no impact at all, neither through the choice of insulation material nor through the layer’s thickness. A priority list for achieving the lowest **MWD** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF2.1** Choice of material: Structural layer
(2) **DF1.3** Choice of construction: Interior finish
(3) **DF3.1** Choice of geometric design: Structural layer
(4) **DF1.1** Choice of construction: Type of component
(5) **DF1.2** Choice of construction: Exterior finish
(6) **DF2.2** Choice of material: Insulation layer
(7) **DF3.2** Choice of geometric design: Insulation layer

The results for the percentage of material for waste disposal (%MWD) differentiate between the effective amounts of material in relation to the overall mass of the building component. Therefore, the results are similar to the MWD results but show interesting aspects of this relation, too. For example, the highest difference in %MWD can be achieved by the choice of interior finish (DF1.3) due to the options of double planking or a visible surface. These two options include relevant factors which lead to this significant difference. On the one hand, the ‘pp’ option covers only timber components, which are lighter in general and therefore show a higher percentage of MWD. On the other hand, the ‘vs’ option is only possible for RC, CS and ST components, which are generally heavier and therefore show a lower percentage of MWD. The design choice of the structural material also reveals a high potential to influence the %MWD results, whereas the choice of geometric design of a layer shows almost no difference, since an increase of MWD comes with an increase of the overall mass of the component. A priority list for achieving the lowest **%MWD** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF1.3** Choice of construction: Interior finish
(2) **DF2.1** Choice of material: Structural layer
(3) **DF1.1** Choice of construction: Type of component
(4) **DF1.2** Choice of construction: Exterior finish
(5) **DF2.2** Choice of material: Insulation layer
(6) **DF3.1** Choice of geometric design: Structural layer
(7) **DF3.2** Choice of geometric design: Insulation layer

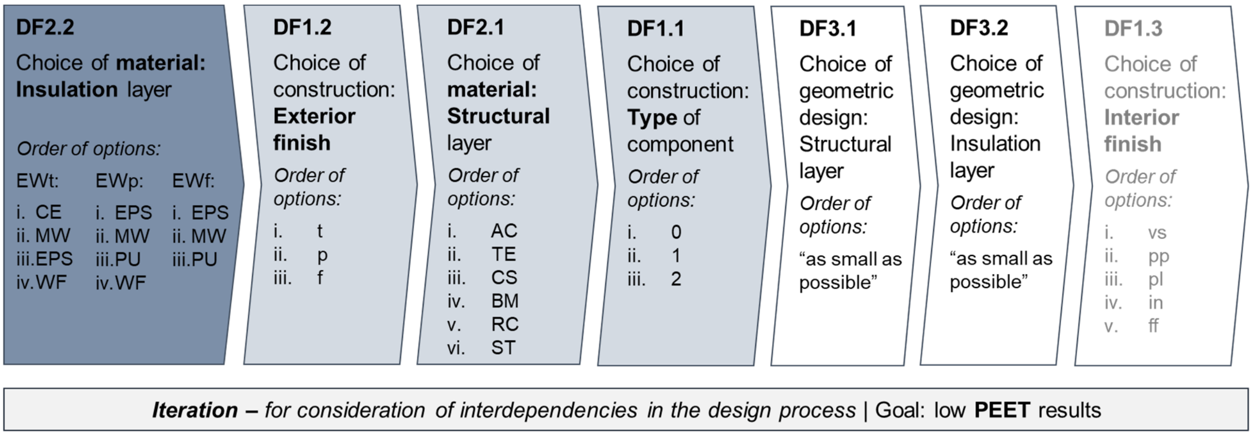


Figure 5-10: Flowchart of an effective decision procedure of EW components for low PEET results

The use of energy resources shows a quite different priority of decision factors compared to the indicators for the material use of raw materials. The highest difference in the PEET results can be achieved through the choice of insulation material (DF2.2). The choice of exterior finish (DF1.2) alongside with the choice of the main structural material (DF2.1) and the type of component (DF1.1) with their different options show similar potential to influence the PEET results. A priority list for achieving the lowest **PEET** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF2.2** Choice of material: Insulation layer
(2) **DF1.2** Choice of construction: Exterior finish
(3) **DF2.1** Choice of material: Structural layer
(4) **DF1.1** Choice of construction: Type of component
(5) **DF3.1** Choice of geometric design: Structural layer
(6) **DF3.2** Choice of geometric design: Insulation layer
(7) **DF1.3** Choice of construction: Interior finish

The renewable share of primary energy can be influenced the most by the choice of exterior finish (DF1.2), with timber cladding being the best option, as well as the choice of insulation material (DF2.2). The similarity to the PEET results is obvious, however, the rs-PEET results reveal the origin of the primary energy. The choice of geometric design of a layer again shows little to almost no difference, because the share of renewable energy is only marginally influenced by increasing the amount of material used, except other materials are affected as well (e.g. insulation between studs in TE components). A priority list for achieving the highest **rs-PEET** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF1.2** Choice of construction: Exterior finish
(2) **DF2.2** Choice of material: Insulation layer
(3) **DF2.1** Choice of material: Structural layer
(4) **DF1.1** Choice of construction: Type of component
(5) **DF1.3** Choice of construction: Interior finish
(6) **DF3.1** Choice of geometric design: Structural layer
(7) **DF3.2** Choice of geometric design: Insulation layer

Once again, the dominating design options are reflected by the results of building components, ranked according to indicator result.

Table 5-13: Overview of the top and bottom ten EW component versions (of 544), sorted by the MWD, %MWD, PEET and rs-PEET indicator results in ascending order

EW comp. versions sorted by **MWD** results in an ascending order	**EW comp. versions** sorted by **%MWD** results in an ascending order	**EW comp. versions** sorted by **PEET** results in an ascending order	**EW comp. versions** sorted by **rs-PEET** re-sults in a descending o.
Top ten results			
EW1p-pl_ST10_WF16a	EW1p-pl_ST14_WF24c	EW1t-pl_TE16_CE	EW1t-pl_ST14_CE24c
EW1p-pl_ST12_WF16a	EW1p-pl_ST12_WF24c	EW1t-pl_TE20_CE	EW1t-pl_ST14_CE20b
EW1p-pl_ST14_WF16a	EW1p-pl_AC17.5_WF24c	EW1t-pl_TE16_MW	EW1t-pl_ST14_CE16a
EW1p-pl_ST10_WF20b	EW1p-pl_ST14_WF20b	EW1t-pl_TE24_CE	EW1t-pl_ST12_CE24c
EW1p-pl_ST12_WF20b	EW1p-pl_AC17.5_WF20b	EW1t-pl_TE20_MW	EW1t-pl_ST12_CE20b
EW1p-pl_ST14_WF20b	EW1p-pl_ST10_WF24c	EW1t-pl_TE28_CE	EW1t-pl_ST12_CE16a
EW1p-pl_ST10_WF24c	EW1p-pl_AC24_WF24c	EW1t-pl_TE16_EPS	EW1t-pl_ST10_CE24c
EW1p-pl_ST12_WF24c	EW1p-pl_ST12_WF20b	EW1t-pl_TE24_MW	EW1t-pl_ST10_CE20b
EW1p-pl_ST14_WF24c	EW1p-pl_ST14_WF16a	EW1p-pl_TE16_EPS8-CE	EW1t-pl_ST10_CE16a
EW1p-pl_ST10_EPS14a	EW1p-pl_AC24_WF20b	EW1t-pl_TE28_MW	EW1t-pl_TE28_CE
…	…	…	…
EW2f-pl_RC18_MW22c	EW1p-pl_TE24_PU6-EPS	EW1p-pl_RC14_WF24c	EW1p-pl_BM17.5_EPS22
EW2f-pl_RC22_EPS14a	EW1p-pl_TE16_PU6-CE	EW1p-pl_CS17.5_WF24c	EW2f-pl_BM24_EPS18b
EW2f-pl_RC22_PU10a	EW1p-pl_TE24_EPS8-EPS	EW1p-pl_AC24_WF24c	EW2f-pl_BM17,5_PU10a
EW2f-pl_RC22_EPS18b	EW1p-pl_TE16_EPS8-CE	EW1p-pl_ST10_WF24c	EW1p-pl_CS15_EPS22c
EW2f-pl_RC22_EPS22c	EW1p-pl_TE16_PU6-MW	EW1p-pl_BM24_WF24c	EW2f-pl_BM24_EPS22c
EW2f-pl_RC22_PU14b	EW1p-pl_TE20_PU6-EPS	EW1p-pl_CS20_WF24c	EW2f-pl_BM17,5_PU14b
EW2f-pl_RC22_PU16c	EW1p-pl_TE16_EPS8-MW	EW1p-pl_RC18_WF24c	EW2f-pl_BM17,5_PU16c
EW2f-pl_RC22_MW14a	EW1p-pl_TE20_EPS8-EPS	EW1p-pl_ST12_WF24c	EW2f-pl_BM17,5_EPS14a
EW2f-pl_RC22_MW18b	EW1p-pl_TE16_PU6-EPS	EW1p-pl_RC22_WF24c	EW2f-pl_BM17,5_EPS18b
EW2f-pl_RC22_MW22c	EW1p-pl_TE16_EPS8-EPS	EW1p-pl_ST14_WF24c	EW2f-pl_BM17,5_EPS22c
Bottom ten results			

The **MWD** results show the dominance of the decision factors for the main structural material (DF2.1), with only solid timber components in the top and concrete components in the bottom list. Since the interior finish is not considered in this list, the DF with the options for exterior finish (DF1.2), in combination with the component type (DF1.1), influence the listing order, with single-shell wall components with EWIS in the top and double-shell components with a facing facade in the bottom list. The other decision factors only play minor parts in ordering the top and bottom ten options. In regard of the relational **%MWD** results of the material waste flows, the top list is complemented by heavier wall components like aerated concrete components. In the bottom list the concrete components are replaced by timber element components, for which the lesser amount of MWD (compared to concrete components) results in a higher %MWD due to their lighter overall weight.

Looking at the wall components from the perspective of energy demand, the dominating DF of the material decision (DF2) for the outcome of the **PEET** results can be seen in the top component versions all including CE or MW as insulation material (best option, with minimal differences, DF2.2, cf. Table 5-12), in combination with timber elements as the structural layer's material option (best option DF2.1). The bottom list reveals the dominance of the insulation material, showing components with different structural material but all with wood fibre insulation. The renewable share of primary energy **rs-PEET** is dominated by the options with the most renewable material like timber cladding for the exterior finish (DF1.2), solid timber (DF2.1), and cellulose insulation (DF2.1) in the top list.

Effectivity of Achieving an Economic Use of Financial Resources (E.1)

In regard to the goal of an economic use of financial resources, only one single indicator of Life Cycle Costs (LCC) yet all relevant decision factors are considered to derive an order of priority for an effective decision procedure for low LCC results.

Table 5-14: Display of the differences in E.1 results (ΔLCC) of different decision factors (DF), with the highest and lowest options for each DF covering exterior wall components.

Choice / option		**ΔLCC** of the mean value [€/m²]	**De-/increase** [%]
DF1.1	highest Δ	**105 (1-0)**	↓-29% | ↑+40%
	lowest Δ	18 (1-2)	↓-5% | ↑+5%
DF1.2	highest Δ	**18** (t-f)	↓-5% | ↑+5%
	lowest Δ	6 (t-p)	↓-2% | ↑+2%
DF1.3	highest Δ	**113** (IW: ff-vs)	↓-42% | ↑+74%
	lowest Δ	2 (IW: pl-vs)	↓-1% | ↑+1%
DF2.1	highest Δ	**52** (ST-TE)	↓-13% | ↑+15%
	lowest Δ	0 (BM-TE)	↓-0% | ↑+0%
DF2.2	highest Δ	**34** (t: PU-MW)	↓-9% | ↑+10%
	lowest Δ	2 (e: PU-EPS)	↓-0% | ↑+0%
DF3.1	highest Δ	**48** (RC: 220-140)	↓-12% | ↑+14%
	lowest Δ	18 (TE: 240-160)	↓-5% | ↑+5%
DF3.2	highest Δ	**33** (R=6-4)	↓-9% | ↑+9%
	lowest Δ	15 (R=5-4)	↓-4% | ↑+4%

Looking at the difference between the mean values of the different options for the different decision factors, the choice of construction (DF1) stands out as the group of decisions with the most influence. For the combination of type of component (DF1.1) and exterior finish (DF1.2), monolithic brick walls with a simple plaster finish show the lowest results and the highest difference compared to wall components with EWIS, where the exterior finish including the insulation layer has to be exchanged over the lifetime of the component. With less potential for difference, the choice of the structural material (DF2.1) and its thickness (DF3.1) follow in the order of priority.

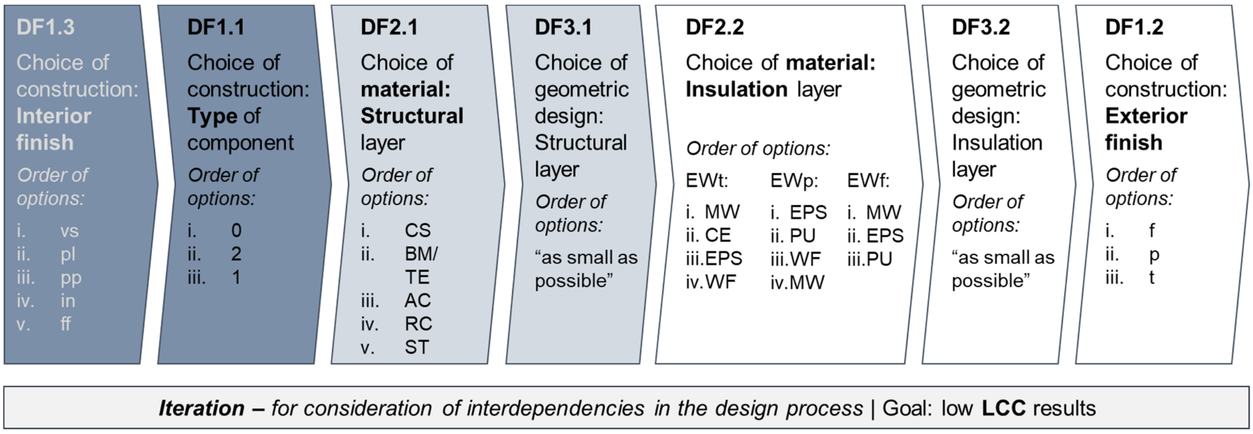


Figure 5-11: Flowchart of an effective decision procedure of EW components for low LCC results

The mean difference of the options for insulation layer and its thickness show the least potential for difference. A priority list for achieving the lowest **LCC** indicator results for exterior wall components can therefore be derived as follows:

(1) **DF1.3** Choice of construction: Interior finish
(2) **DF1.1** Choice of construction: Type of component
(3) **DF2.1** Choice of material: Structural layer
(4) **DF3.1** Choice of geometric design: Structural layer
(5) **DF2.2** Choice of material: Insulation layer
(6) **DF3.2** Choice of geometric design: Insulation layer
(7) **DF1.2** Choice of construction: Exterior finish

The priority of the decision procedure for low LCC results can be subdivided into three main decisions, starting with the type of construction and the interior finish, followed by the choice of structural layer in material and thickness and ending with the choice of insulation layer in material and thickness and the exterior finish (cf. Figure 5-11).

Table 5-15: Overview of the top and bottom ten EW component versions, sorted by the indicator LCC result in ascending order

Top ten EW component versions sorted by **LCC** results in an ascending order	**Bottom ten** EW component versions sorted by **LCC** results in an ascending order
EW0p-pl_AC30_HS	…
EW0p-pl_AC36,5_HS	EW1p-pl_ST14_WF20b

EW0p-pl_BM30a_MW	EW1t-pl_RC22_WF24c
EW0p-pl_BM30b_HS	EW1p-pl_ST12_PU16c
EW0p-pl_AC42,5_HS	EW1p-pl_ST12_MW22c
EW0p-pl_BM36,5a_MW	EW1p-pl_RC22_MW22c
EW0p-pl_BM36,5b_HS	EW1p-pl_ST14_EPS22c
EW0p-pl_AC48a_HS	EW1p-pl_ST12_WF24c
EW0p-pl_AC48b_HS	EW1p-pl_ST14_PU16c
EW0p-pl_AC50a_HS	EW1p-pl_ST14_MW22c
…	EW1p-pl_ST14_WF24c

The ascending order of EW components sorted by **LCC** results emphasises the dominance of the choice of construction (DF1.1/DF1.1), listing only monolithic wall components in the top results and single-shell wall components in at the bottom. As mentioned earlier, the variation of the interior finish was not part of the EW analysis but of the IW analysis. The minor part played by the choice of material (DF2) or a layer's thickness (DF3) can be observed by the mixed results in the top and bottom ten results of both the structural material and the insulation material.

With the **effectivity analysis** for all four goals (B.1, D.1, D.2 and E.1) and their respective indicators having been completed in detail, a major step in developing a guideline for an effective achievement of each goal could be developed. However, the different lists of priority in addition to concurrent orders of the available options to choose – depending on which goal receives the focus – reveal the problem of interdependencies: Not all goals can be achieved in the same way at the same time. Compromises have to be made and are a common part of everyday planning.

5.1.3 Regression Analysis – Interdependencies Between Indicators

The sensitivity analysis revealed the effect of different study design options on the outcome of the study. The effectivity analysis showed a possibility to effectively achieve a goal. However, the system model (cf. chapter 3.2) and the analysis of this model (cf. chapter 4.1) made it clear that each decision in the design process effects different goals at the same time, but not in the same way. This chapter therefore investigates the correlation between different goal indicators, based on the causal similarity of the order of options for specific decision factors.

Statistical research in the field of LCA has been used to analyse the correlation between LCA indicators (Huijbregts et al., 2010; Huijbregts et al., 2006; Marsh, 2016) and can be applied to this thesis as well while being extended by additional non-LCA indicators. Each indicator result can be put into relation with the other indicator results via the method of **linear regression**. The goal of a simple linear regression is to explain one metric variable by another metric variable. To be able to estimate the interrelations between the respective indicators, the **(Pearson) product-moment correlation r** can be identified in combination with the **significance s** of the data. The (Pearson) product-moment correlation describes the linear correlation between two variables and can vary between 0.0 and the absolute value of 1.0. The higher the absolute value, the stronger the correlation, with the maximum of 1.0 indicating a strong relationship and the minimum of 0.0 indicating the absence of a relationship. The correlation can be positive or negative. The maximum would be synonymous with all data lying on one straight ascending (if positive) or descending (if negative) line. The **significance** describes the probability of a random correlation depending on the number of datasets used in the analysis (Kosfeld et al., 2016, p.199 ff).

Table 5-16: Matrix of correlation and significance of the indicator data with each other

	UF	GWP	AP	EP	POCP	PEET	rs-PEET	MWD	%MWD	LCC
TF	1 544									
GWP	-0.2930 0.000 544	1 544								
AP	-0.1093 0.011 544	0.5823 0.000 544	1 544							
EP	-0.2875 0.000 544	0.2261 0.000 544	0.7311 0.000 544	1 544						
POCP	-0.0048 0.911 544	0.2251 0.000 544	-0.1369 0,001 544	-0.3357 0.000 544	1 544					
PEET	-0.2199 0.000 544	0.4085 0.000 544	0.6621 0.000 544	0.7484 0.000 544	-0.0267 0.534 544	1 544				
rs-PEET	-0.1375 0.001 544	-0.8016 0.000 544	-0.3978 0.000 544	0.1281 0.003 544	-0.2587 0.000 544	-0.0527 0.220 544	1 544			
MWD	-0.1435 0.001 544	0.4572 0.000 544	0.2742 0.000 544	0.0916 0.033 544	-0.0907 0.034 544	0.1182 0.006 544	-0.4414 0.000 544	1 544		
%-MWD	0.6989 0.000 544	-0.4145 0.000 544	-0.2033 0.000 544	-0.2051 0.000 544	0.0717 0.095 544	-0.2934 0.000 544	0.0095 0.825 544	-0.0534 0.214 544	1 544	
LCC	-0.2978 0.000 544	-0.0060 0.890 544	0.1726 0.000 544	0.4716 0.000 544	0.1716 0.000 544	0.3219 0.000 544	0.3174 0.000 544	-0.1009 0.019 544	-0.0829 0.053 544	1 544

Annotation:
- First line of every box: Correlation r (Pearson)
- Second line of every box: Significance
- Third line of every box: Number of EW datasets
- The correlation r can be grouped according to:
  - strong correlation for | r | ≥ 0.8
  - rather strong correlation for 0.5 ≤ | r | < 0.8
  - rather weak correlation for 0.3 ≤ | r | < 0.5
  - weak correlation for | r | < 0.3

It is important to keep in mind that a high correlation in the data does not automatically assume a causality and doesn't lend itself to universal conclusions on how the variables interact (Fahrmeir et al., 2016, p. 140 ff). The data does however reveal four groups of indicators pairs according to their degree of correlation, which is also determined to be statistically significant (less than 0.001):

- **Strong** correlation for | r | ≥ 0.8
  - Negative correlation between the indicator GWP and rs-PEET
- **Rather strong** correlation for 0.5 ≤ | r | < 0.8
  - Positive correlation between the indicator UF and %MWD
  - Positive correlation between the indicator GWP and AP
  - Positive correlation between the indicator AP and EP
  - Positive correlation between the indicator AP and PEET
  - Positive correlation between the indicator EP and PEET
- **Rather weak** correlation for 0.3 ≤ | r | < 0.5
  - Positive correlation between the indicator GWP and PEET
  - Positive correlation between the indicator GWP and MWD
  - Negative correlation between the indicator GWP and %MWD
  - Negative correlation between the indicator AP and rs-PEET
  - Negative correlation between the indicator EP and POCP
  - Positive correlation between the indicator EP and LCC
  - Positive correlation between the indicator PEET and LCC
  - Negative correlation between the indicator rs-PEET and MWD
  - Positive correlation between the indicator rs-PEET and LCC
- **Weak** correlation for | r | < 0.3
  - All other indicator pairs (some not showing statistical significance > 0.05)

The strong correlation between GWP and rs-PEET is concurrent with other research (Marsh, 2016; Huijbregts et al., 2010) and can be explained by additional causal correlation due to the fact that the renewable share indirectly reflects the amount of non-renewable primary energy used in the life cycle of the building component (negative correlation), which is primarily responsible for the majority of the GHG emissions which contribute to the GWP indicator (Gustavsson and Sathre, 2006). Those indicator pairs showing a rather weak correlation need further investigation and specification concerning the resilience of possible conclusions. The indicator pairs with rather strong correlations can be compared to existing research for LCA indicators. The results of correlation between LCA indicators deviate in some cases (e.g. between AP-POCP), yet they show the same trend of strong positive correlations between the indicators of GWP, AP and EP. The effectivity analysis provides additional conclusions in regard to the causality of these indicators. For example, the rather strong correlation between AP and GWP can be explained by the same four prioritised decision factors, whereas the negative correlation between EP and POCP can be partially explained by the opposing priority of insulation material as part of the decision factor with the highest priority (cf chapter 5.1.2).

In addition to the correlation coefficient, the **coefficient of determination R^2** can also be presented. The coefficient of determination is calculated as the square of the correlation coefficient and indicates the possibility to explain the two variables through a linear relation. Like the correlation coefficient, the absolute value R^2 can vary between 0.0 and 1.0. While the coefficient of correlation (r) measures the magnitude of a linear relationship, the coefficient of determination represents the proportion of the variation in the results that is shared by both variables. For example, if R^2 is 0.70, this implies that 70% of the results can be explained by the linear relationship between the two variables (Fahrmeir et al., 2016, p.126 ff; Marsh, 2016).

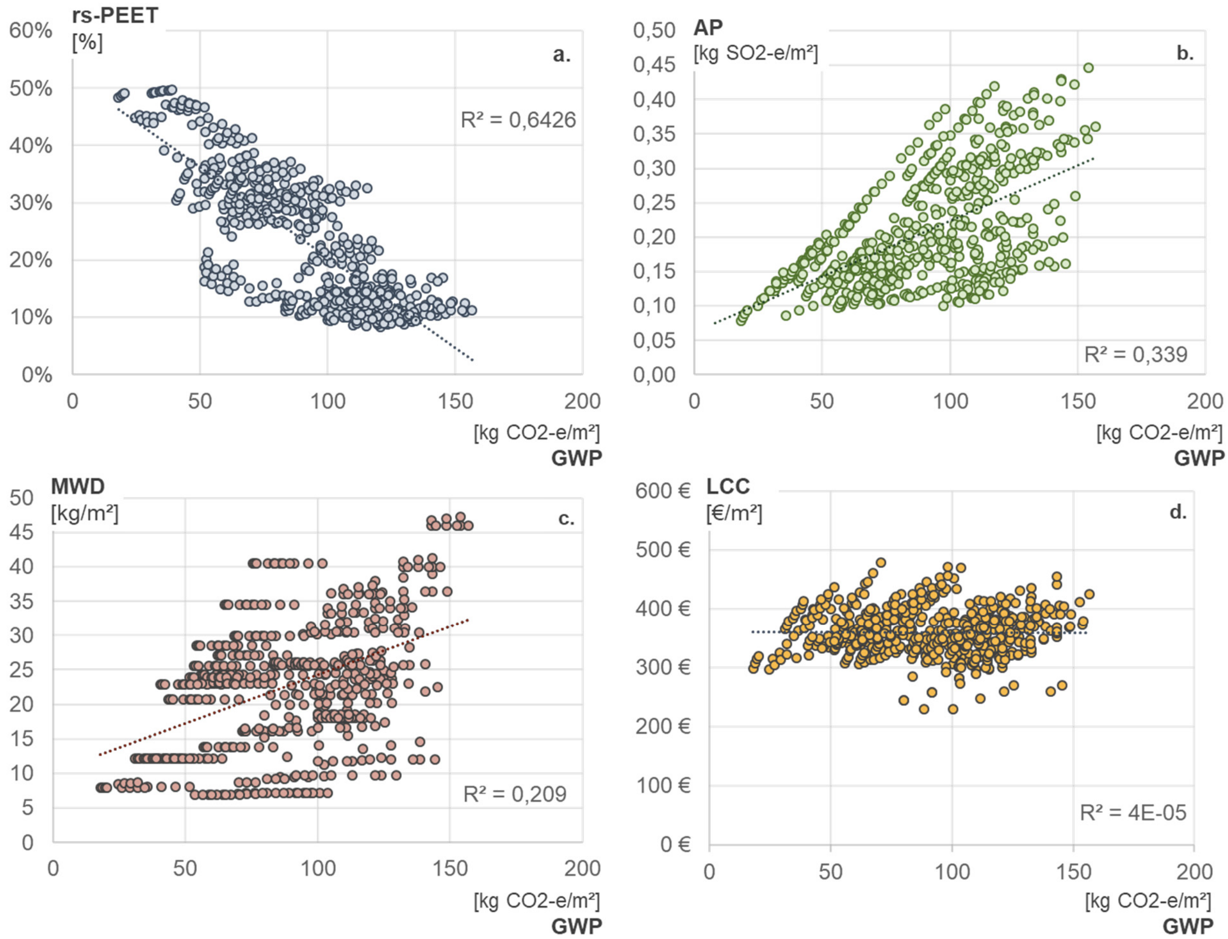


Figure 5-12: Illustration of linear regression between various indicators, showing a strong (GWP-rs-PEET, r=-0.802), a rather strong (GWP-AP, r=0.582), a rather weak (GWP-MWD, r=0.457), and a weak to no correlation (GWP-LCC, r=-0.006 and not statistical significant)

The illustration helps to understand the statistical results and portray the explanatory power of the regression analysis. The case of strong correlation between the indicator GWP and rs-PEET (scatter diagram a.) suggests that the higher the renewable share of primary energy, the lower the GWP results, which can be backed by the causality behind this analysis.

The linear regression between AP and GWP results with a rather strong correlation already implies additional reasons for the conclusion that the higher the GWP results, the higher also the AP results. For instance, scatter diagram (b.) shows several groups of data that ought to be investigated further. The more specifically the data is grouped, the more detailed conclusions can be made.

A rather weak correlation between the indicator MWD and GWP (c.) is illustrated by various groups of data where the GWP results vary while the MWD results seem to remain constant. This leads to the conclusion that part of the data does not show a linear regression at all, which could be caused by the variation of insulation material influencing the GWP results, but with almost no influence on the MWD results. The overall data for all EW components concerning the LCC and GWP indicators shows almost no correlation at all, illustrated by scatter diagram (d.). Further investigation and detailed analysis are needed to confirm this missing correlation.

5.2 Multicriteria Evaluation Between Multiple Indicator Results

"The foundation of truth lies in correlations" – G.W. Leibniz[26]

5.2.1 Deriving a Valuation Standard for Indicators

After deriving a method to effectively achieve a goal and knowing how these goals interrelate (cf. chapter 5.1), a method of arriving at a compromise between every decision option is needed in order to finally make a practical decision. With the groundwork of the concept of goals and values (cf. chapter 2.1.2) as well as the method of evaluation (cf. chapter 2.1.5) being laid, the basis for value-based decision-making stands to reason.

Evaluation provides the opportunity of equally assessing different indicators using the same valuation standard. The valuation score that will be used in this thesis is **percentage**, because it is easy to understand and to interpret when compared with any kind of grading, pointing or labelling system that requires additional explanation. The cost that comes with this equalizing benefit is the loss of reference to the absolute value of the indicator and its referencing unit. In the context of multicriteria decision-making, however, the need for a contrasting comparison outweighs the loss of direct reference.

In the following sections, a valuation standard based on percentage (0-100%) is developed as a valuation score for every indicator considering the characteristics of the indicator and the goal described by the indicator in the context of the parameter variation of exterior wall components.

Evaluation of Adequate Structural Safety (B.1)

The goal of adequate structural safety of a building component can be described by the indicator 'utilisation factor' (UF), which has a metric characteristic resulting from the relation between the design value of stress and the design value of resistance (E_d/R_d). The possible UF results can vary, starting from 0.0 and open to the top. The goal, however, is described by the normative value that the design value of stress has to be lower than the design value of resistance, which is reflected by a utilisation factor of UF ≤ 1.0.

This target value for the utilisation factor implies a multitude of elements regarding the method of calculation, the concept of safety (cf. chapter 3.2.3) as well as political, social or historical aspects. Questions of safety (B) are highly related to the question of probability and can never be answered with one hundred percent certainty. The objective for every goal regarding safety is to reach a point that is safe enough, implying a compromise between the probability of occurrence and cost. This makes the evaluating nature of goals regarding safety a binary valua-

[26] German Source: „Das Fundament der Wahrheit liegt in der Verknüpfung." Leibniz (1966).

tion score: The result is considered either safe or not. The discussion leading to this assessment can of course be widely controversial, due to different point of views considering the probability-cost compromise.

In terms of the single goal of adequate structural safety, all different issues (e.g. probability of load occurrence, probability of material failure, etc.) are taken into account if this normative value of 1.0 for the utilisation factor is achieved (cf. chapter 3.2.3). Therefore, the optimum for goal achieving is the value of 1.0, with every lower value implying the goal was achieved, and all higher values implying it was not achieved. This relation can be depicted by a merit function, with the maximum score (100%) for every UF value ≤1.0 and the minimum score (0.0%) for every UF value >1.0 as well as with discontinuities at the optimum point (UF=1.0). The valuation area ranges from an UF value of 0.0 to an open end. The UF values for exterior wall components cover an area of UF results between 0.04 and 1.75.

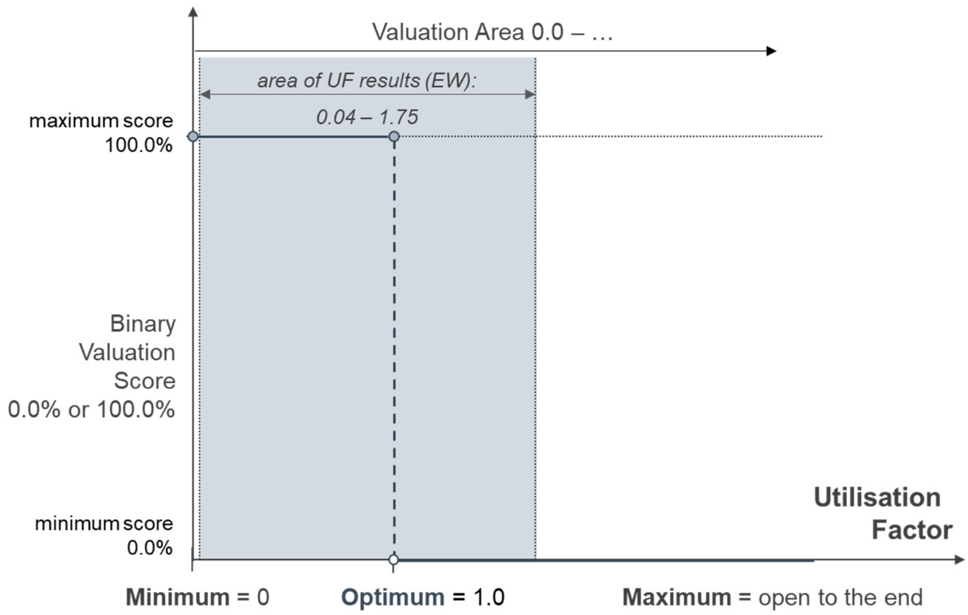


Figure 5-13: Valuation standard for the goal of adequate structural safety (B.1) – UF indicator

This valuation standard (see Figure 5-13) illustrates the very specific nature of safety goals. The possibility of rating a UF value near zero as “better” or “worse” than a higher UF value near 1.0 reflects a premature mixing of different goals, e.g. already knowing that a low UF value implies low costs (why it should be worse) or offers the possibility of flexibility for future changes (why it should be better). It has to be kept in mind that in regard to the goal of adequate structural safety there is only the binary evaluation between ‘considered safe’ and ‘considered not safe’. The value of safety in general is to be considered as non-negotiable, which is why many safety goals are mandatory by law, especially if they describe the safety of life.

Evaluation of Minimising Environmental Impacts (D.1)

The goal of minimising environmental impacts is described by multiple indicators (cf. chapter 3.2.4). Nevertheless, certain characteristics can be described for every indicator the same way. The indicator results are represented in different referencing units but can be measured by a metric ratio scale. The general goal is to minimize the emissions or, in the best-case scenario, even avoid emissions at all. Therefore, the optimum with the maximum score (100.0%) regarding the valuation score comes with zero emissions regarding the indicator result.

To further develop the valuation standard and to derive a specific valuation area and merit function, each indicator has to be analysed in detail. For the example indicator of GWP, the indicator results for exterior wall components range from 18.1 kg CO_2-e/m² to 156.8 kg CO_2-e/m². By extending the scope on all building components, the indicator results range from 9.4-238.6 kg CO_2-e/m². The maximum possible results for a building component can be higher than the maximum result within the scope of this thesis, and since the possible maximum cannot be determined precisely within this thesis, the maximum of the valuation area is randomly set at the maximum result of all components, plus the standard deviation, at 283.3 kg CO_2-e/m². This maximum result is equalled with the minimum valuation score (0.0%), including all higher indicator results. All GWP results between zero and the maximum result are described by a linear descending merit function.

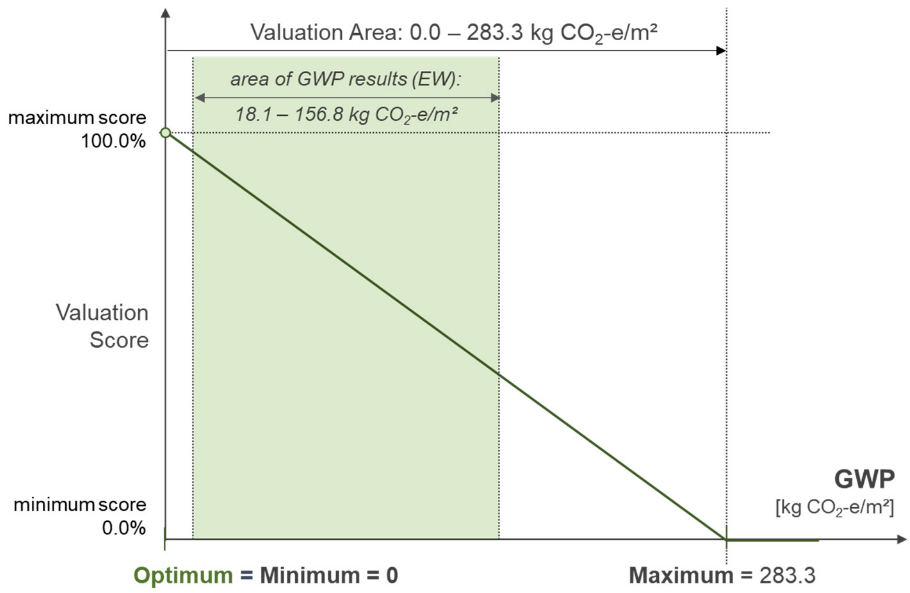


Figure 5-14: Valuation standard for the goal of minimizing environmental impact (D.1) – GWP indicator

As a result of this valuation standard, the lowest indicator result of 18.1 kg CO_2-e/m² corresponds to a valuation score of 93.6%, and the highest GWP result of 156.8 kg CO_2-e/m² corresponds to a valuation score of 44.6%. All other GWP results for exterior wall components score somewhere between these two limits. There are reasons for an alternative valuation area covering only the respective GWP results of the parameter variation in this thesis. This would lead to a 100.0% score for the lowest result and a 0.0% score for the highest GWP result, which would limit the possibility to apply this valuation standard beyond the scope of the parameter variation in this thesis.

This procedure to determine a valuation standard for the GWP indicator can be adapted for the other indicators of the goal D.1 (AP, EP, POCP, and ODP) in the same way.

Evaluation of Sustainable Use of Resources (D.2)

The goal of an economic use of raw materials covers two main aspects: use of energy and material use. As described earlier (cf. chapter 3.2.5), different indicators depict different aspects of the respective goal. In the context of a circularity of material flows, the indicator MWD describes the share of material to be deposited and therefore diminishes the circularity or recyclability of a component. This implies a normative characteristic for this indicator, with its optimum MWD being as small as possible or zero in the best case. On the other hand, the indicator MRU describes the share of a component that can be reused, where the optimum MRU indicator result should be as high as possible. These characteristics define the two extremes of all material indicators (MRU, MSM, MMR, MMRf, MERf, MWD) and imply a descending order according to the priority of recycling (see Figure 3-12). However, there are many special cases and differences in regard to the material group that need further discussion in order to achieve a consistent valuation standard for all individual material indicators. For example, it is open for discussion if and how the indicator MERf can be evaluated differently if renewable materials are combusted for energy use when compared with non-renewable or fossil resources. In the context of the indicators of energy use, the evaluation is easier with the general goal of using as little energy as needed, and, if necessary, as much renewable energy as possible. The balance between these two indicators, especially in addition with the indicators for material use, are part of a later discussion (see chapter 5.2.2).

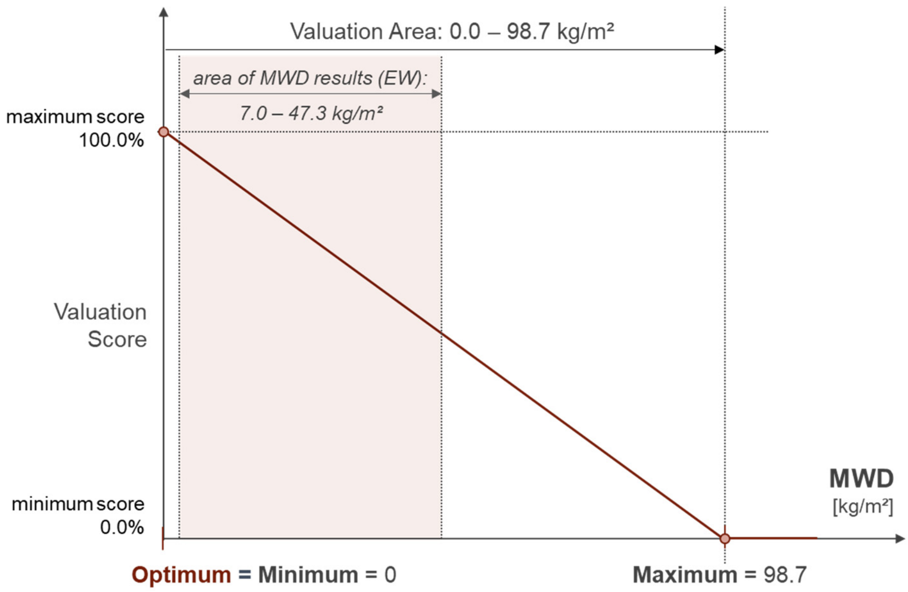


Figure 5-15: Valuation standard for the goal of economic use of raw materials (D.2) – MWD indicator

Deriving a detailed valuation standard for the MWD indicator, the optimum is defined as zero waste material, which is also covered by the indicator results of EW components. The range of the indicator results stretches from 7.0 kg/m² to a maximum of 47.3 kg/m², which is also the maximum in the context of all building components. This maximum result in combination with the standard deviation for all components defines the maximum of the validation area at 98.7 kg/m² and all results above with the minimum score (0.0%). All possible MWD indicator results are described by a descending linear merit function between these two limits of the validation area. This means that the best possible valuation score for EW components is 92.9% for the MWD indicator result of 7.0 kg/m², and the worst possible valuation score is 52.1% for the highest MWD result (47.3 kg/m²).

The development of a variation standard for the indicators of energy use is illustrated by two indicators for total energy use (PEET), with its renewable share (rs-PEET) used to illustrate the differences. As mentioned earlier, the optimum with a maximum score of 100.0% regarding the valuation score comes with zero energy regarding the PEET indicator result and with 100% for the rs-PEET indicator result. The PEET indicator results for EW components range from a minimum of 520 MJ/m² to a maximum of 2227 MJ/m². The maximum for the valuation area results from the maximum PEET indicator results of all building components at 4802 MJ/m², in addition to the standard deviation resulting in 5507 MJ/m². All possible PEET indicator results are described by a descending linear merit function between these two limits of the validation area.

Although the rs-PEET indicator results of EW components only vary between 8.3% and 49.7%, the natural area of possible results between a 0.0% and a 100% share of renewable energy is used to determine the valuation area. According to the characteristic of the goal, all possible rs-PEET indicator results are described by an ascending linear merit function between these two limits of the validation area.

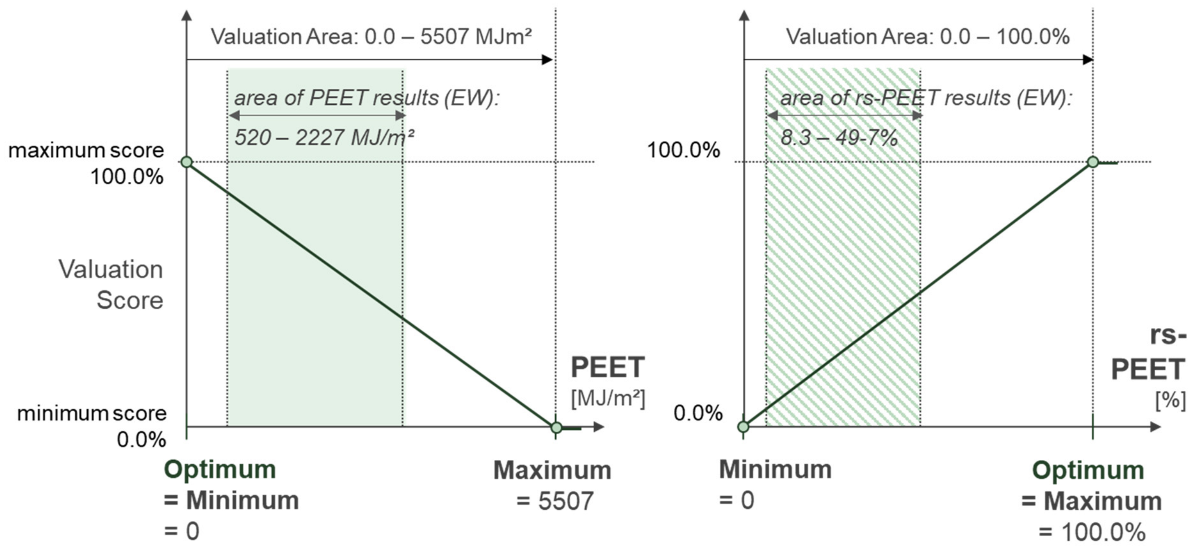


Figure 5-16: Valuation standard for the goal of economic use of raw materials (D.2) – energy use with PEET indicator and rs-PEET indicator

The minimum and maximum PEET indicator values of 4.9% and 87.2% can be translated into the valuation score. The rs-PEET indicator values are described by a one-to-one translation, due to the special case that the indicator value is also represented in percentage.

Evaluation of Economic Use of Financial Resources (E.1)

The goal of an economic use of financial resources is described by the indicator of life cycle costs (LCC). Since there are many parallels to our everyday life, it is somewhat easier to understand the characteristics of this goal and to define an optimum. Costs accumulate over the whole life cycle, and no matter the influencing parameters, the goal of an economic use is to keep the costs as low as possible, or in other words, to achieve as much as possible with the invested financial resources. Since it is obvious that, when compared to other indicators, the costs cannot be zero, the lowest LCC indicator value is described by the minimum result minus the standard deviation.

The derivation of a valuation standard for costs is based on the context of the building components, given that the data and common perception is used to such a reference. The LCC results for exterior wall components range from a minimum of 230 €/m² to a maximum of 479 €/m². Adding a standard deviation of +/- 39 €/m², the valuation area can be defined starting from 191 €/m² to 518 €/m². Thus, all LCC results are described by a descending linear merit function between these two limits of the validation area, with all results lower than the minimum achieving the best score, and all results higher than the maximum achieving a zero score.

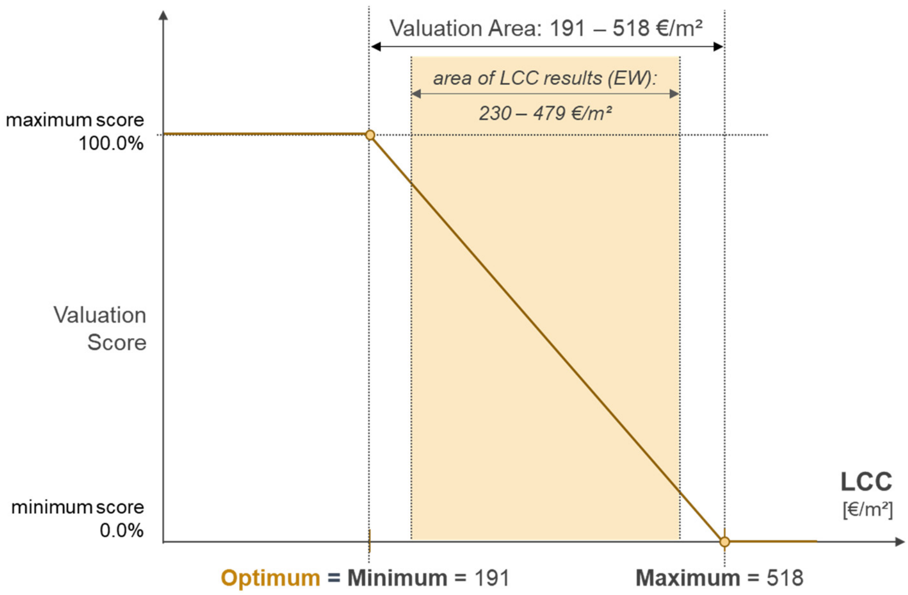


Figure 5-17: Valuation standard for the goal of economic use of financial resources (E.1) – LCC indicator

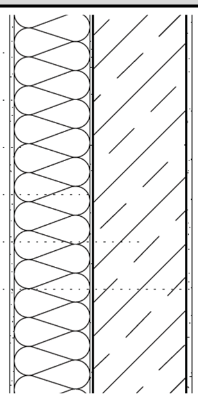
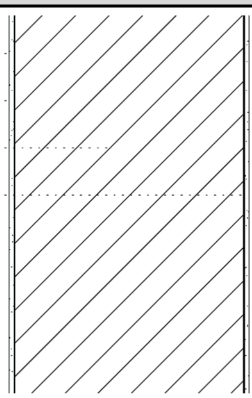
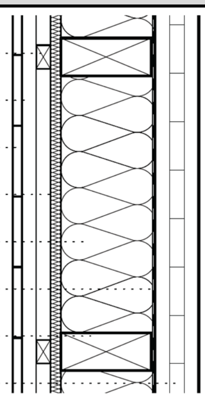
As a result of this valuation standard the lowest LCC indicator result of 230 €/m² corresponds to a valuation score of 88.1%, while the highest LCC result of 479 €/m² corresponds to a valuation score of 11.9%. All other LCC results for exterior wall components (if they are within the valuation area) will score somewhere between these two limits. Referring to the development of a valuation standard for the other indicators, the valuation standard for the LCC indicator could also be based on the results for all building components. The only difference would be that the valuation area would be extended and would have to include more possible LCC indicator results. If the validation area does not cover the area of indicator results adequately, the valuation standard needs adjustment. This illustrates the fact that the derivation of the variation standard is not as important as its consistent application as long as all indicator results are covered by the valuation area.

5.2.2 Multicriteria Evaluation of Building Components

The presented method to equalize all different indicator results through evaluation using a uniform performance-based depiction by percentage will also form the basis for multicriteria comparison. This means that now different criteria – or in this case indicators – can be compared with the same standard by percentage.

To elaborate further, this interrelation will be discussed using two examples of exterior wall components. The examples refer to the research project 'THG-Holzbau' (German for GHG in timber construction) (Hafner et al., 2017) and are part of an LCA study within this project which was done according to the standards (DIN EN ISO 14040/44, DIN EN 15978, 15804, and 16485). In addition, a critical review according to DIN EN ISO 14044 and meeting the requirements according to ISO/TS 14071 (2014) confirmed the calculation of the LCA study. The wall components belong to buildings that share the same functional quality regarding standards, requirements, stability etc. and can be considered as functional equivalents, meaning all variations show the same main performance or better. The exterior wall components chosen are a **single-shell concrete wall with mineral wool EWIS** (EW1p-RC-HS), a **monolithic brickwork wall with a plaster facade** (EW0p-BM-HS) and a **single-shell solid timber wall component with a timber cladding and cellulose insulation** (EW1t-ST-CE).

Table 5-17: Overview of the sample exterior wall components of the 'THG-Holzbau' research project

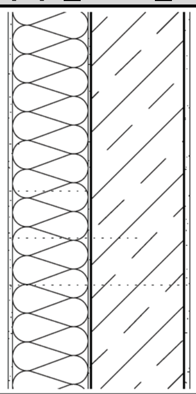
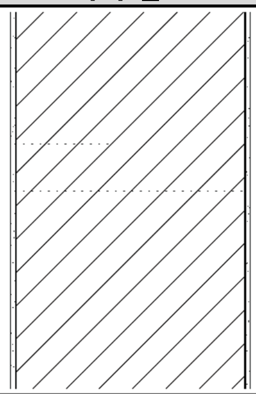
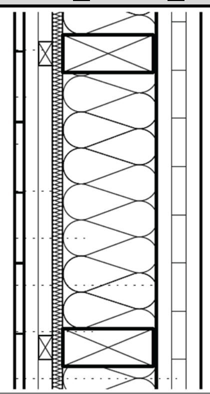
Reinforced concrete wall with MW EWIS	**Monolithic brick masonry wall**	**Solid timber wall with timber cladding**
M1 M2 M3 M4 M5+6 M7 	M1 M2 M3 M4 	M3 M2 M1 M4 M6 M7 M5 M8 
U-value: 0.21 W/m²K	U-value: 0.16 W/m²K	U-value: 0.19 W/m²K
Thickness: 383.2 mm	Thickness: 515.2 mm	Thickness: 395.2 mm
Mass: 541.6 kg/m²	Mass: 337.9 kg/m²	Mass: 87.4 kg/m²

M1 0.2 mm exterior paint **M2** 8 mm plaster layer **M3** 160 mm MW insul. (EWIS), **M4** 5 mm bonding mortar **M5** 200 mm concrete C20/25 **M6** 1 % steel reinforcement **M7** 10 mm gypsum plaster	**M1** 0.2 mm exterior paint **M2** 15 mm plaster layer **M3** 490 mm brickwork (filled) **M4** 10 mm gypsum plaster	**M1** 20 mm spruce cladding **M2** 30 mm timber battens (w/d = 80/200, e = 625 mm) **M3** 30 mm timber battens (w/d = 80/200, e = 625 mm) **M4** 22 mm WF insulation board **M5** 200 mm construction timber (w/d = 80/200, e = 625 mm) **M6** 200 mm cellulose insulation **M7** 0.15 mm vapour retarder **M8** 93 mm solid timber (CLT)
Note: Graphics of building components made by Marco Krechel.		

A detailed composition of the building components as well as real building examples using similar components can be found in the Appendix. These building components form the basis of the following example of multicriteria evaluation. The calculations of all individual indicator results are based on the scope of this thesis (cf. chapter 4.1) and can also be found in the Appendix. Although these specific wall components are partly covered by a variation within the parameter variation, they include different decision factors and have a common basis. The denotation can be defined according to the parameter variation and version notation (cf. Figure 4-2).

In the first step all individual indicator results for all four different goals are presented according to the indicator unit.

Table 5-18: Calculation results of the sample wall components according to the scope of the parameter variation

		EW1p-pl_RC20_MW20	**EW0p-pl_BM49**	**EW1t-vs_ST9.3_CE20**
Goal	**Indicator**			
B.1	**UF**	0.05	0.25	0.20
D.1	**GWP**	118.0 kg CO_2-e/m²	110.1 kg CO_2-e/m²	28.1 kg CO_2-e/m²
	AP	341 g SO^2-e/m²	245 g SO^2-e/m²	113 g SO^2-e/m²
	EP	47 g PO_4^{3}-e/m²	34 g PO_4^{3}-e/m²	29 g PO_4^{3}-e/m²
	ODP	1.1 E-07 kg CFC11-e/m²	2.4 E-08 kg CFC11-e/m²	1.4 E-07 kg CFC11-e/m²
	POCP	18.3 g ethene-e/m²	5.8 g ethene-e/m²	20.7 g ethene-e/m²
	ADPE	2.5 E-04 kg Sb-e/m²	1.4 E-04 kg Sb-e/m²	8.2 E-04 kg Sb-e/m²
	ADPF	966.2 MJ/m²	1054.1 MJ/m²	380.5 MJ/m²
D.2	**MRU**	0.0 kg/m² (0.0%)	0.0 kg/m² (0.0%)	11.3 kg/m² (11.4%)
	MSM	15.3 kg/m² (2.7%)	0.0 kg/m² (0.0%)	0.6 kg/m² (0.6%)

	MMR	432.2 kg/m² (74.9%)	278.1 kg/m² (77.7%)	10.1 kg/m² (10.1%)
	MMRf	94.5 kg/m² (16.4%)	57.6 kg/m² (16.1%)	0.0 kg/m² (0.0%)
	MERf	0.0 kg/m² (0.0%)	0.0 kg/m² (0.0%)	77.4 kg/m² (77.8%)
	MWD	35.2 kg/m² (6.1%)	22.2 kg/m² (6.2%)	0.0 kg/m² (0.0%)
	PEET	1,111.2 MJ/m²	1,266.7 MJ/m²	810.8 MJ/m²
	rs-PEET	16.6%	13.6%	51.4%
	PEMT	40.9 MJ/m²	1.7 MJ/m²	1,441.6 MJ/m²
	rs-PEMT	28.6 %	0.0 %	97.3 %
E.1	**CC**	265 €/m²	238 €/m²	271 €/m²
	LCC	397 €/m²	306 €/m²	372 €/m²

This presentation of the indicator results offers the chance of direct comparisons between different construction components and a glimpse at the total results as well as at possible differences and substitution potential. It offers the highest degree of transparency and differentiation and goes hand in hand with the most detailed and demanding examination, where individual indicator results can be selected for further comparison and discussions.

In a second step, the indicator results are reduced to those indicators with a consistent basis for conclusions according to the discussion of the outcomes (cf. chapter 4.2) and their interpretation (cf. chapter 5.1). Additionally, the indicator results are translated into a valuation score in percentage according to the derivation of each valuation standard (cf. chapter 5.1.3) in order to receive a uniform basis for comparison.

Table 5-19: Evaluation scoring results of the sample wall components

		EW1p-pl_RC20_MW20	**EW0p-pl_BM49**	**EW1t-vs_ST9.3_CE20**
B.1	**UF**	100.0%	100.0%	100.0%
D.1	**GWP**	58.4%	61,1%	90.1%
	AP	66.0%	75,6%	88.7%
	EP	66.4%	75,4%	79.4%
	POCP	98.2%	99,4%	98.0%
D.2	**MWD**	64.3%	77,5%	100.0%
	PEET	79.8%	77,0%	85.3%
	rs-PEET	16.6%	13,6%	51.4%
E.1	**LCC**	37.0%	64,9%	44.7%

At this stage of the interpretation and evaluation of results, a uniform basis for a multicriteria comparison is achieved. The indicator results are not only compared to each other in quality but, by using the valuation score, also in a quantitative way, concerning a variety of possible outcomes (valuation area). The evaluation score reflects the performance of a building component concerning one specific indicator and can directly be compared to its performance in regard to other indicators and goals. For example, it can be seen that the biggest differences in the performance happen in regard to the indicators GWP, MWD, rs-PEET and LCC, while all different components fulfil the goal of structural safety (cf. Figure 5-18). With this multicriteria depiction a final decision can be made that manages to keep an overview over all criteria.

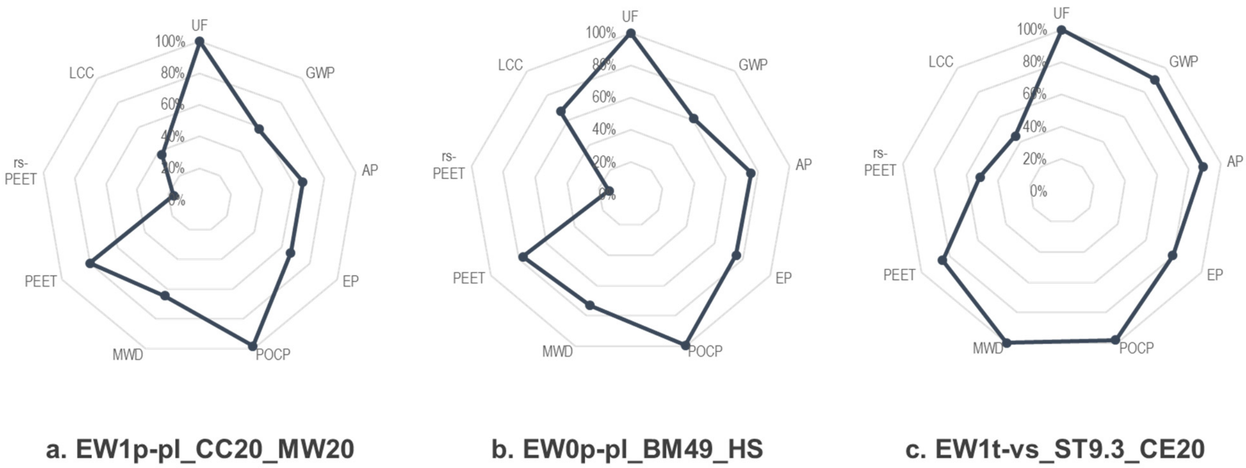


Figure 5-18: Illustration of the evaluation scoring result of each indicator for each wall component

5.2.3 The Concept of Value-Based Decision Making

Although the derivation of valuation standards offers the opportunity of multicriteria comparisons, a final decision has still not necessarily become easier. It might even have become even harder, now that the whole picture has been revealed. At this point the individual criteria or indicator results often stand in contrast to each other, meaning there is no obvious choice available. For example, the cheapest component is not simultaneously the component with the best GWP or MWD result and so on.

The following draft for a value-based decision-making process is aimed at clarifying the path towards a final decision. As the diversity in building components clearly teaches us, there is no singular perfect solution. However, in having to choose to realise one building component, an inner weighting process deciding which indicator seems to be important always takes place. In fact, this process takes place multiple times in the daily life of every person, e.g. when buying an expensive item like a car: "*How much is this function worth paying? What is more important, design or robustness?"* etc. This decision-making process is made consciously or unconsciously and is often a mix between some criteria being chosen willingly, while one is unaware of others which are therefore not considered. This chapter gives a breakdown of which aspects are decisive in deriving at a final decision. Once this procedure becomes transparent and comprehensible, it can be used for a value-based approach for decision-making.

Three different evaluation approaches will be illustrated, based on the previous selection of EW components in combination with the component variations of the parameter variation and according to a limited set of goals according to this thesis' scope. The four different goals represent three different underlying values. The value of safety (B), the value of environmental quality (D) and the value of economical quality (E).

Evaluation Approach Based on Equality

The first approach is based on the principle of equality, treating all indicators and goals equally. In this approach, however, one value has to be excluded. The value of health and safety regarding life are commonly seen as non-negotiable, meaning there is no scaling option of how important this goal might be; the decision rather has to meet a commonly accepted safety level. This perception and approach in safety issues is already integrated in the goal of safety, e.g. in the calculation of an utilisation factor (E.1). Therefore, the evaluation of the goal of structural safety (E.1) is considered as a knock-out criterion, leading to its exclusion if the valuation score for UF is not one hundred percent.

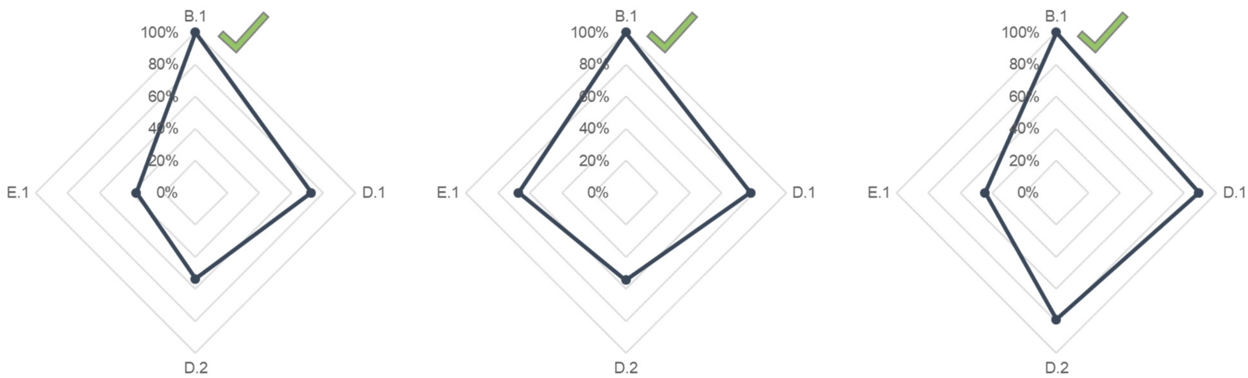
An equal distribution of weighting factors starts with the values, resulting in a fifty-fifty share for the value of environmental and economic quality, since safety is considered as a knock-out criterion. Going deeper, the goals covered by the value of environmental quality get the same share, with 25% for the goal of minimising environmental impacts (D.1) and 25% for an economic use of raw materials (D.2). The goal D.1 itself is described by four different indicators, where every indicator gets the same share, resulting in a total share of 6.3% per D.1 indicator (GWP, AP, EP, POCP). The same approach is done for the three indicators of goal D.2, resulting in a total share of 8.3% per D.2 indicator (MWD, PEET, rs-PEET). The weighting distribution illustrates that with an increasing number of indicators the respective weighting factor of the indicator decreases. On the other side, with only one indicator (LCC) for one goal (E.1) for the value of economic quality (E), the indicator's weighting factor equals the weighting factor of the value (50%). An alternative equal approach would be to assign the same weighting factor for every goal. This would lead to an imbalance of the total weighting system towards the value with the most goals or indicators. This total weighting distribution can be illustrated vividly with a tree map diagram (see Figure 5-19).

Figure 5-19: Illustration of the weighting distribution of the 'equality approach', with check box for a binary knockout criterion B.1

By combining every indicator valuation score and the respective weighting factor, a final single scoring result can be derived by accumulation for either a goal, a value or the entire component, showing an overall performance (in percentage) according to the underlying valuation standards and weighting approach (see Table 5-19).

Table 5-20: Overview of the weighting factors and weighted scoring results of the 'equality approach' for the sample wall components

Goals		Weighting Factor			EW1p_RC20		EW0p_BM49		EW1t_ST9.3	
B.1	**UF**	K.O.	K.O.	K.O.	*passed*		*passed*		*passed*	
D.1	**GWP**	50%	25%	6.3%	58.4%	**72.2%**	61,1%	**77.9%**	90.1%	**89.0%**
	AP			6.3%	66.0%		75,6%		88.7%	
	EP			6.3%	66.4%		75,4%		79.4%	
	POCP			6.3%	98.2%		99,4%		98.0%	
D.2	**MWD**		25%	8.3%	64.3%	**53.6%**	77,5%	**56.0%**	100.0%	**78.9%**
	PEET			8.3%	79.8%		77,0%		85.3%	
	rs-PEET			8.3%	16.6%		13,6%		51.4%	
E.1	**LCC**	50%	50%	50.0%	**40.6%**		**64.9%**		**44.7%**	
Result		100%	100%	100%	**51.7%**		**65.9%**		**64.3%**	



a. EW1p-pl_CC20_MW20 **b. EW0p-pl_BM49_HS** **c. EW1t-vs_ST9.3_CE20**

Figure 5-20: Illustration of the weighted scoring result of the 'equality approach'

The big advantage of this approach is a simplification of the multicriteria problem to a single value for comparison. Yet it is not only the entire **mix** of values, goals and indicators of a single component that can be compared to each other, but also the **accumulation** of indicators – into goals, and those goals again accumulated into values. This offers the opportunity to shift the discussion away from individual indicators and towards the greater question of goals and their underlying values.

On the other hand, the resulting single scoring value hides the underlying evaluation approach. In this example of equal weighting factors, the brick masonry wall component has the highest score (with 65.9%) followed by the solid timber component (with 64.3%) and the concrete component (49.9%). To illustrate the power of the weighting approach in regard to possible conclusions, two more evaluations approaches will be presented and discussed.

Evaluation Approach Based on Interest

The equal distribution of weighting factors provides mathematically equal factors per value, per goal and per indicator. It is also possible to argue that some indicators are more important than others. A ranking of values, goals, and indicators from most important to least important is called an ‘interest approach’, since the order of the ranking represents a personal interest and priority. One of many different possibilities of ranking is portrayed to illustrate a possible procedure. The weighting factor for each ranking decision is calculated by the relation between the opposite rank and the total sum of rank values (e.g. 1st rank of four equals – 4 / [1+2+3+4] = 40%). The first question of rank comes with the question of which value is more important, the value of environmental quality (D) or economical quality (E)? In this case, we choose environmental quality (1st – 66.7%) over economical quality (2nd – 33.3%). In regard to the different goals in D concerning environmental impacts or the use of raw materials, the goal of minimising environmental impacts (D.1 with 66.7% of 66.7%) is chosen over the goal of economic use of raw materials (D.2 with 33.3% of 66.7%). Finally, the different indicators of each goal are ranked for environmental impact (GWP > EP > AP > POCP) and for economic use of raw materials (MWD > PEET > rs-PEET).

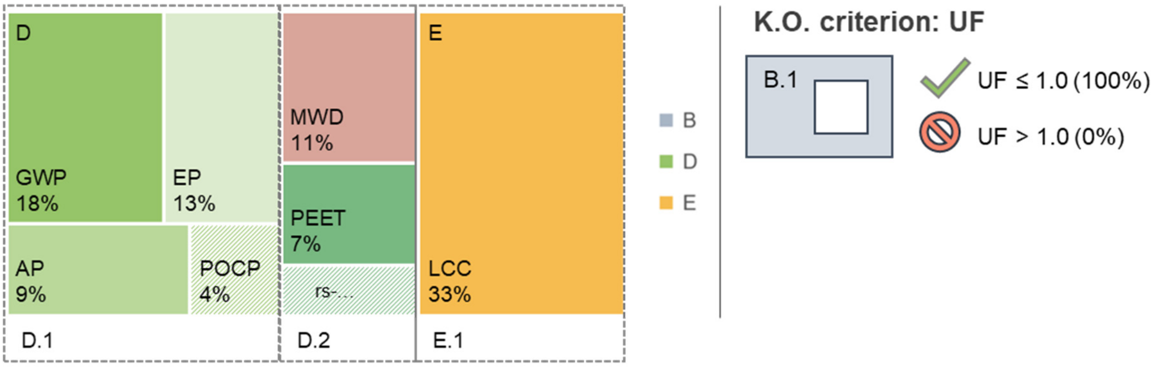


Figure 5-21: Illustration of the weighting distribution of the ‘interest approach’, with check box for a binary knockout criterion B.1

Due to a different weighting factor, the weighted scoring results change according to the ranking order. The more important the aspect, the higher the ranking order and therefore the higher the weighting factor.

Table 5-21: Overview of the weighting factors and weighted scoring results of the ‘interest approach’ for the sample wall components

Goals		**Weighting Factor**			**EW1p_RC20**		**EW0p_BM49**		**EW1t_ST9.3**	
B.1	**UF**	K.O.	K.O.	K.O.	*passed*		*passed*		*passed*	
D.1	**GWP**	66.7%	44.4%	17,8%	58.4%	**66.3%**	61,1%	**72.1%**	90.1%	**87.4%**
	AP			8,9%	66.0%		75,6%		88.7%	
	EP			13,3%	66.4%		75,4%		79.4%	
	POCP			4,4%	98.2%		99,4%		98.0%	
D.2	**MWD**		22.4%	11,1%	64.3%	**61.5%**	77,5%	**66.7%**	100.0%	**87.0%**
	PEET			7,4%	79.8%		77,0%		85.3%	
	rs-PEET			3,7%	16.6%		13,6%		51.4%	
E.1	**LCC**	33.3%	33.3%	33.3%	**40.6%**		**64.9%**		**44.7%**	
Result		100%	100%	100%	**56.7%**		**68.5%**		**73.1%**	

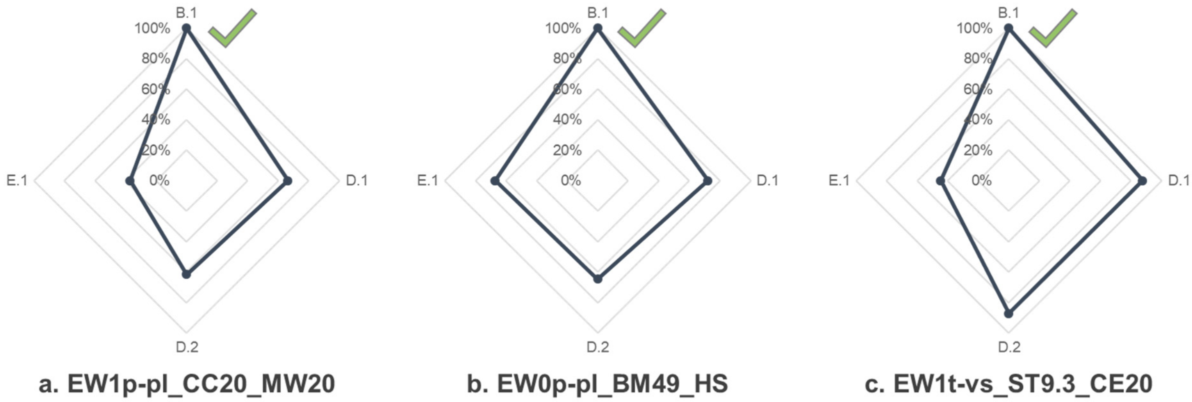


Figure 5-22: Illustration of the weighted scoring result of the ‘interest approach’

The scoring result of the ‘interest approach’ consequently shows a different result than the scoring results of the ‘equality approach’, with the solid timber component showing the best result (73%), followed by the brick masonry component (69%) and the concrete component (56%). However, with the ranking procedure distinguishing between values in the first place before ranking goals or even indicators, the single goal of economic quality with LCC as its indicator has a higher weighting factor (33%) than the first choice of every level of decision (D – D.1 – GWP with 18%). This illustrates the problem between choosing an evaluation approach based on different individual goals or even single indicators and a set of goals combined in one value.

Evaluation Approach Based on Personal Preference

Displaying the other side of the possibilities for an evaluation procedure, the focus is now put on single indicators. According to one’s own values, goals and preferences, an arbitrary weighting system can be defined that reflects a person’s personal opinion. In fact, this evaluation approach is most common, since there is no universal weighting procedure determined or officially required.

An example for a personal evaluation approach is presented based on an individual preference, like, for example: The most urgent problem in regard to environmental impacts is global warming. Additional environmental problems represented by other indicators then disappear into the background. The problem of a resource efficient use of raw materials is reflected by two topics: material use and energy use. Since energy use is connected with the indicator for GWP emissions, it is ranked lower than the problem of material use, illustrated by the material exiting the circularity (MWD). The three goals of minimising environmental impact (D.1) as well as an economic use of raw materials (D.2) and financial resources (E.1) are equally important. A distribution of the weighting factors is therefore derived as follows (see Figure 5-23).

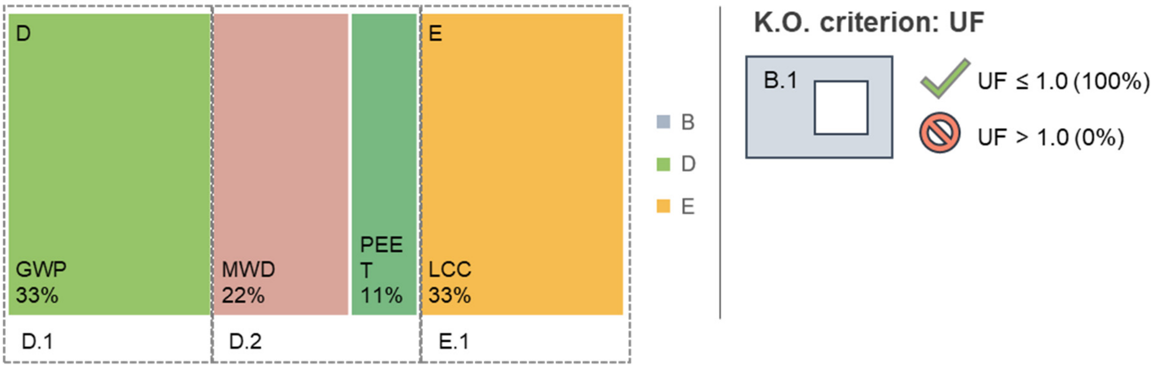
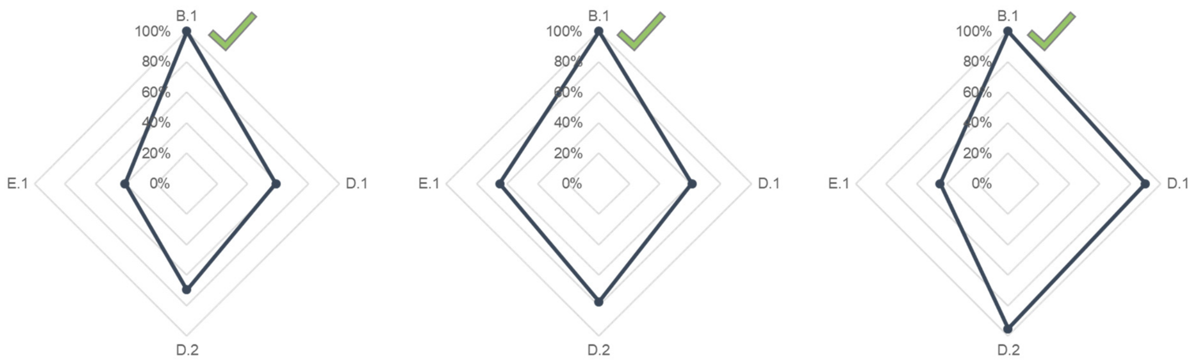


Figure 5-23: Illustration of the weighting distribution of the 'personal preference approach', with check box for a binary knockout criterion B.1

According to this personal valuation of the equality of all three goals, the weighting factors for every goal (D.1, D.2, and E.1) are equalised with 33.3%. The selection of single indicators over others is illustrated by a weighting factor of zero for the indicators not represented in this personal reference approach. The ranking of the indicator MWD being more important than the indicator PEET is reflected in the indicators as well.

Table 5-22: Overview of the weighting factors and weighted scoring results of the 'personal preference approach' for the sample wall components

Goals		**Weighting Factor**			**EW1p_RC20**		**EW0p_BM49**		**EW1t_ST9.3**	
B.1	**UF**	K.O.	K.O.	K.O.	*passed*		*passed*		*passed*	
D.1	**GWP**	66.7%	33.3%	33.3%	58.4%	**58.4%**	61,1%	**61.1%**	90.1%	**90.1%**
	AP			0.0%	66.0%		75,6%		88.7%	
	EP			0.0%	66.4%		75,4%		79.4%	
	POCP			0.0%	98.2%		99,4%		98.0%	
D.2	**MWD**		33.3%	22.2%	64.3%	**69.5%**	77,5%	**77.3%**	100.0%	**95.1%**
	PEET			11.1%	79.8%		77,0%		85.3%	
	rs-PEET			0.0%	16.6%		13,6%		51.4%	
E.1	**LCC**	33.3%	33.3%	33.3%	**40.6%**		**64.9%**		**44.7%**	
Result		100%	100%	100%	**56.1%**		**67.8%**		**76.7%**	



a. EW1p-pl_CC20_MW20 **b. EW0p-pl_BM49** **c. EW1t-vs_ST9.3_CE20**

Figure 5-24: Illustration of the weighted scoring result of the 'personal preference approach'

The focus on four single indicators influences the final evaluation scoring results in such a way that the differences between the different EW components are increasing, although the order stays the same, with the solid timber component showing the highest evaluation score (77%), followed by the brick masonry component (68%) and the concrete component (56%).

The results also demonstrate the earlier mentioned effect (cf. chapter 5.2.1) that *the derivation of the variation standard is not as important as the consistent application of this standard*. For example, the LCC indicator is derived from the results for EW components, while the D.1 indicators are derived from the results for all components. As long as the same valuation standard is applied in the comparison of different components, the relation and ranking order between them stay the same, only the total possible scoring result may vary.

Different evaluation and weighting approaches were demonstrated explicitly to illustrate the importance and methodology behind finding a final 'best' solution. It has to be outlined that in this case only four different goals were merged to distil an evaluation score. Referring to the method used in this thesis, every additional goal can be added to this evaluation approach.

The evaluation scores do not show the best universal EW component, but clarify the procedure of how to arrive at a final decision and to present the possibilities for value-based decision-making. The results clearly show that the possibilities of evaluation are vast, and valid arguments can be presented for multiple approaches. That is why it is difficult to advocate for one universal evaluation approach. On the other hand, knowing the difficulties of evaluation, personal preferences and weighting distributions can reveal one's own priorities of goals and underlying values. This can be tremendously helpful to lead the discussion towards a more value-based focus and away from arguing over which solution is 'better', knowing that 'better' only reflects a specific, personal evaluation.

6 Conclusion and Prospect

6.1 Summary and Conclusion of the Thesis

> *"The real trouble with this world of ours is not that it is an unreasonable world, nor even that it is a reasonable one. The commonest kind of trouble is that it is nearly reasonable, but not quite. Life is not an illogicality; yet it is a trap for logicians. It looks just a little more mathematical and regular than it is." – G. K. Chesterton, 20th century writer* (Chesterton, 1909, p.146)

Summary

This thesis describes the systematic development of a system model of building construction to derive a value-based approach for decision-making within the complexity of goals in the context of building construction. The depiction of the challenges due to increasing complexity in the construction industry has already been outlined in the introduction (cf. chapter 1).

Chapter 2 | The clarification and illustration of the terms and meanings concerning indicators, requirements, goals and values (chapter 2.1) become crucial for defining goals and as the guiding principle for sustainability in this thesis. The derivation of this top-down, value-based approach becomes the basic orientation in the process of decision-making at the end of the thesis (chapter 5). Furthermore, the definition of and distinction between goals and values lead to a new structuring of goals in the construction industry that contrasts with traditional functional structuring systems (chapter 3.1.5). Deriving essential requirements for indicators and a basic approach to evaluation form the groundwork for defining the indicator models in chapter 3.2 and valuation standards in chapter 5.2.1.

Chapter 3 | The method of general system theory for technical systems by G. Ropohl (chapter 2.2) proves to be a powerful tool to describe systems of different disciplines. Defining and differentiating all system concepts and all parts of a general system becomes the basis for the bottom-up development of the desired indicator models, which then consolidate into a draft for a system model of building construction (chapter 3.2). The implementation reveals that the structural and hierarchical system concept serves best in a preliminary modelling phase, supplemented by the functional concept when quantifying the model (chapter 4.1). The illustration and definition of all different aspects of building construction in general regarding the building and all its physical parts as a product, the process that leads to this final product, as well as an overview of all the different functions and goals, becomes valuable structure for developing system models. For example, the level of perspective (building, room, component, and product) serves as a structure for the hierarchy of systems, while the differentiation between physical product and processes aligns with the structuring of a general system into matter, energy and information.

Before developing the general system model of building construction, different subsystems are developed. These subsystems describe four pre-selected goals and lead to individual indicator models. Whereas standards and approved indicators already exist for the goals of structural safety, LCA, and costs, appropriate indicators concerning the use of raw materials are still in discussion. Followed from the overarching value of environmental quality and the goal of an economic use of raw materials, appropriate indicators to portray these goals are defined (chapter 3.2.5). Each indicator model itself illustrates on the one hand the complexity of the goal and on the other hand the integral combination of all essential aspects into one model. Combining and integrating the indicator models into one final draft for a system model for building construction (chapter 3.2.7) proves the applicability of the method of system theory to combine disparate disciplines.

Chapter 4 | Subsequently, applying the system model proves the adaptability of the method of system theory in fundamentally different contexts like structural safety, environmental impacts (LCA), use of raw materials and cost calculation. For the quantification and calculation of the indicator results, a method for determining each indicator is shown (chapter 4.1) as well as the scope of the parameter variation defined. Every goal and its indicator(s) reveal different aspects and parameters of importance, which are considered in the scope of the parameter variation (chapter 4.1). Once more, approved indicators and standards lead to approved methods for calculation and determination of the indicators for structural safety, LCA and costs.

Since there is no pre-existing method to determine the use of raw materials in building construction, a method is developed that goes beyond merely considering building materials. Instead, it describes the overall recyclability of existing or new building structures or components. In this way, aspects of joining and separability of building materials as well as construction and dismantling processes come to the fore (chapter 4.1.4). During the development of this new approach, care is taken to ensure that its structure is compatible with existing circular economy categories and is linked to existing European frameworks and assessment methods of sustainability of construction works. The description of the methods used to determine the indicator results contributes to the detailed development of the indicator system in the first place.

The outcomes of the system model's application show the importance of thoroughly defining the scope of the parameter variation. Various iteration loops are needed to define valid and informative scopes and outcomes. The outcomes illustrate significant characteristics and possible benchmarks of each indicator in regard to upper and lower limits, mean values and shift of the specific value if grouped differently (chapter 4.2).

Chapter 5 | The analysis of the outcomes reveals different insights regarding a focus on single indicator results (chapter 5.1), compared to considering multiple indicator results at the same time (chapter 5.2). Before going into an in-depth analysis, the sensitivity of the results is examined in regard to nine different study design options, varying parameters of structural design, data selection and necessary assumptions (chapter 5.1.1). The results of the sensitivity analysis show that outcomes can be influenced significantly (e.g. structural design choices), marginally (e.g. assumptions for costs) or both (e.g. LCA datasets). This illustrates the necessity of putting the outcomes in relation to the scope and raises awareness of the significance of the thoroughly chosen scope of the study.

The effectivity analysis (chapter 5.1.2) describes an exemplary approach to identify the relevant decision factors within the design process in order to effectively reach a goal and its indicators. This process is illustrated for each indicator separately, deriving a priority list of different decision factors and a hierarchy of the different options within each decision. Comparing the top with the bottom results according to each indicator manifests the effective decision procedure developed previously. The fact that every effective decision procedure for a specific indicator is different demonstrates the conflict between the indicators and the problem of multicriteria decisions.

The regression analysis (chapter 5.1.3) examines the correlation between the indicator results. Its outcome describes different degrees of correlation, which can partly be described as a causality between indicators, but mainly describes the behaviour of the indicator values and reveals their interdependencies.

The consideration of multiple indicator results at the same time (chapter 5.2) takes up this thread and begins to define a valuation standard for each indicator, using the indicator results and the previous developed remarks on general evaluation (chapter 2.1.5). The different characteristics of the goals are reflected in the different deviation of valuation standards. In the first step, these valuation standards are used to compare the different indicator results with each other, using a similar valuation scoring system of percentage. This opens up the possibility to directly compare indicators of all different kinds of goals and characteristics. To dissolve the paralyzing effect of complexity explained in the beginning, the concept of general and personal weighting and evaluation is outlined. The depiction of different approaches based on equality, interest or personal preference illustrates transparently the process of dissolving a multicriteria problem into a single decision based on a pre-elected set of values.

Conclusion

This thesis makes a contribution to achieving the goal of managing complexity and developing a value-based decision-making process in the context of building construction.

The top-down approach to derivate goals in connection with their underlying values offers a direct link from specific indicators to a basic value and therefore a transparent depiction of the goal system in the context of building construction. The general goal system illustrates the variety of goals of every discipline and importance and indicates the individual weighting and selection according to personal preference, as outlined at the end (chapter 5.2.3). As a result, the goal system represents a **holistic overview for decision-making,** structured and based on **underlying values**. In addition to the overview of the goals, the categorisation and structural order of building construction in itself contributes to an improved accessibility, comprehension and differentiation and can be – and is already – used in other (e.g. academic) contexts for a comprehensible communication of knowledge.

The implementation and application of the method of general system theory in the context of building construction proves to be a helpful tool to find a **common "language"** for different disciplines and for an integral portrayal of specific topics. This way, the development and depiction of a goal and its indicators can be established step by step, building a system from the bottom up, with a focus on connection, transparency and comprehension.

Both the top down approach for goals and indicators in combination with the bottom up method of system theory turn out to be suitable approaches to address new topics and indicators, as it is shown in the case for the goal of an economic use of raw materials, where no standard indicators and methods existed previously. The derivation of the goal (chapter 3.1.5), the development of an indicator model (chapter 3.2.5), and the draft of a method to determine the indicator results (chapter 4.1.4) in order to achieve a circular economy in the construction industry, are the result of this double-sided approach. The indicator results (chapter 4.2.4) demonstrate the significance of this approach for making the depiction of the amount of material that is disposed and “goes lost” possible. The approach shows that a realistically available recycling potential can only be determined at the component level. Only considering the building materials cannot depict the essential aspects of construction (joining), dismantling (detachability) and waste treatment. The developed model is able to describe the building component in its entirety, including the joints, in the context of construction (A5) and deconstruction (C1), beyond the sum of the individual building materials. In the sense of the definition of recyclability, a further differentiation of material output indicators (in MRU, MSM, MMR, MMRf, MERf, MWD) in LCA should be the goal in the future. The outcome reveals the importance of balancing the economic use of energy (PEET) and materials (MWD) as well as the total amount of waste flow and its proportional share (MWD and %MWD). In the medium term, the **Recyclability Tool** provides the basis for a holistic development and discussion of closed-loop recycling in the construction industry and is intended to make a long-term contribution to the development of a verification procedure for mapping the sustainable use of resources.

With the variety of goals in mind, the selection of four exemplary goals and their indicators covers a variety of different results and characteristics. This selection follows the idea of choosing fundamentally different goals regarding their indicator results and evaluation in order to develop as much of a holistic model as possible. The extensive scope of the parameter variation, including all different results, is useful in itself as a **database for LCA and LCC results** as well as for material flow data **for building components**. Furthermore, the numerous results for 1472 building components with all their different variations can serve as a **comparison** and **benchmark** for future calculations. A specific building component of any background can easily be classified and compared in regard to its results and performance. As shown with the different possibilities for the illustration of and focus on the outcome (see chapter 4.2), the well-founded establishing of the different parameters and decision factors (chapter 4.1) payed off in the end.

The analysis of the outcome of the parameter variation leads to multiple conclusions. The sensitivity analysis reveals the importance of the study design. As a main conclusion stands the urgency to carefully select and transparently portray the underlying choice of datasets in an LCA study. As a new development, the effective decision-making procedure as a result of the effectivity analysis is based on the previous described developing of the different parameters and decision factors (chapter 4.1). This development is as a major contribution to the goal of the thesis to arrive at an **effective approach to decision-making**.

The counterpart of the thesis' main goal – to arrive at a **balanced** approach to decision-making – is delivered by the final examination of the topic of evaluation. The problem of comparing different goals with indicators of a different nature is addressed by the method of evaluation employed. It includes two aspects: The first aspect provides a unifying element by translating every indicator into a valuation score using a valuation standard. As a result, all different indicators are comparable with the same unit of the valuation score, e.g. percentage. This method proves successful in the translation of indicators with different characteristics (e.g. in the case of structural safety with an "all or nothing" approach). The second aspect of evaluation deals with not only comparing but weighting and balancing all indicators at the same time. The work on multicriteria evaluation delivers not a universal sample solution, but aims at a deeper awareness and comprehensible depiction of how this selection and weighting takes place. This **multicriteria evaluation approach** provides a method to balance different indicators and to arrive at one single solution. However, the hierarchy, including the priority of values, goals and their indicators, is the determining factor. By showing different hierarchy and priority approaches as well as highlighting the approach of personal preference, the special nature of weighting regarding individuality and personality is addressed.

In conclusion, it is the hope and aim of the author to trigger a shift in the discussion about sustainable decision-making in building construction with this thesis, away from individual solutions and towards recognizing and incorporating the underlying values that lead to these solutions. Clarifying and distinguishing between values and goals results in an effective and balanced decision-making process and helps to illuminate and mitigate the challenge of complexity in building construction.

6.2 Prospects for Further Development

As stated in the introduction to this thesis, the challenge of complexity more often than not leads to a reaction of either ignoring or avoiding a direct confrontation. Yet in the light of the increasing severity of the consequences of such a reaction (see chapter 1.1), this approach is no longer justifiable. The outcome of this thesis aims to be an essential contribution to the discussion of managing the complexity in building construction. However, one thesis in itself cannot of course deliver the scope and extent necessary to comprehensively and conclusively cover this topic. Additional examinations are obviously necessary.

In regard to the development and application of the system model, the scope of this thesis is concentrated on four exemplary goals. Although these goals already cover a variety of different characteristics, additional goals are necessary to arrive at a complete picture. Every expert in his or her field knows which respective goals to focus on accordingly. The approach shown in this thesis on how to derive the goal and its indicators (top-down) can contribute to a new perspective on necessary indicators. In combination with the development of **indicator models for additional goals** (bottom-up), a more complete system model of building construction can then be established. The more different goals and indicators are added, the more complicated the model becomes, but due to the structure and approach developed in this thesis, the complexity remains manageable – and therefore applicable to practical matters.

As shown with the development of new indicators and a method to determine indicator results, the **recyclability tool** used in this thesis to describe the goal of an economic use of raw materials shows the potential to attend to other goals and indicators that cannot yet be depicted appropriately. The development of this tool showed that with the basic structuring of the LCA data, a suitable model structure already exists and is used. The author therefore recommends that further developments be based on this framework. In this way, the issue of recyclability and resource efficiency can also be compared with the issue of environmental impacts, and interactions can be taken into account. The tool in its current development status still offer room for optimisation by improving the underlying statistical data as well as including additional intersections (like contamination during use, reuse potential, transport and transport distances, etc.). Further developments could be the up-scaling of the tool to the building level as well as the integration of construction and deconstruction processes affecting both the environmental impacts and the raw material use. In conclusion, it can be said that with the current model, an approach has been developed which offers a basis and framework for further discussion of the assessment of the recyclability of buildings. The long-term goal of this development is a suitable verification procedure to **map the essential requirements** (CPD, ER7) **of a sustainable use of natural resources**.

The structure and method of system theory suggests an implementation of the system model and the method to determine the indicator results into a **computable model**. In fact, a lot of the methods of determination of indicator results are already calculated with different software and computer models. A main criticism towards these kinds of models is the loss of insight and traceability that comes with them. A system model can therefore be a valuable complement.

Regarding the application of the system model, the scope of the parameter variation has to be extended as well. **Additional variations of building components** and their variations would also expand the scope of possible conclusions concerning the results. The scope of the parameter variation already covers many essential aspects, so that every added variation concerning, for example, an alternative façade finish or roofing option, can already be compared and set into context. The more variations are added, the more significant the outcome becomes. The author also suggests to establish **an infrastructure for an open access database** of building components and even buildings, including different indicator results. This would open up the enormous potential of putting every specific solution for a building component or even whole buildings in relation to each other and to derive valuable information of any solution's individual performance.

The level of perspective in this thesis focuses on building components. With the help of the tools developed here, **the scope can be expanded on the building level as well**. The outcome of a parameter variation of buildings can be structured referring to the parameter variation in this thesis and would of course comprise additional aspects. The collection and setup of an open access database of buildings and their respective indicator results would contribute decisively to a comparison and benchmarking system for different kinds of goals and their respective indicators. **This would be an important milestone in the evaluation of the performance of buildings in many regards.**

The sensitivity analysis reveals – amongst other things – **the importance of the underlying data**. Additionally, the development of the model of recyclability shows the necessity to establish standardised calculation rules for the individual material resource indicators across all product categories. From the author's perspective, the basic principles of LCA concerning transparency and comprehensiveness are yet to be strengthened to increase the willingness for disclosure and an open discussion in the LCA community.

The analysis of correlations and **interdependencies between indicators and goals** could only be addressed briefly within this thesis. In the future, this topic deserves to be examined in depth, since it significantly contributes to complexity, while it also offers a huge potential to manage multiple aspects with single factors due to interdependencies. The possibility to manage multiple indicators with the same decision factor is outlined in this thesis, but it comes with various conflicts of interest, since the results show concurrent behaviour, which is therefore discussed in the context of decision-making.

When it comes to the topic of **evaluation,** endurance and mediation is needed, since it is difficult – if not impossible – to derive a universal valuation standard of weighting goals and values in such a way that every party completely agrees. In general, every pre-set weighting system has to be a compromise within a specific setting and group of representatives. The larger the group, the harder the process to arrive at a compromise becomes. This reality notwithstanding, a derivation of a weighting system that reflects the urgency of the current situation in combination with agreed values of society should be pursued. The author is aware that this discussion will always create conflict between satisfying the different interests involved and considering the challenges that need to be solved.

In the end, this thesis outlines the importance of considering an interdisciplinary approach to managing the complexity in building construction. As shown in the beginning, complexity demands interdisciplinary thinking. Interdisciplinarity, however, implies the openness and willingness to address multiple disciplines and the demand to examine these disciplines in necessary depth in order to emerge with a suitable solution approach. Therefore, expertise and holism have to go hand in hand instead of competing with each other. With this thesis, the author aims to contribute to manage the challenge of decision-making within the complexity of one of these fields: building construction.

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Appendix

Material List for LCA datasets

Table A 1: Material list for all ÖKOBAUDAT datasets with ID and reference unit

Material	UUID [ÖKOBAUDAT]	Data Type	ÖKOBAUDAT Dataset	
Adhesive mortar	6124aaeb-24df-4d6a-86a6-549925aacc22	average dataset	Putzmörtel-Normalputz/Edelputz mit besonderen Eigenschaften	kg
Aerated Concrete EW0 - SFK 4	1a43ae76-2dc9-4a3a-9926-47e7137e773d	generic dataset	Porenbeton P4 05 unbewehrt	m3
Aerated Concrete EW0 - SFK 2	906b4864-0511-480f-a8bc-7b8302efbf0b	generic dataset	Porenbeton P2 04 unbewehrt	m3
Aerated Concrete EW1 - SFK 4	1a43ae76-2dc9-4a3a-9926-47e7137e773d	generic dataset	Porenbeton P4 05 unbewehrt	m3
Aerated Concrete IW - SFK 4-115	1a43ae76-2dc9-4a3a-9926-47e7137e773d	generic dataset	Porenbeton P4 05 unbewehrt	m3
Barrier layer FR	73d1c1b7-d509-44c8-8518-848babdd7c01	generic dataset	Bitumenbahnen V 60	qm
Base layer, anti-capillary	26ad7410-7fcb-42e8-b622-d1ba2edbf10c	generic dataset	Splitt 2/15	kg
Bituminous sealing layer	ff9336ea-fb7f-4299-8a40-5e9a28538c85	generic dataset	Bitumenbahnen PYE PV 200 S5 (ungeschiefert)	qm
Bonding layer, flooring	42353c68-1c95-4078-b03d-6d02f0c921c1	average dataset	Dispersionsbasierte Klebstoffe, Fixierungen, Vorstriche und Grundierungen der Klasse a für Bodenbelags- bzw. Parkettarbeiten	kg
Bonding layer, tiles	894c26b5-a6b8-4044-b0a1-b282a70530bc	average dataset	Dispersionsbasierte Fliesenklebstoffe der Klasse a	kg
Brick masonry EW0 - SFK 10,RDK 0,75	8a7bcf84-f0a1-46fe-a146-4af9a182edfe	average dataset	Mauerziegel (Dämmstoff gefüllt)	m3
Brick masonry EW0 - SFK 6,RDK 0,6	8a7bcf84-f0a1-46fe-a146-4af9a182edfe	average dataset	Mauerziegel (Dämmstoff gefüllt)	m3
Brick masonry EW1 - SFK 12	f98eea66-671c-4014-bfbb-2db1ffba8331	average dataset	Mauerziegel	m3
Brick masonry IW - SFK 12	f98eea66-671c-4014-bfbb-2db1ffba8331	average dataset	Mauerziegel	m3
Calcium silicate bricks CS - KS 12-1,8-14DF	f7235d64-16e5-42d0-94c8-797a3cd6cd37	average dataset	Kalksandstein	kg
Calcium sulfate screed layer	069696d9-65fe-4d35-9a0b-f9ea560868b5	average dataset	Estrichmörtel-Calciumsulfatestrich	kg
Cavity insulation CE, DZ/WH	adbef3b8-9350-48e2-9f1c-e164793fcdd5	average dataset	ISOCELL-Einblasdämmstoff aus Zellulosefasern Raum ausfüllend 65 kg/m³	m3
Cavity insulation EPS, DZ/WH	c5edec42-1921-46c6-a3aa-5cbd27685a74	average dataset	EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035	m3
Cavity insulation MW, DZ/WH	ec17f51c-27ff-4729-977e-cd0e273c2ee3	average dataset	ROCKWOOL Steinwolle-Dämmstoff im niedrigen Rohdichtebereich	m3
Cavity insulation WF, DZ/WH	d601d54e-a2eb-42bb-b32b-c59d1b2332a9	average dataset	Holzfaserdämmstoff	m3
Cement screed layer	0864927a-1f93-4a07-a39c-51725a8b967e	average dataset	Estrichmörtel-Zementestrich	kg
Composite timber-concrete slab, CLT	954a286e-36e6-4ceb-9ab9-ec4270b618aa	representative dataset	Brettsperrholz (Durchschnitt DE)	m3
Composite timber-concrete slab, GLT	65088842-af32-46a8-819d-b92901c9e91e	representative dataset	Brettschichtholz - Standardformen (Durchschnitt DE)	m3
Composite timber-concrete slab, top concrete layer	71667cf3-ede8-42d2-b0ff-6f1071ad3b86	average dataset	Beton der Druckfestigkeitsklasse C 25/30	m3
Concrete C25/30, in-situ	71667cf3-ede8-42d2-b0ff-6f1071ad3b86	average dataset	Beton der Druckfestigkeitsklasse C 25/30	m3
Core insulation, EPS	c5edec42-1921-46c6-a3aa-5cbd27685a74	average dataset	EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035	m3

Core insulation, MW	eca9691f-06d7-48a7-94a9-ea808e2d67e8	average dataset	ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich	m3
Core insulation, PU	880e05ea-55c6-4346-a3ea-5af0e5f299e2	average dataset	PU-Dämmplatten aus Blockschaumstoff	kg
Cross-laminated timber panel	954a286e-36e6-4ceb-9ab9-ec4270b618aa	representative dataset	Brettsperrholz (Durchschnitt DE)	m3
Drainage layer	26ad7410-7fcb-42e8-b622-d1ba2edbf10c	generic dataset	Splitt 2/15	kg
Dispersion, visible masonry	d55294cf-5a8b-48c9-b459-bdc2bdd8c9b3	average dataset	Dispersionsbasierte Grundierungen, Sperrbeschichtungen, Lacke und Lasuren der Klasse a	kg
EW, timber panel wall	b6f81ab5-4055-4597-afae-b1462dcfc128	representative dataset	Konstruktionsvollholz (Durchschnitt DE)	m3
EWIS fastener	f90555ee-c8b1-4027-8040-96a7f070e1ec	average dataset	Befestigungssysteme für WDVS	pcs.
EWIS insulation, EPS	c5edec42-1921-46c6-a3aa-5cbd27685a74	average dataset	EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035	m3
EWIS insulation, MW	eca9691f-06d7-48a7-94a9-ea808e2d67e8	average dataset	ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich	m3
EWIS insulation, PU	880e05ea-55c6-4346-a3ea-5af0e5f299e2	average dataset	PU-Dämmplatten aus Blockschaumstoff	kg
EWIS insulation, WF	d601d54e-a2eb-42bb-b32b-c59d1b2332a9	average dataset	Holzfaserdämmstoff	m3
Facade paint	fcf6494c-aad2-4180-b1a2-392cc954ae52	generic dataset	Fassadenfarbe Dispersionsfarbe	kg
Facing facade, calcium silicate bricks KS-Vb-2DF	f7235d64-16e5-42d0-94c8-797a3cd6cd37	average dataset	Kalksandstein	kg
Facing facade, concrete bricks	bdda4364-451f-4df2-a68b-5912469ee4c9	generic dataset	Beton-Mauersteine	m3
Facing facade, red bricks	86986c2b-a3fc-454a-b02f-7f62fb54ca87	average dataset	Vormauerziegel, Pflasterziegel und Riemchen	kg
Fastener	1b45f4e3-74c9-4d00-9a45-136ca36d37c8	average dataset	Gewindefurchende Schrauben aus Stahl	kg
Floor insulation EPS, internal DEO	ee10b277-07b5-4c0a-8a48-e0412a9630ff	average dataset	EPS-Hartschaum (Styropor ®) für Decken/Böden und als Perimeterdämmung B/P-035	m3
Floor insulation MW internal DEO	eca9691f-06d7-48a7-94a9-ea808e2d67e8	average dataset	ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich	m3
Floor insulation PUR, internal DEO	880e05ea-55c6-4346-a3ea-5af0e5f299e2	average dataset	PU-Dämmplatten aus Blockschaumstoff	kg
Floor insulation WF, internal DEO	d601d54e-a2eb-42bb-b32b-c59d1b2332a9	average dataset	Holzfaserdämmstoff	m3
Flooring layer, carpet	76ab64f6-6d08-4b67-8cd7-13d26e68d95a	generic dataset	Fußbodenbelag mehrschichtiges Nadelvlies (Teppichboden, 1400 g/m²)	qm
Flooring layer, linoleum	56e977b3-d042-4843-b40d-3a33dbb5a555	generic dataset	Linoleum	qm
Flooring layer, PVC	39da14a3-8f39-4af9-955c-6a70f091acb8	generic dataset	PVC Fußbodenbelag	qm
Flooring layer, tiles	a2b5b7c9-db13-4dbd-be23-b0ff9f0cbd98	average dataset	Keramische Fliesen und Platten	qm
Flooring layer, timber parquet	1e86515c-3d07-4c59-8f81-84cc5fe0fca7	representative dataset	Massivholzparkett (Durchschnitt DE)	qm
Gravel filling	7502766c-df2f-4f8d-8d45-17bb6938eac8	generic dataset	Splitt 2/15 (getrocknet)	kg
Gravel roofing layer, 5cm	bd6aa879-e6e6-4181-afc5-1374b2f32dd1	generic dataset	Schotter 16/32	kg
Grounding and reinforcement plaster (EW)	0bef1249-f998-491a-aa40-d7b2b7bc3dbd	average dataset	Putzmörtel-Armierungsputz	kg
Impact sound insulation MW, DES	eca9691f-06d7-48a7-94a9-ea808e2d67e8	average dataset	ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich	m3
Interior paint	35be6146-5a80-4a9e-a32d-5d05c03a8d5c	generic dataset	Innenfarbe Dispersionsfarbe scheuerfest	kg
Interior plaster	647835db-d887-4d74-8113-1d3ccf3aa1dd	average dataset	Putzmörtel-Normalputz/Edelputz	kg

Joints, screws and fastener	1b45f4e3-74c9-4d00-9a45-136ca36d37c8	average dataset	Gewindefurchende Schrauben aus Stahl	kg
Lightweight plaster	ffcfca40-7a91-4cea-87f5-ff21c2a778df	average dataset	Putzmörtel-Leichtputz	kg
Masonry mortar (facing facade)	a3e5834e-b6a0-4684-ad45-585fad23b7ca	average dataset	Mauermörtel-Vormauermörtel/Mörtel mit besonderen Eigenschaften	kg
Masonry mortar (thin-bed-method)	41cf6418-c26f-4ef5-a04b-f6ea773941a0	average dataset	Mauermörtel-Normalmauermörtel	kg
Medium density fibreboard, MDF	e5141109-efd6-4fbc-a850-53a48ad30f18	representative dataset	Mitteldichte Faserplatte (Durchschnitt DE)	m3
Metal roofing	50c9e674-afd9-456c-9440-6506bec6d55b	generic dataset	Feuerverzinktes Stahlblech	qm
Metal spring bar	9cbdbafe-8377-46ca-a640-8e3c8fc518c0	generic dataset	Stahl Feinblech (0,3-3,0mm)	kg
Oriented Strand Board, OSB	e71b8242-eda8-408a-9ff8-37cd28896b4a	representative dataset	Oriented Strand Board (Durchschnitt DE)	m3
Perimeter insulation CG, beneath FO	9ca6d998-da4f-42f7-a2dc-565a89134cce	specific dataset	FOAMGLAS® S3	kg
Perimeter insulation XPS beneath FO	43e99b8c-90d8-4fcd-90ce-342fb0b7366e	generic dataset	XPS-Dämmstoff	m3
Planking gypsum board type DF (GKF)	c1001ac9-6409-4759-8d40-838b5ca4128f	average dataset	Rigips Feuerschutzplatte RF,RFI - 12,5 mm (820 kg/m³ u. 10,25 kg/m²)	qm
Roofing tiles	eec9c184-852b-47e5-b380-7ae5af203b65	average dataset	Dachziegel	kg
Roof insulation CG, high pressure-resistant DAA-ds	9ca6d998-da4f-42f7-a2dc-565a89134cce	specific dataset	FOAMGLAS® S3	kg
Roof insulation EPS, pressure-resistant DAA	ee10b277-07b5-4c0a-8a48-e0412a9630ff	average dataset	EPS-Hartschaum (Styropor ®) für Decken/Böden und als Perimeterdämmung B/P-035	m3
Roof insulation MW, pressure-resistant DAA	b0e3aedd-a5e2-4b97-b0f3-e51548912687	average dataset	ROCKWOOL Steinwolle-Dämmstoff im hohen Rohdichtebereich	m3
Roof insulation PU, high pressure-resistant DAA-ds	880e05ea-55c6-4346-a3ea-5af0e5f299e2	average dataset	PU-Dämmplatten aus Blockschaumstoff	kg
Roof insulation WF, pressure-resistant DAA	d601d54e-a2eb-42bb-b32b-c59d1b2332a9	average dataset	Holzfaserdämmstoff	m3
Roof insulation XPS, high pressure-resistant DAA-ds	43e99b8c-90d8-4fcd-90ce-342fb0b7366e	generic dataset	XPS-Dämmstoff	m3
Root protective layer	8a37ac61-585c-43a8-9773-10fce30096e4	generic dataset	Folie für Gründach	qm
Protection layer, separating fleece	95a4f4b3-b354-4e2c-9046-0a36175cd768	generic dataset	PE/PP Vlies	qm
Metal whip arm	9cbdbafe-8377-46ca-a640-8e3c8fc518c0	generic dataset	Stahl Feinblech (0,3-3,0mm)	kg
Screws, wide back clips	1b45f4e3-74c9-4d00-9a45-136ca36d37c8	average dataset	Gewindefurchende Schrauben aus Stahl	kg
Sealing layer (FO) W1-E	ff9336ea-fb7f-4299-8a40-5e9a28538c85	generic dataset	Bitumenbahnen PYE PV 200 S5 (ungeschiefert)	qm
Sealing Layer (FR), sd<100 (e.g. EPDM)	341e2e42-dab2-427b-86f6-a80c701b6071	generic dataset	Dachbahnen EPDM	qm
Sealing layer (FR), synthetic (PVC)	4f4e989b-bd5e-4d85-9a50-53f3c61eea70	generic dataset	PVC-Dachbahnen	qm
Sealing layer acc. DIN 18195	73d1c1b7-d509-44c8-8518-848babdd7c01	generic dataset	Bitumenbahnen V 60	qm
Separating core insulation MW	eca9691f-06d7-48a7-94a9-ea808e2d67e8	average dataset	ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich	m3
Separating layer, EW	95a4f4b3-b354-4e2c-9046-0a36175cd768	generic dataset	PE/PP Vlies	qm
Separating layer, FR	bc50a404-ddf0-4f37-b62f-95130786b004	generic dataset	Dampfbremse PET gitterverstärkt	qm
Separating layer, FS	b1ea7c10-4471-4485-95bf-7dc0a00025b6	generic dataset	Kraftpapier	qm
Separating layer, FS	fa976ebb-09ce-4e5b-9976-621d9ac1f12e	generic dataset	Glasvlies	qm

Particleboard	1270c857-6de2-484f-aed0-251b3b7b6965	representative dataset	Spanplatte, roh (Durchschnitt DE)	m3
Standard plaster	647835db-d887-4d74-8113-1d3ccf3aa1dd	average dataset	Putzmörtel-Normalputz/Edelputz	kg
Steel reinforcement	e9ae96ee-ba8d-420d-9725-7c8abd06e082	generic dataset	Bewehrungsstahl	kg
Suspension (steel)	9cbdbafe-8377-46ca-a640-8e3c8fc518c0	generic dataset	Stahl Feinblech (0,3-3,0mm)	kg
Three-ply-sheeting	6f6fdc0b-4163-4f99-92cb-7b9e3008bae4	representative dataset	3- und 5-Schicht Massivholzplatte (Durchschnitt DE)	m3
Timber battens	76c249ab-1481-4af8-9e98-39c3073eda6f	representative dataset	Nadelschnittholz - getrocknet (Durchschnitt DE)	m3
Timber beam, C24, construction timber	b6f81ab5-4055-4597-afae-b1462dcfc128	representative dataset	Konstruktionsvollholz (Durchschnitt DE)	m3
Timber beams/rafters, GLT	65088842-af32-46a8-819d-b92901c9e91e	representative dataset	Brettschichtholz - Standardformen (Durchschnitt DE)	m3
Timber casing	2103d7e9-529e-45da-8549-892598dba5f3	representative dataset	Hobelware (Durchschnitt DE)	m3
Timber cladding (EW)	2103d7e9-529e-45da-8549-892598dba5f3	representative dataset	Hobelware (Durchschnitt DE)	m3
Timber spare casing	2103d7e9-529e-45da-8549-892598dba5f3	representative dataset	Hobelware (Durchschnitt DE)	m3
Timber substructure	76c249ab-1481-4af8-9e98-39c3073eda6f	representative dataset	Nadelschnittholz - getrocknet (Durchschnitt DE)	m3
Vapour retarder	99792cbc-c5f4-4d2d-bc9e-3790509891a0	generic dataset	Dampfbremse PE	qm
Vapour retarder, moisture adapting	99792cbc-c5f4-4d2d-bc9e-3790509891a0	generic dataset	Dampfbremse PE	qm
Vegetation substrate	5cc8769c-da1b-4967-bb4d-c8fe7b4c359d	generic dataset	Vegetationssubtrat	kg
Wall insulation EPS	c5edec42-1921-46c6-a3aa-5cbd27685a74	average dataset	EPS-Hartschaum (Styropor ®) für Wände und Dächer W/D-035	m3
Wall insulation MW	ec17f51c-27ff-4729-977e-cd0e273c2ee3	average dataset	ROCKWOOL Steinwolle-Dämmstoff im niedrigen Rohdichtebereich	m3
Wall insulation WF	d601d54e-a2eb-42bb-b32b-c59d1b2332a9	average dataset	Holzfaserdämmstoff	m3
WF insulation board	d601d54e-a2eb-42bb-b32b-c59d1b2332a9	average dataset	Holzfaserdämmstoff	m3
Wind barrier layer	95a4f4b3-b354-4e2c-9046-0a36175cd768	generic dataset	PE/PP Vlies	qm
Wire tie	1b45f4e3-74c9-4d00-9a45-136ca36d37c8	average dataset	Gewindefurchende Schrauben aus Stahl	kg
Wood glaze	d55294cf-5a8b-48c9-b459-bdc2bdd8c9b3	average dataset	Dispersionsbasierte Grundierungen, Sperrbeschichtungen, Lacke und Lasuren der Klasse a	kg

Material List for Cost Data

Table A 2: Material list for the BKI cost datasets with ID and reference unit

Material	BKI-Nr.	BKI dataset	
Aerated Concrete EW0 - SFK 4	331.16.09	PB-Plansteine N+F, Dünnbettmörtel, d=24-36,5cm	m2
Aerated Concrete EW0 - SFK 2	331.16.09	PB-Plansteine N+F, Dünnbettmörtel, d=24-36,5cm	m2
Aerated Concrete EW1 - SFK 4	331.12.02	PB-Mauerwerk, d=24cm	m2
Aerated Concrete IW - SFK 4-115	342.12.P27	IW, Porenbeton, 11,5cm, n.tr.	m2
Aerated Concrete IW - SFK 4-175	342.12.P28	IW, Porenbeton, 17,5cm, n.tr.	m2
Aerated Concrete IW - SFK 4-240	341.12.01	PB-Plansteine, Dünnbettmörtel, d=17,5-24cm	m2
Base layer, anti-capillary	325.10.P04	Tragschicht, kapillarbrechend	m2
Bituminous sealing layer	363.21.P28	Dachabdichtung, PYE PV200, S4/5, Wurzelschutz, obere Lage	m2
Bituminous sealing layer	363.21.P26	Dachabdichtung, PYE G200, S4/5, untere Lage	m2
Bituminous sealing layer	363.21.P27	Dachabdichtung, PYE PV200, S4/5, obere Lage	m2
Brick masonry EW0 - SFK 6,RDK 0,6	331.12.P66	AW, LHlz 36,5cm, mit Dämmstofffüllung, tragend, SFK 6, RDK 0,6	m2
Brick masonry EW0 - SFK 6,RDK 0,6	331.12.P68	AW, LHlz 42,5cm,tragend, SFK 6, gefüllt	m2
Brick masonry EW1 - SFK 12	331.16.02	Wärmedämmziegel, MG II, d=36,5cm, Sturz und Öffnungen	m2
Brick masonry EW1 - SFK 12	331.16.01	Ziegel-Mauerwerk, d=24-49 mit Stürzen, Rolläden, Sperre, Ringbalken	m2
Brick masonry IW - SFK 12	342.12.P07	Innenwand, Hlz, 11,5cm	m2
Brick masonry IW - SFK 12	341.16.06	Hlz-Mauerwerk, d=17,5cm, MGII-III	m2
Brick masonry IW - SFK 12	341.16.08	Hlz-Mauerwerk, d=24,0cm, MGII-III	m2
Calcium silicate bricks CS IW - KS 12-2,0-175	331.14.11	KS-Mauerwerk, MG II, d=17,5cm	m2
Calcium silicate bricks CS IW - KS 12-2,0-200	342.13.P22	Innenwand, KS-Mauerwerk, Dünnbett, d=20cm	m2
Calcium silicate bricks CS IW - KS 12-2,0-240	341.14.07	KS-Mauerwerk, MG II, d=24,0cm, mit Stürzen	m2
Calcium silicate bricks CS EW1 - KS 12-1,8-12DF-175	331.14.11	KS-Mauerwerk, MG II, d=17,5cm	m2
Calcium silicate bricks CS EW1 - KS 12-1,8-14DF-240	331.14.08	KS-Mauerwerk, MG II, d=24,0cm	m2
Calcium silicate bricks CS IW - KS 12-2,0-115	342.13.P20	Innenwand, KS-Mauerwerk, Dünnbett, d=11,5cm	m2
Calcium sulphate screed layer	353.25.P24	Estrich CA C25 F4 S45	m2
Calcium sulphate screed layer	353.25.P26	Estrich CAF C25 F4 S50	m2
Cavity insulation CE, DZ/WH	363.16.P55	Einblasdämmung, Zellulose, DZ, 100mm	m2
Cavity insulation CE, DZ/WH	363.16.P56	Einblasdämmung, Zellulose, DZ, 140mm	m2
Cavity insulation CE, DZ/WH	363.16.P57	Einblasdämmung, Zellulose, DZ, 180mm	m2
Cavity insulation CE, DZ/WH	363.16.P58	Einblasdämmung, Zellulose, DZ, 300mm	m2
Cavity insulation EPS, DZ/WH	335.17.09	Wärmedämmung aus Polystyrol-Hartschaum 030/040 100-200mm	m2
Cavity insulation MW	342.39.P92	Wärmedämmung zwischen Unterkonstruktion, bis 80mm	m2
Cavity insulation MW, DZ/WH	363.16.P36	Zwischensparrendämmung MW DZ-034, 120mm	m2
Cavity insulation MW, DZ/WH	363.16.P37	Zwischensparrendämmung MW DZ-034, 180mm	m2
Cavity insulation MW, DZ/WH	363.16.P38	Zwischensparrendämmung MW DZ-034, 220mm	m2
Cavity insulation WF, DZ/WH	363.16.P39	Zwischensparrendämmung HF DZ-038, 180mm	m2
Cavity insulation WF, DZ/WH	363.16.P40	Zwischensparrendämmung HF DZ-038, 220mm	m2
Ceiling planking on metal spring bar	354.39.P05	Deckenbekleidung Gipsplatte, einlagig, Federschiene	m2
Ceiling with substructure, ff	354.39.P13	Decke abgehängt, selbsttragend F90A/EI90	m2
Cement screed layer	353.25.P20	Estrich CT C25 F4 S45	m2
Cement screed layer	353.25.P21	Estrich CT C25 F4 S70	m2
Composite timber-concrete slab, CLT	361.16.P06	BSH, Nadelholz, GL24h, Industriequalität	m3

Composite timber-concrete slab, GLT	361.16.P06	BSH, Nadelholz, GL24h, Industriequalität	m3
Composite timber-concrete slab, top concrete layer	351.13.P63	Decke, Ortbeton, C25/30, bis 25cm	m3
Concrete C25/30, in-situ, EW with formwork	331.13.P33	Wand, Stahlbeton C25/30, d=20cm, mit Schalung	m2
Concrete C25/30, in-situ, EW with formwork	331.13.P34	Wand, Stahlbeton C25/30, d=25cm, mit Schalung	m2
Concrete C25/30, in-situ, EW with formwork	331.21.02	Betonwände, Ortbeton d=20cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, EW with formwork	331.21.03	Betonwände, Ortbeton d=15-35cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, EW with formwork	331.21.05	Betonwände, Ortbeton d=24cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, EW with formwork	331.21.06	Betonwände, Ortbeton d=30cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, EW/IW	331.13.P30	Wand Ortbeton, C25/30, bis 25cm	m3
Concrete C25/30, in-situ, FO with formwork	322.13.P19	Bodenplatte Ortbeton, bis d=25cm, Randschalung	m2
Concrete C25/30, in-situ, FO with formwork	322.13.P20	Bodenplatte Ortbeton, bis d=30cm, Randschalung	m2
Concrete C25/30, in-situ, FO with formwork	322.41.09	Bodenplatte Ortbeton, d=15cm, Schalung, Bewehrung	m2
Concrete C25/30, in-situ, FO with formwork	322.41.12	Bodenplatte Ortbeton, d=25cm, Schalung, Bewehrung	m2
Concrete C25/30, in-situ, FO with formwork	322.13.P16	Bodenplatte WU-Beton, bis d=25cm, Randschalung	m2
Concrete C25/30, in-situ, FO with formwork	322.13.P17	Bodenplatte WU-Beton, bis d=30cm, Randschalung	m2
Concrete C25/30, in-situ, FO with formwork	322.13.P18	Bodenplatte WU-Beton, über d=30cm, Randschalung	m2
Concrete C25/30, in-situ, FO with formwork	322.41.11	Bodenplatte WU-Ortbeton, d=25-30cm, Schalung, Bewehrung	m2
Concrete C25/30, in-situ, FO with formwork	322.41.14	Bodenplatte WU-Ortbeton, d bis 35cm, Schalung, Bewehrung	m2
Concrete C25/30, in-situ, FS	351.13.P63	Decke, Ortbeton, C25/30, bis 25cm	m3
Concrete C25/30, in-situ, IW with formwork	341.21.01	Tr. Betonwände, Ortbeton d=17,5cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, IW with formwork	341.21.03	Tr. Betonwände, Ortbeton d=20cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, IW with formwork	341.21.04	Tr. Betonwände, Ortbeton d=24cm, Schalung, Bewehrung, Aussparungen	m2
Concrete C25/30, in-situ, IW with formwork	341.21.05	Tr. Betonwände, Ortbeton d=30cm, Schalung, Bewehrung, Aussparungen	m2
Construction timber, KVH	331.34.01	Vollholz (BSP, BSH, KVH) abbinden und aufstellen, Verankerung und Winkelverbinder	m2
Core insulation, EPS	335.17.06	Wärmedämmung aus Polystyrol-Hartschaum 030/040 50-80mm	m2
Core insulation, MW	330.12.P74	Kerndämmung, Außenwand, MW 140mm	m2
Core insulation, MW	335.12.P73	Kerndämmung, Außenmauerwerk, MW 80mm	m2
Core insulation, PU	335.17.04	Wärmedämmung aus Polyurethan-Hartschaum 40-60mm	m2
Cross-laminated timber panel	361.16.P06	BSH, Nadelholz, GL24h, Industriequalität	m3
Dispersion, visible masonry	345.34.P16	Erstbeschichtung, Dispersion Sichtmauerwerk innen	m2
Double Planking gypsum board type DF (GKF)	364.39.P79	Gipsplatten-/Gipsfaser-Bekleidung, zweilagig	m2
EW timber panel wall (comparison)	331.33.01	Holzrahmenkonstruktion, KVH, Dämmung, Beplankung mit Holzwerkstoffen	m2
EW timber panel wall (comparison)	331.33.02	Holz-Fertigteilwände, d=391-395, KVH, Zellulose 040, d=360mm, OSB d=15mm, Holzweichfaser d=16mm	m2
EW timber panel wall (comparison)	331.33.03	Holz-Fertigteilwände, d=356-384, Doppelsteg, Zellulose 040 d=356mm, OSB d=15mm, DWD d=16mm, inen GK d=12,5mm	m2
EW timber panel wall (comparison)	331.34.02	Holzrahmenwandelement, Dämmung, Dampfsperre, beidseitige Beplankung, d=200-300mm	m2
EW timber panel wall (comparison)	341.31.01	Holzrahmenkonstruktion, beidseitig GKF 15 cm, d=80-140cm	m2
EW timber panel wall (comparison)	341.33.01	Holzrahmenwände, Dämmung, KVH, beidseitige Beplankung, d=120-180mm	m2
EW timber panel wall (comparison)	337.16.P75	Außenwand, Holzrahmen, 16cm, OSB, WF-Dämmung	m3
EW timber panel wall (comparison)	337.16.P76	Außenwand, Holzrahmen, OSB, ZE-Dämmung, WF-Dämmplatte	m2
EWIS fastener	335.23.P62	WDVS, Dübelung, Wärmedämmung	m2
EWIS insulation, EPS	335.23.P53	WDVS, EPS 035, 100mm	m2

EWIS insulation, EPS	335.23.P54	WDVS, EPS 035, 180mm	m2
EWIS insulation, EPS	335.23.P55	WDVS, EPS 035, 300mm	m2
EWIS insulation, EPS	335.23.P51	WDVS, EPS 035, d=120mm, mit Silikat-Reibeputz	m2
EWIS insulation, EPS	335.23.P52	WDVS, EPS 035, d=180mm, mit Silikat-Reibeputz	m2
EWIS insulation, MW	335.23.P49	WDVS, MF 035, d=120mm, mit Silikat-Reibeputz	m2
EWIS insulation, MW	335.23.P50	WDVS, MF 035, d=180mm, mit Silikat-Reibeputz	m2
EWIS insulation, MW	335.23.P56	WDVS, MF 035, 160mm	m2
EWIS insulation, MW	335.23.P57	WDVS, MF 035, 200mm	m2
EWIS insulation, PU	335.17.04	Wärmedämmung aus Polyurethan-Hartschaum 40-60mm	m2
EWIS insulation, WF	335.16.P63	Dämmung AW, Holzfaserplatte, d=160mm, Putzträger, WLG 040	m2
EWIS insulation, WF	364.16.P62	Dämmung Holzfaserplatte, d=80mm, N+F	m2
EWIS plaster layer	335.23.P70	WDVS Mineralischer Oberputz	m2
EWIS plaster layer	335.23.P63	WDVS Armierungsputz, Glasfasereinlage	m2
Facade paint	335.34.P21	Erstbeschichtung, Dispersions-Silikatfarbe, auf Außenputz	m2
Facing facade, calcium silicate bricks KS-Vb-2DF	335.12.P82	Verblendmauerwerk, Kalksandsteine	m2
Facing facade, concrete bricks	335.12.P83	Verblendmauerwerk, Betonsteine	m2
Facing facade, red bricks	335.12.P81	Verblendmauerwerk, VMz, 115mm	m2
Facing framework	345.39.P65	Vorsatzschale. GK/GF	m2
Facing framework	345.39.P68	Vorsatzschale Wand, freistehend GK/GF	m2
Floor insulation EPS, internal DEO	353.25.P10	Wärmedämmung, Estrich EPS 60mm, 040 DEO-dm	m2
Floor insulation MW internal DEO	324.26.00	Wärme- und Trittschalldämmung WLG 035, Mineralfaser, d=50-90mm	m2
Floor insulation PUR, internal DEO	353.25.P12	Wärmedämmung, Estrich PUR 60mm, 025 DEO-dh	m2
Floor insulation WF, internal DEO	364.16.P61	AW-Dämmung, Holzfaser, 80mm	m2
Flooring layer, carpet	353.36.P20	Textiler Belag, Nadelvlies, verklebt	m2
Flooring layer, carpet	353.61.01	Teppichbelag, Untergrundvorbereitungen, Sockelleisten	m2
Flooring layer, carpet	353.65.02	Teppichbelag, Trittschalldämmung, Estrich d=40-50mm, Sockelleisten	m2
Flooring layer, linoleum	353.36.P28	Bodenbelag, Linoleum, über 2,5mm	m2
Flooring layer, linoleum	353.81.01	Linoleumbelag, d=2,5-3,2, Ausfugen, Sockelleisten, Untergrundvorbereitung	m2
Flooring layer, linoleum	353.85.02	Linoleumbelag, Trittschalldämmung und Estrich	m2
Flooring layer, PVC	353.36.P31	Bodenbelag, PVC, 3,0mm	m2
Flooring layer, PVC	353.82.01	Kunsstoffbelag (PVC/Linoleum), Trittschalldämmung und Estrich	m2
Flooring layer, tiles	353.31.02	Steinzeugfliesen im Dünnbett	m2
Flooring layer, tiles	353.35.03	Fliesenbelag. Zementestrich, Dämmung, Sockelfliesen	m2
Flooring layer, tiles	353.24.P36	Bodenfliesen im Dünnbettmörtel, 20x20cm	m2
Flooring layer, timber parquet	353.28.P27	Fertigpakett Eiche, bis 15mm, beschichtet	m2
Flooring layer, timber parquet	353.71.01	Parkettbelag Eiche, d=20-23, schleifen, versiegeln, Sockelleisten	m2
Flooring layer, timber parquet	353.71.05	Fertigparkett Untergrundvorbereitung, Sockelleisten	m2
Flooring layer, timber parquet	353.75.01	Parkett Trittschalldämmung, Estrich, Sockelleisten	m2
Formwork (in-situ concrete)	331.13.P32	Schalung Wand glatt, sichtbar	m2
Formwork (in-situ concrete)	331.13.P37	Schalung, Wand, rau	m2
Formwork (in-situ concrete)	331.13.P38	Schalung, Wand, glatt	m2
Formwork (in-situ concrete)	331.13.P39	Schlaung Wand glatt, Sichtbar, SB3	m2
FS, solid timber, dowel laminated timber	351.16.P80	Brettstapel, Massivholzdecke bis 14cm, gehobelt, inkl. Aussparungen	m2
FS, solid timber, dowel laminated timber	351.16.P81	Brettstapel, Massivholzdecke bis 16cm, gehobelt, inkl. Aussparungen	m2
FS, solid timber, dowel laminated timber	351.16.P82	Brettstapel, Massivholzdecke bis 20-22cm, gehobelt, inkl. Aussparungen	m2

FS, timber beam, C24, construction timber	351.41.01	Holzbalkendecke, BSH, 12/12, n. sichtbar, MF, Schalung d=22mm	m2
Gravel filling	353.25.P04	Trockenschüttung, bis 30mm	m2
Gravel roofing layer, 5cm	363.21.P57	Kiesschüttung, 16/32, Dach	m2
Impact sound insulation MW, DES	353.25.P06	Trittschalldämmung, MW, 30-5mm 035, sh	m2
Interior plaster	345.23.P32	Kalk-Gipsputz, Innenputz, einlagig, Q2	m2
Interior plaster	345.23.P37	Gipsputz, Innenputz, einlagig, Q3	m2
Interior plaster	345.23.P26	Innenputz, einlagig, Q3, geglättet	m2
IW timber panel wall (comparison)	342.16.P77	Innenwand, Holzständer, 11,5cm, Sperrholz, WF-Dämm-platte	m2
IW timber panel wall (comparison)	342.39.P28	Montagewand, Holz-UK, 85mm, GF einlagig, MW 40mm, EI30	m2
IW timber panel wall (comparison)	342.39.P29	Montagewand, Holz-UK, 100mm, GF zweilagig MW 50mm, EI90	m2
IW timber panel wall (comparison)	342.52.01	n. Tr. Holzständerwand, beidseitige Beplankung	m2
Masonry mortar tiles (thin-bed-method)	353.24.P37	Bodenfliesen im Dünnbettmörtel, 30x30cm	m2
Medium density fibreboard, MDF	335.16.P51	AW-Dämmung, WF 040, bis 20mm, regensicher	m2
Metal roofing	363.22.P67	Dachdeckung, Doppestehfalz, verzinkt	m2
Oriented Strand Board, OSB	336.16.P22	Schalung OSB/3, Flachpressplatte, 12-15mm	m2
Particleboard	363.16.P19	Schalung, Holzspanplatte P5, N+F	m2
Perimeter insulation CG, beneath FO	325.13.P112	Schaumglasdämmung unter Bodenplatte 120-140mm	m2
Perimeter insulation XPS beneath FO	325.18.P08	Perimeterdämmung, Bodenplatte, XPS 040, bis 100mm	m2
Perimeter insulation XPS beneath FO	325.18.P09	Perimeterdämmung, Bodenplatte, XPS 040, bis 240mm	m2
Planking gypsum board type DF (GKF)	364.39.P78	Gipsplatten-/Gipsfaser-Bekleidung, einlagig	m2
Roofing tiles	363.20.P36	Dachdeckung Hohlfalzziegel	m2
Roof insulation CG, high pressure-resistant DAA-ds	363.21.P18	Wärmedämmung, CG, bis 140mm	m2
Roof insulation EPS, pressure-resistant DAA	363.21.P11	Wärmedämmung DAA, EPS 035, bis 140mm	m2
Roof insulation EPS, pressure-resistant DAA	363.21.P12	Wärmedämmung DAA, EPS 035, bis 240mm	m2
Roof insulation MW, pressure-resistant DAA	363.21.P20	Wärmedämmung DAA, MW, 120-160mm	m2
Roof insulation PU, high pressure-resistant DAA-ds	363.21.P13	Wärmedämmung DAA, PUR 024, bis 120mm	m2
Roof insulation PU, high pressure-resistant DAA-ds	363.21.P14	Wärmedämmung DAA, PUR 024, bis 180mm	m2
Roof insulation WF, pressure-resistant DAA	364.16.P62	Dämmung Holzfaserplatte, d=80mm, N+F	m2
Roof insulation XPS, high pressure-resistant DAA-ds	363.21.P19	Wärmedämmung DUK, XPS, bis 140mm	m2
Root protective layer	363.03.P134	Durchwurzlungsschicht	m2
Sealing layer (FO) W1-E	324.18.P18	Bodenabdichtung, Bodenfeuchte, Bitumen-Schweibahn ein-lagig, G200DD	m2
Sealing Layer (FR), sd<100 (e.g. EPDM)	363.21.P34	Dachabdichtung, EPDM-Kunsstoffbahn, einlagig	m2
Sealing layer (FR), synthetic (PVC)	363.21.P32	Dachabdichtung, Kunststoffbahn, einlagig, Wurzelschutz	m2
Sealing layer acc. DIN 18195	363.21.P08	Dampfsperre, V60S4	m2
Separating core insulation MW	331.13.P109	StB, Trennwanddämmung, MW, d=20/30mm	m2
Separating layer, FO	325.18.P14	Trennlage, PE-Folie, unter Bodenplatte	m2
Separating layer, FR	363.21.P58	Trennlage, PE-Folie, Dach	m2
Separating layer, FR	363.22.P64	Trennlage, Kunststoffbahn, Gespinstlage	m2
Separating layer, FR	363.21.P58	Trennlage, PE-Folie, Dach	m2
Separating layer, FS	353.28.P08	Trennlage, Wellpappe	m2
Separating layer, FS	353.25.P16	Trennlage, Dämmung-Estrich, PE-Folie, 0,2mm	m2
Barrier layer	363.21.P08	Dampfsperre, V60S4	m2
Barrier layer (on timber)	363.21.P05	Trennlage/untere Lage, G200 DD, auf Holz	m2
Standard plaster layer	335.23.P71	Außenputz zweilagig, Wand	m2
Steel reinforcement	331.13.P116	Bewehrung (Betonstabstahl)	t
Steel reinforcement	331.13.P115	Bewehrung (Betonstahlmatten)	t

Suspended ceiling	354.39.P06	Decke abgehängt, Gipsplatte, einlagig	m2
Suspended ceiling	354.39.P09	Decke abgehängt, GK/GF, zweilagig	m2
Thick interior plaster layer, pp	345.23.P29	Mehrdicke, 10mm, Putz	m2
Three-ply-sheeting	335.16.P31	Bekleidung, Massivholzplatte	m2
Timber battens	363.20.P17	Konterlattung 30x50	m2
Timber battens	363.20.P19	Dachlattung 30x50, Ziegel	m2
Timber battens	335.38.P01	Unterkonstruktion, Holz, Lattung 30/50 od. 40/60	m2
Timber battens	363.20.P18	Konterlattung 40x60	m2
Timber battens	335.38.P02	Unterkonstruktion, Holz, Lattung 2-lagig mit Konterlattung 30/50	m2
Timber battens, PR	363.20.P20	Dachlattung 40x60, Ziegel	m2
Timber beam, C24, construction timber	361.16.P06	BSH, Nadelholz, GL24h, Industriequalität	m3
Timber beams/rafters, GLT	361.16.P06	BSH, Nadelholz, GL24h, Industriequalität	m3
Timber casing	363.20.P26	Dachschalung, Nadelholz, Rauspund, 28mm	m2
Timber casing	351.13.P66	Schalung, Decken, glatt	m2
Timber casing	363.16.P16	Schalung, Nadelholz, gehobelt	m2
Timber cladding (EW)	335.38.P14	Fassadenbekleidung, Holz-Stülpschlaung	m2
Timber spare casing	363.16.P18	Schalung, Rauspund, genagelt	m2
Timber substructure	335.38.P03	Unterkonstruktion, Rauspund	m2
Vapour retarder	364.16.P46	Dampfbremse, sd bis 2,0m	m2
Vapour retarder, moisture adapting	364.16.P47	Dampfbremse, feuchteadaptiv, sd-variabel	m2
Vegetation substrate	363.16.01	Abdichtung, Belag, extensive Dachbegrünung	m2
Visible surface, concrete	345.23.01	Zuschlag für Sichtschalung an Betonwänden	m2
Wall insulation EPS	335.17.09	Wärmedämmung aus Polystyrol-Hartschaum 030/040 100-200mm	m2
Wall insulation MW	335.38.P06	Fassadendämmung, MW 034, 120mm, kaschiert	m2
Wall insulation MW	335.38.P07	Fassadendämmung, MW 034, 160mm, kaschiert	m2
Wall insulation MW	335.16.P60	AW-Dämmung, MW WH-035, 240mm	m2
Wall insulation WF	335.16.P52	AW-Dämmung, WF 040, 80mm, regensicher	m2
WF insulation board	363.20.P07	Unterdeckplatte, UDP-A, WF 045, bis 22mm	m2
Wind barrier layer	335.38.P12	Winddichtung, Polyestervlies	m2
Wire tie	335.12.P76	Drahtanker, Hintermauerung/Tragschale	m2
Wood glaze	345.34.P35	Erstbeschichtung, Lasur, Holzbauteile, innen	m2

Reference of real buildings for every basic version

Table A 3: Basic versions of all exterior wall components with real references

Basic V.	Building and building site	Reference
EW0p_AC	Wohnen am Mittleren Ring in München	www.baunetzwissen.de/mauerwerk/objekte/wohnen-mfh
EW1t_AC	-	-
EW1p_AC	Gemeinschaftliches Wohnprojekt „Open House" in Hamburg	www.baunetzwissen.de/mauerwerk/objekte/wohnen-mfh
EW2f_AC	-	-
EW0p_BM	Mehr als Wohnen in Zürich, CH; Duplex Architekten, pool Architekten	Hofmeister, Sandra (Hg.) (2018): Wohnungsbau. Kostengünstige Modelle für die Zukunft. München: Detail, S.35ff
EW1t_BM	-	-
EW1p_BM	-	-
EW2f_BM	Vaudeville Court in London, GB; Levitt Bernstein	Hofmeister, Sandra (Hg.) (2018): Wohnungsbau. Kostengünstige Modelle für die Zukunft. München: Detail
EW1t_CS	-	-
EW1p_CS	Wohnanlage in Groningen, Niederlande	Pfeifer, Achtziger et al (2001): Mauerwerk Atlas (DETAIL Atlas), S.272ff
EW2f_CS	Wohnanlage in Berlin, DE	Pfeifer, Achtziger et al (2001): Mauerwerk Atlas (DETAIL Atlas), S.276ff
EW1t_RC	Sozialwohnungen in Paris, FR; Dietmar Feichtinger Architectes	Hofmeister, Sandra (Hg.) (2018): Wohnungsbau. Kostengünstige Modelle für die Zukunft. München: Detail, S.159ff
EW1p_RC	Wohnungsbau in Schwabing, München	Schittich, Christian (Hg.) (2017): Urbanes Wohnen = Urban Housing. München: Detail (Best of Detail), S.132ff
EW2f_RC	Wohnsiedlung in Rungsted, DK	Pfeifer, Achtziger et al (2001): Mauerwerk Atlas (DETAIL Atlas), S.338ff
EW1t_ST	Woddie in Hamburg, DE; Sauerbruch Hutton	Hofmeister, Sandra (Hg.) (2018): Wohnungsbau. Kostengünstige Modelle für die Zukunft. München: Detail, S.127ff
EW1p_ST	Wohn- und Geschäftshaus c 13	Kaufmann, Winter et al (2017): Atlas mehrgeschossiger Holzbau, S.170ff
EW2f_ST	-	-
EW1t_TE	Wohnungsbau Kalkbreite in Zürich Wohnhaus am Dantebad in München, DE; Florian Nagler Architekten	Schittich, Christian (Hg.) (2017): Urbanes Wohnen = Urban Housing. München: Detail (Best of Detail), S.88ff Hofmeister, S. (Hg.) (2018): Wohnungsbau. Kostengünstige Modelle für die Zukunft. München: Detail, S.87ff
EW1p_TE	Wohnungsbau Kalkbreite in Zürich	Schittich, Christian (Hg.) (2017): Urbanes Wohnen = Urban Housing. München: Detail (Best of Detail), S.88ff
EW2f_TE	-	-
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Total Results of the Parameter Variation

Indicator AP

Table A 4: Overview of the variation of the AP results due to the choice of exterior finish (DF1.2)

AP in [g SO^2-e/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	113.2 (f)	74.3 (m)	130.3 (g)	172.9 (x)
Decrease / increase	↓-45% | ↑+83%	↓-16% | ↑+19%	↓-13% | ↑+14%	↓-6% | ↑+7%
Lowest mean value	61.7 (t)	62.2 (r)	114.0 (s)	162.1 (i)

Table A 5: Overview of the variation of the AP results due to the choice of interior finish (DF1.3)

AP in [g SO^2-e/m²]	**IW**	**FS** (ceiling)	**FS** (flooring)	**FO**
Highest mean value	68.3 (ff)	121.6 (ff)	145.7 (ca)	197.6 (ca)
Decrease / increase	↓-19% | ↑+23%	↓-10% | ↑+12%	↓-37% | ↑+58%	↓-27% | ↑+37%
Lowest mean value	55.6 (vs)	109.0 (vs)	92.0 (pa)	144.0 (pa)

Table A 6: Overview of the variation of the AP results due to the choice of structural material (DF2.1)

AP in [g SO^2-e/m²]	**FR**	**EW**	**IW**	**FS**
Highest mean value	157.3 (CC)	108.0 (CC)	87.9 (AC)	132.0 (CC)
Decrease / increase	↓-38% | ↑+60%	↓-37% | ↑+59%	↓-66% | ↑+191%	↓-26% | ↑+36%
Lowest mean value	98.1 (TE)	68.1 (TE)	30.2 (TE)	97.1 (TE)

Table A 7: Overview of the variation of the AP results due to the choice of insulation material (DF2.2)

AP in [g SO^2-e/m²]	**EWe**	**EWt**	**EWf**
Highest mean value	103.4 (PU)	72.7 (EPS)	81.9 (EPS)
Decrease / increase	↓-24% | ↑+31%	↓-28% | ↑+40%	↓-31% | ↑+45%
Lowest mean value	78.9 (WF)	52.0 (CE)	56.5 (CE)
AP in [g SO^2-e/m²]	**PR**	**FR**	**FO**
Highest mean value	81.9 (EPS)	145.9 (CG)	81.9 (EPS)
Decrease / increase	↓-31% | ↑+45%	↓-35% | ↑+54%	↓-31% | ↑+45%
Lowest mean value	56.5 (CE)	94.6 (WF)	56.5 (CE)

Table A 8: Overview of the variation of the AP results for exterior wall components due to the choice of the thickness of the structural layer

AP in [g SO^2-e/m²]	**AC**	**BM**	**CS**
Highest mean value	177.7 (240)	95.9 (240)	103.9 (200)
Decrease / increase	↓-14% | ↑+16%	↓-10% | ↑+11%	↓-12% | ↑+14%
Increase of GWP per mm of thickness	**+0.20/mm**	**+0.14/mm**	**+0.25/mm**
Lowest mean value	164.7 (175)	86.3 (175)	91.4 (150)
AP in [g SO^2-e/m²]	**CC**	**ST**	**TE**
Highest mean value	118.6 (220)	78.4 (140)	72.3 (240)

Decrease / increase	↓-18% | ↑+22%	↓-8% | ↑+9%	↓-8% | ↑+8%
Increase of GWP per mm of thickness	**+0.27/mm**	**+0.16/mm**	**+0.07/mm**
Lowest mean value	97.4 (140)	72.0 (100)	66.7 (160)

Table A 9: Overview of the variation of AP results for EW, PR, FR and FO components due to the choice of the thickness of the insulation layer

AP in [g SO^2-e/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	225.7 (R=6)	206.0 (R=7)	332.1 (R=7)	167.2 (R=3)
Decrease / increase	↓-12% | ↑+14%	↓-10% | ↑+11%	↓-17% | ↑+20%	↓-3% | ↑+3%
Lowest mean value	193.3 (R=4)	183.5 (R=5)	296.0 (R=5)	161.9 (R=2)

Indicator EP

Table A 10: Overview of the variation of the EP results due to the choice of exterior finish (DF1.2)

EP in [g PO_4^{3}-e/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	113.2 (f)	74.3 (m)	130.3 (g)	172.9 (x)
Decrease / increase	↓-45% | ↑+83%	↓-16% | ↑+19%	↓-13% | ↑+14%	↓-6% | ↑+7%
Lowest mean value	61.7 (t)	62.2 (r)	114.0 (s)	162.1 (i)

Table A 11: Overview of the variation of the EP results due to the choice of interior finish (DF1.3)

EP in [g PO_4^{3}-e/m²]	**IW**	**FS** (ceiling)	**FS** (flooring)	**FO**
Highest mean value	68.3 (ff)	121.6 (ff)	145.7 (ca)	197.6 (ca)
Decrease / increase	↓-19% | ↑+23%	↓-10% | ↑+12%	↓-37% | ↑+58%	↓-27% | ↑+37%
Lowest mean value	55.6 (vs)	109.0 (vs)	92.0 (pa)	144.0 (pa)

Table A 12: Overview of the variation of the EP results due to the choice of structural material (DF2.1)

EP in [g PO_4^{3}-e/m²]	**FR**	**EW**	**IW**	**FS**
Highest mean value	157.3 (CC)	108.0 (CC)	87.9 (AC)	132.0 (CC)
Decrease / increase	↓-38% | ↑+60%	↓-37% | ↑+59%	↓-66% | ↑+191%	↓-26% | ↑+36%
Lowest mean value	98.1 (TE)	68.1 (TE)	30.2 (TE)	97.1 (TE)

Table A 13: Overview of the variation of the EP results due to the choice of insulation material (DF2.2)

EP in [g PO_4^{3}-e/m²]	**EWe**	**EWt**	**EWf**
Highest mean value	103.4 (PU)	72.7 (EPS)	81.9 (EPS)
Decrease / increase	↓-24% | ↑+31%	↓-28% | ↑+40%	↓-31% | ↑+45%
Lowest mean value	78.9 (WF)	52.0 (CE)	56.5 (CE)
EP in [g PO_4^{3}-e/m²]	**PR**	**FR**	**FO**
Highest mean value	81.9 (EPS)	145.9 (CG)	81.9 (EPS)
Decrease / increase	↓-31% | ↑+45%	↓-35% | ↑+54%	↓-31% | ↑+45%

Lowest mean value	56.5 (CE)	94.6 (WF)	56.5 (CE)

Table A 14: Overview of the variation of the EP results for exterior wall components due to the choice of the thickness of the structural layer

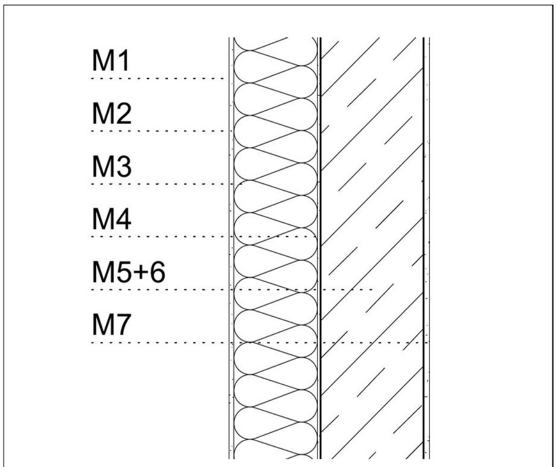
EP in [g PO_4^{3}-e/m²]	**AC**	**BM**	**CS**
Highest mean value	29.7 (240)	32.5 (240)	28.7 (200)
Decrease / increase	↓-14% | ↑+16%	↓-10% | ↑+11%	↓-12% | ↑+14%
Increase of GWP per mm of thickness	**+0.03/mm**	**+0.04/mm**	**+0.04/mm**
Lowest mean value	27.5 (175)	30.0 (175)	26.7 (150)
EP in [g PO_4^{3}-e/m²]	**CC**	**ST**	**TE**
Highest mean value	42.1 (220)	40.1 (140)	31.6 (240)
Decrease / increase	↓-18% | ↑+22%	↓-8% | ↑+9%	↓-8% | ↑+8%
Increase of GWP per mm of thickness	**+0.09/mm**	**+0.13/mm**	**+0.05/mm**
Lowest mean value	35.2 (140)	35.0 (100)	27.7 (160)

Table A 15: Overview of the variation of EP results for EW, PR, FR and FO components due to the choice of the thickness of the insulation layer

EP in [g PO_4^{3}-e/m²]	**EW**	**PR**	**FR**	**FO**
Highest mean value	35.7 (R=6)	38.7 (R=7)	57.1 (R=7)	167.2 (R=3)
Decrease / increase	↓-12% | ↑+14%	↓-10% | ↑+11%	↓-17% | ↑+20%	↓-3% | ↑+3%
Lowest mean value	30.6 (R=4)	34.0 (R=5)	53.0 (R=5)	161.9 (R=2)

Reinforced concrete wall with mineral wool EWIS: EW1p-pl_RC20_MW16

Single-shell exterior wall with reinforced concrete and EWIS	I	EW1p_RC



Source: THG Holzbau

Parameters of Construction

all results are related to 1.0 m² of the building component

Fire Resistance:		*n/s*	
Thermal insulation:	U =	**0,21**	[W/m²K]
Noise insulation:	R_w =	*n/s*	
Thickness:	d=	**383,15**	[mm]
Mass:	m =	**541,60**	[kg/m²]
	g =	**5,31**	[kN/m²]
Stress resistance:	N_{Rd} =	**2721,7**	[N/mm²]

Layer [-]	[mm]	Building Material (description)	area-% b/e in [%]	thickness [mm]	V [m³]	ρ [1] [kg/m³]	m [kg]	λ [1] [W/mK]	R [m²K/W]	μ [1] [-]	V-% [%]	M-% [%]
außen									0,04			
1	0,2	Exterior Paint		0,2	0,000	1300,0	0,20				0,0%	0,0%
2	3,0	Finishing Plaster Layer		3,0	0,003	1000,0	3,00	0,800	0,00		0,8%	0,6%
3	5,0	Base Plaster Layer		5,0	0,005	1600,0	8,00	0,800	0,01		1,3%	1,5%
4	160,0	Mineral Wool Exterior Wall Insulation System		160,0	0,160	100,0	16,00	0,035	4,57		41,8%	3,0%
5	5,0	Bonding Mortar		5,0	0,005	1600,0	8,00	0,800	0,01		1,3%	1,5%
5	200,0	Concrete C20/25	99,0%	200,0	0,198	2400,0	475,20	2,300	0,09		51,7%	87,7%
		Steel Reinforcement	1,0%	200,0	0,002	7850,0	15,70				0,5%	2,9%
6	10,0	Interior Gypsum Plaster		10,0	0,010	1550,0	15,50	0,800	0,01		2,6%	2,9%
innen					0,383 m³/m²		541,6 kg/m²		0,13		100%	100%

Dimensions of the Building Component

[m]		Area [m²]	Volume [m³]	Mass [kg/m²]	U-value [W/m²K]	R-value [m²K/W]
0,38	component's thickness	**1,00**	**0,383**	**541,6**	**0,21**	**4,86**
1,00	component's length					
1,00	component's height					

Annotations

[1] if specific information is missing: material information according to DIN EN ISO 10456:2010-05

Graphic: made by Marco Krechel
Source: THG-Holzbau
Examples: München | Schittich, Christian (Hg.) (2017): Urbanes Wohnen = Urban Housing. München: Detail (Best of Detail).

Ökobilanzierung

Ökobilanzielle Berechnung* der Umweltauswirkungen und des Ressourceneinsatzes

Berechnung nach DIN EN 15804 & 15978 basierend auf DIN EN ISO 14040 & 14044

Umweltwirkungen

alle Werte bezogen auf 1 m² Konstruktionsfläche

Über den gesamten Lebenszyklus (cradle-to-gate m. Optionen):

Stoffliche Nutzung:	Verbaute Menge an nawaros:		**0,0**	[kg]	
Biogener Kohlenstoff:	Biogener Kohlenstoff in kg CO_2-äq.:		**0,0**	[kg CO_2]	
Energetische Nutzung:	Einsatz an Primärenergie:	**PEET**	**1111,22**	[MJ]	
(Benötigte Primärenergie)	davon Anteil erneuerbar:	**rs-PEET**	**16,59**	[%]	
Bauteil:	Bauteil Eigengewicht:		**540,96**	[kg/m²]	*Rohdichte gemäß ÖKOBAUDAT*
	Bauteildicke:		**383**	[mm]	
	Bauteilfläche:		**1,0**	[m²]	

Datenbank

ÖKOBAUDAT BMUB, Version: 2019-III vom 29.05.2019

Baustoffangaben zur Konstruktion, Schichtaufbau

(von außen nach innen, Maße in mm)

Schicht	Deklar. Einheit	Baustoff / Schicht	Datensatz-ID (ÖKOBAUDAT)	Austausch (B4)	nawaro	Lebenszyklusphasen A1-A3	A4-A5	B1-B7	C1-C4	Potential Modul D
1	kg	Exterior Paint	fcf6494c-aad2-4180-b1a2-392cc954ae52	3		x	x	x		x
2	kg	Finishing Plaster Layer	ffcfca40-7a91-4cea-87f5-ff21c2a778df	1		x	x	x	x	x
3	kg	Base Plaster Layer	0bef1249-f998-491a-aa40-d7b2b7bc3dbd	1		x	x	x	x	x
4	m3	Mineral Wool Exterior Wall Insulation System	eca9691f-06d7-48a7-94a9-ea808e2d67e8	1		x	x	x	x	x
5	kg	Bonding Mortar	6124aaeb-24df-4d6a-86a6-549925aacc22	1		x	x	x	x	x
5	m3	Concrete C20/25	d9fd76f0-190d-437d-bb07-549963b32d65			x	x	x	x	x
	kg	Steel Reinforcement	e9ae96ee-ba8d-420d-9725-7c8abd06e082			x				
6	kg	Interior Gypsum Plaster	647835db-d887-4d74-8113-1d3ccf3aa1dd			x	x	x	x	x
	kg		56d90d2e-11c8-4b49-bc6c-c61f682d0be1						x	x
	kg		4a937f66-c9c2-402b-9a00-83767031bfa7						x	
	kg		b7cacb37-7945-4518-be5a-bf7df7edf5c2						x	

Ökologische Bewertung im Detail

Ökologische Bewertung der Umweltindikatoren

Lebenszyklus (Phasen)	**GWP** [kg CO_2 -äq.]	**AP** [kg SO_2 -äq.]	**EP** [kg PO_4 -äq.]	**ODP** [kg R11 -äq.]	**POCP** [kg Ethen-äq.]	**ADPE** [kg Sb-Äq.]	**ADPF** [MJ]
Herstellung A1-A3	77,600	0,192	0,027	6,24E-08	0,015	2,00E-04	564,47
Errichtung A4-A5	5,118	0,008	0,002	2,94E-11	-0,002	3,66E-07	30,55
Nutzung/Austausch B	30,283	0,122	0,014	4,50E-08	0,006	4,71E-05	290,32
Entsorgung C1-C4	4,988	0,019	0,004	3,97E-10	-0,001	9,91E-07	64,78
Lebenszyklus A/B/C	117,988	0,341	0,047	1,08E-07	0,018	2,48E-04	950,12

Ökologische Bewertung des Ressourceneinsatzes

Lebenszyklus (Phasen)	**PERE** [MJ]	**PENRE** [MJ]	**PERM** [MJ]	**PENRM** [MJ]	**PERT** [MJ]	**PENRT** [MJ]
Herstellung A1-A3	126,85	579,70	11,72	29,18	139,07	624,37
Errichtung A4-A5	11,50	25,63	-8,80	-4,38	3,32	31,58
Nutzung/Austausch B	38,77	261,39	2,92	23,87	42,81	310,32
Entsorgungsphase C	7,27	60,11	0,00	0,00	7,81	67,30
Lebenszyklus A/B/C	184,39	926,84	5,84	48,66	193,00	1033,56

Recyclingfähigkeit

Berechnung* der Stoff- und Abfallströme

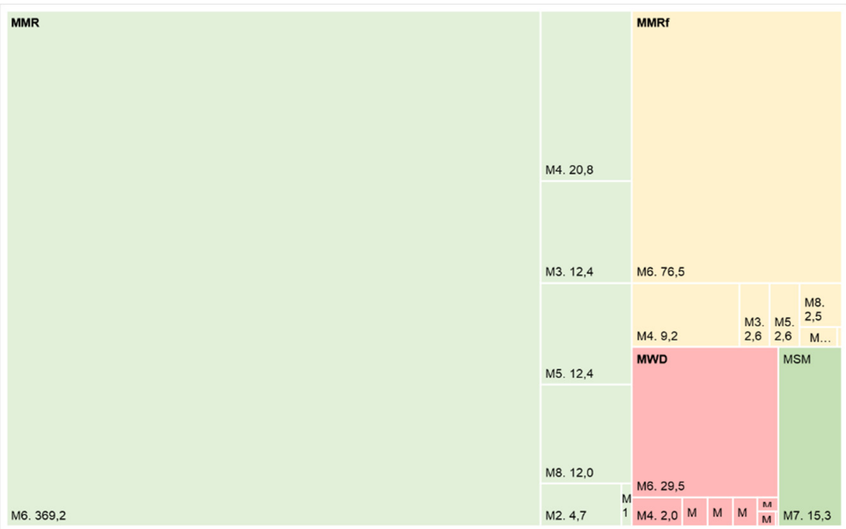
Berechnung mit Modellansatz aus dem Projekt DBU Ressourcennutzung Gebäude

Ressourcen und Recyclingfähigkeit
alle Werte bezogen auf 1 m² Konstruktionsfläche
Über den gesamten Lebenszyklus (cradle-to-gate m. Optionen):

			Masse		Anteil
Material zur ...	Wiederverwendung:	**MRU**	**0,0**	[kg]	**0,0%**
	gleichwertigen stofflichen Verwertung:	**MSM**	**15,3**	[kg]	**2,7%**
	minderwertigen stofflichen Verwertung:	**MMR**	**432,2**	[kg]	**74,9%**
	endgültigen stoflichen Verwertung:	**MMRf**	**94,5**	[kg]	**16,4%**
	endgültige energetischen Verwertung:	**MERf**	**0,0**	[kg]	**0,0%**
	Deponierung / therm. Beseitigung:	**MWD**	**35,2**	[kg]	**6,1%**
Bauteil:	Ausgangs-Eigengewicht des Bauteils:		**541,60**	[kg/m²]	
	Summe an Stoffströmen über den Lebenszyklus:		**577,18**	[kg/m²]	**107%**

Baustoffangaben zur Konstruktion, Schichtaufbau
(von außen nach innen, Maße in mm)

Schicht	Baustoff / Schicht	Masse m [kg]	Masse-% [%]	1 [kg]	2 [kg]	3 [kg]	4 [kg]	5 [kg]	6 [kg]
1	Exterior Paint	0,78	0%		0,00	0,61	0,13	0,00	0,05
2	Finishing Plaster Layer	6,00	1%		0,00	4,66	0,97	0,00	0,37
3	Base Plaster Layer	16,00	3%		0,00	12,43	2,58	0,00	0,99
4	Mineral Wool Exterior Wall Insulation System	32,00	6%		0,00	20,78	9,24	0,00	1,98
5	Bonding Mortar	16,00	3%		0,00	12,43	2,58	0,00	0,99
5	Concrete C20/25	475,20	82%		0,00	369,23	76,51	0,00	29,46
	Steel Reinforcement	15,70	3%		15,31	0,00	0,00	0,00	0,39
6	Interior Gypsum Plaster	15,50	3%		0,00	12,04	2,50	0,00	0,96
		577,18	100%	0,00	15,31	432,19	94,48	0,00	35,20
				0,0%	2,7%	74,9%	16,4%	0,0%	6,1%



Kostenrechnung

Berechnung* der Bauteilkosten

Abschätzende Berechnung anhand der BKI Baukosten

Kosten

alle Werte bezogen auf 1 m² Konstruktionsfläche

Herstellungskosten

Herstelllungskosten …	oberer Kostenwert:	bis <	**291,47 €**
	mittlerer Kostenwert:	Mittel Ø	**257,00 €**
	unterer Kostenwert:	> von	**227,87 €**

Kostenstand

1. Quartal 2019, Bundesdurchschnitt, inkl. 19% MwSt. **BKI** Baukosteninformationszentrum, Stuttgart

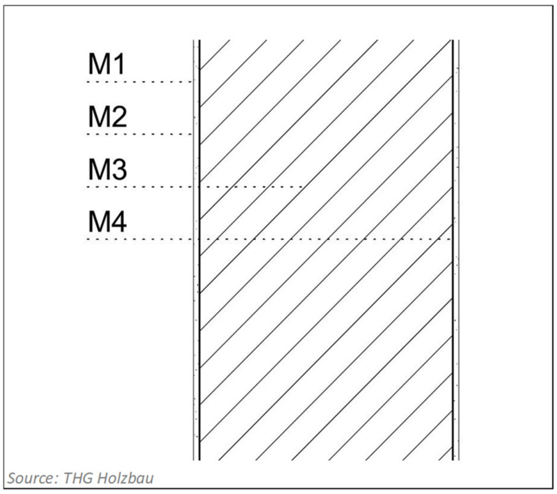
Baustoffangaben zur Konstruktion, Schichtaufbau

(von außen nach innen, Maße in mm)

Schicht	Baustoff / Schicht	Daten-Grundlage (BKI)	Faktor	Austausch	BKI-Nr.
1	Exterior Paint	Erstbeschichtung, Dispersions-Silikatfarbe, auf Außenputz	1,00	3,00	335.34.P21
2	Finishing Plaster Layer	WDVS Mineralischer Oberputz			335.23.P70
3	Base Plaster Layer	WDVS Armierungsputz, Glasfasereinlage			335.23.P63
4	Mineral Wool Exterior Wall Insulation System	WDVS, MF 035, d=180mm, mit Silikat-Reibeputz	0,90	0,90	335.23.P50
5	Bonding Mortar	WDVS, Dübelung, Wärmedämmung			335.23.P62
5	Concrete C20/25	Wand, Stahlbeton C25/30, d=20cm, mit Schalung	1,00		331.13.P33
	Steel Reinforcement	Bewehrung (Betonstahlmatten)	0,02		331.13.P115
6	Interior Gypsum Plaster	Innenputz, einlagig, Q3, geglättet	1,00		345.23.P26

Brick masonry wall with plaster facade: EW0p-pl_BM49

Monolithic brick masonry exterior wall with plaster facade | EW0p_BM



Parameters of Construction
all results are related to 1.0 m² of the building component

Fire Resistance:		*n/s*	
Thermal insulation:	U =	**0,16**	[W/m²K]
Noise insulation:	R_w =	*n/s*	[dB]
Thickness:	d=	**515,15**	[mm]
Mass:	m =	**337,92**	[kg/m²]
	g =	**3,31**	[kN/m²]
Stress resistance:	N_{Rd} =	**458,0**	[kN/m]

Layer [-]	[mm]	Building Material (description)	area-% b/e in [%]	thickness [mm]	V [m³]	ρ [1] [kg/m³]	m [kg]	λ [1] [W/mK]	R [m²K/W]	μ [1] [-]	V-% [%]	M-% [%]
außen									0,04			
1	0,2	Fassadenfarbe		0,2	0,000	1300,0	0,20				0,0%	0,1%
2	7,0	Oberputz/Leichtputz		7,0	0,007	1000,0	7,00	0,800	0,01		1,4%	2,1%
3	8,0	Unterputz		8,0	0,008	1550,0	12,40	0,800	0,01		1,6%	3,7%
4	490,0	Brick Masonry (insulation filing optional)	98,0%	490,0	0,480	600,0	288,12	0,080	6,13		93,2%	85,3%
		Brick Mortar (thin-bed)	2,0%	490,0	0,010	1500,0	14,70				1,9%	4,4%
5	10,0	Interior Plaster Layer		10,0	0,010	1550,0	15,50	0,800	0,01		1,9%	4,6%
innen					0,515 m³/m²		337,9 kg/m²		0,13		100%	100%

Dimensions of the Building Component

[m]		Area [m²]	Volume [m³]	Mass [kg/m²]	U-value [W/m²K]	R-value [m²K/W]
0,52	component's thickness	**1,00**	**0,515**	**337,9**	**0,16**	**6,33**
1,00	component's length					
1,00	component's height					

Annotations

[1] if specific information is missing: material information according to DIN EN ISO 10456:2010-05
[2] e.g. Poroton U8

Graphic: made by Marco Krechel
Source: THG-Holzbau
Examples: Mehr als Wohnen in Zürich, CH | Hofmeister, Sandra (Hg.) (2018): Wohnungsbau. Kostengünstige Modelle für die Zukunft. München: Detail, S.35ff
Drei Wohngebäude in Wien | www.baunetzwissen.de/mauerwerk/objekte/wohnen-mfh
Wohnblock Tetris in Berlin | www.baunetzwissen.de/mauerwerk/objekte/wohnen-mfh

Ökobilanzierung

Ökobilanzielle Berechnung* der Umweltauswirkungen und des Ressourceneinsatzes

Berechnung nach DIN EN 15804 & 15978 basierend auf DIN EN ISO 14040 & 14044

Umweltwirkungen
alle Werte bezogen auf 1 m² Konstruktionsfläche
Über den gesamten Lebenszyklus (cradle-to-gate m. Optionen):

Stoffliche Nutzung:	Verbaute Menge an nawaros:		**0,0**	[kg]	
Biogener Kohlenstoff:	Biogener Kohlenstoff in kg CO_2-äq.:		**0,0**	[kg CO_2]	
Energetische Nutzung:	Einsatz an Primärenergie:	**PEET**	**1266,67**	[MJ]	
(Benötigte Primärenergie)	davon Anteil erneuerbar:	**rs-PEET**	**13,61**	[%]	
Bauteil:	Bauteil Eigengewicht:		**325,91**	[kg/m²]	*Rohdichte gemäß ÖKOBAUDAT*
	Bauteildicke:		**515**	[mm]	
	Bauteilfläche:		**1,0**	[m²]	

Datenbank
ÖKOBAUDAT BMUB, Version: 2019-III vom 29.05.2019

Baustoffangaben zur Konstruktion, Schichtaufbau

(von außen nach innen, Maße in mm)

Schicht	Deklar. Einheit	Baustoff / Schicht	Datensatz-ID (ÖKOBAUDAT)	Austausch (B4)	nawaro	Lebenszyklusphasen A1-A3	A4-A5	B1-B7	C1-C4	Potential Modul D
1	kg	Fassadenfarbe	fcf6494c-aad2-4180-b1a2-392cc954ae52	3		x	x	x		x
2	kg	Oberputz/Leichtputz	ffcfca40-7a91-4cea-87f5-ff21c2a778df	1		x	x	x	x	x
3	kg	Unterputz	647835db-d887-4d74-8113-1d3ccf3aa1dd	1		x	x	x	x	x
4	m3	Brick Masonry (insulation filing optional)	8a7bcf84-f0a1-46fe-a146-4af9a182edfe			x	x	x	x	x
	kg	Brick Mortar (thin-bed)	41cf6418-c26f-4ef5-a04b-f6ea773941a0			x	x	x	x	x
5	kg	Interior Plaster Layer	647835db-d887-4d74-8113-1d3ccf3aa1dd			x	x	x	x	x
	kg		56d90d2e-11c8-4b49-bc6c-c61f682d0be1						x	x
	kg		4a937f66-c9c2-402b-9a00-83767031bfa7						x	
	kg		b7cacb37-7945-4518-be5a-bf7df7edf5c2						x	

Ökologische Bewertung im Detail

Ökologische Bewertung der Umweltindikatoren

Lebenszyklus (Phasen)	GWP [kg CO_2 -äq.]	AP [kg SO_2 -äq.]	EP [kg PO_4 -äq.]	ODP [kg R11 -äq.]	POCP [kg Ethen-äq.]	ADPE [kg Sb-Äq.]	ADPF [MJ]
Herstellung A1-A3	96,075	0,191	0,023	1,63E-08	0,014	8,84E-05	892,30
Errichtung A4-A5	8,082	0,016	0,004	4,80E-11	-0,006	2,77E-07	37,14
Nutzung/Austausch B	8,206	0,018	0,003	7,18E-09	0,000	4,83E-05	76,29
Entsorgung C1-C4	-2,243	0,020	0,004	5,74E-10	-0,002	1,46E-06	48,37
Lebenszyklus A/B/C	110,120	0,245	0,034	2,41E-08	0,006	1,38E-04	1054,10

Ökologische Bewertung des Ressourceneinsatzes

Lebenszyklus (Phasen)	PERE [MJ]	PENRE [MJ]	PERM [MJ]	PENRM [MJ]	PERT [MJ]	PENRT [MJ]
Herstellung A1-A3	157,24	954,52	0,00	1,67	157,24	956,20
Errichtung A4-A5	1,65	27,35	0,00	0,00	2,27	37,50
Nutzung/Austausch B	11,67	73,10	0,00	0,74	12,24	82,31
Entsorgungsphase C	1,85	39,28	0,00	0,00	2,60	49,43
Lebenszyklus A/B/C	172,42	1094,26	0,00	2,42	174,36	1125,44

Recyclingfähigkeit

Berechnung* der Stoff- und Abfallströme

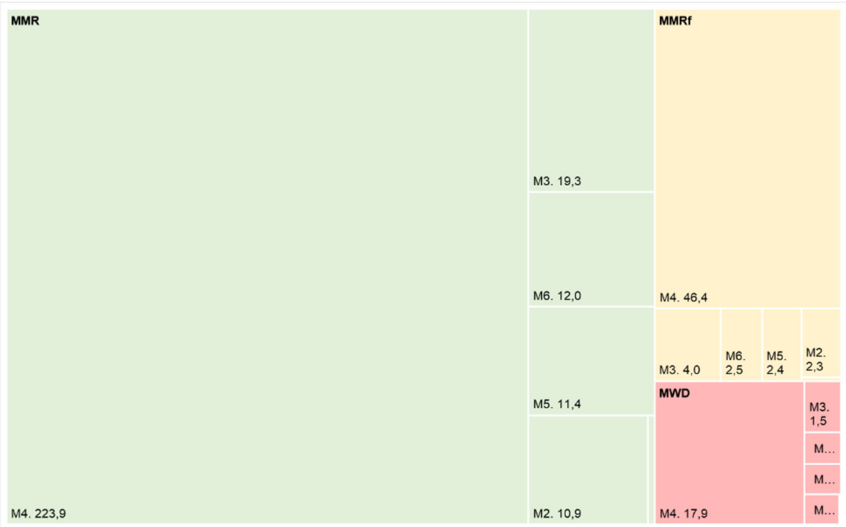
Berechnung mit Modellansatz aus dem Projekt DBU Ressourcennutzung Gebäude

Ressourcen und Recyclingfähigkeit
alle Werte bezogen auf 1 m² Konstruktionsfläche
Über den gesamten Lebenszyklus (cradle-to-gate m. Optionen):

			Masse		Anteil
Material zur ...	Wiederverwendung:	**MRU**	**0,0**	[kg]	**0,0%**
	gleichwertigen stofflichen Verwertung:	**MSM**	**0,0**	[kg]	**0,0%**
	minderwertigen stofflichen Verwertung:	**MMR**	**278,1**	[kg]	**77,7%**
	endgültigen stoflichen Verwertung:	**MMRf**	**57,6**	[kg]	**16,1%**
	endgültige energetischen Verwertung:	**MERf**	**0,0**	[kg]	**0,0%**
	Deponierung / therm. Beseitigung:	**MWD**	**22,2**	[kg]	**6,2%**
Bauteil:	Ausgangs-Eigengewicht des Bauteils:		**337,92**	[kg/m²]	
	Summe an Stoffströmen über den Lebenszyklus:		**357,90**	[kg/m²]	**106%**

Baustoffangaben zur Konstruktion, Schichtaufbau
(von außen nach innen, Maße in mm)

Schicht	Baustoff / Schicht	Masse m [kg]		Masse-% [%]	1 [kg]	2 [kg]	3 [kg]	4 [kg]	5 [kg]	6 [kg]
1	Fassadenfarbe	0,78	○	0%		0,00	0,61	0,13	0,00	0,05
2	Oberputz/Leichtputz	14,00	○	4%		0,00	10,88	2,25	0,00	0,87
3	Unterputz	24,80	○	7%		0,00	19,27	3,99	0,00	1,54
4	Brick Masonry (insulation filing optional)	288,12	●	81%		0,00	223,87	46,39	0,00	17,86
	Brick Mortar (thin-bed)	14,70	○	4%		0,00	11,42	2,37	0,00	0,91
5	Interior Plaster Layer	15,50	○	4%		0,00	12,04	2,50	0,00	0,96
		357,90		100%	0,00	0,00	278,09	57,62	0,00	22,19
					0,0%	0,0%	77,7%	16,1%	0,0%	6,2%



Kostenrechnung

Berechnung* der Bauteilkosten

Abschätzende Berechnung anhand der BKI Baukosten

Kosten
alle Werte bezogen auf 1 m² Konstruktionsfläche
Herstellungskosten

Herstelllungskosten …	oberer Kostenwert:	bis <	**256,30 €**
	mittlerer Kostenwert:	Mittel Ø	**237,95 €**
	unterer Kostenwert:	> von	**220,60 €**

Kostenstand
1. Quartal 2019, Bundesdurchschnitt, inkl. 19% MwSt. **BKI** Baukosteninformationszentrum, Stuttgart

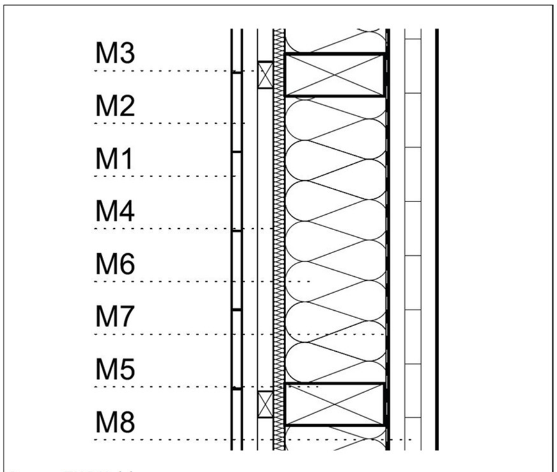
Baustoffangaben zur Konstruktion, Schichtaufbau

(von außen nach innen, Maße in mm)

Schicht	Baustoff / Schicht	Daten-Grundlage (BKI)	Faktor	Austausch	BKI-Nr.
1	Fassadenfarbe	Erstbeschichtung, Dispersions-Silikatfarbe, auf Außenputz	1,00	3,00	335.34.P21
2	Oberputz/Leichtputz	Außenputz zweilagig, Wand	1,00	1,00	335.23.P71
3	Unterputz				
4	Brick Masonry (insulation filing optional)	AW, LHlz 42,5cm,tragend, SFK 6, gefüllt	1,15		331.12.P68
	Brick Mortar (thin-bed)				
5	Interior Plaster Layer	Innenputz, einlagig, Q3, geglättet	1,00		345.23.P26

Solid timber wall with timber cladding: EW1t-vs_ST9.3_CE20

Single-Shell Exterior Wall with Solid Timber and Timber Cladding Facade | EW1t_ST



Source: THG Holzbau

Parameters of Construction

all results are related to 1.0 m² of the building component

Fire Resistance:		*n/s*	
Thermal insulation:	U =	**0,19**	[W/m²K]
Noise insulation:	R_w =	*n/s*	[dB]
Thickness:	d=	**395,15**	[mm]
Mass:	m =	**87,36**	[kg/m²]
	g =	**0,86**	[kN/m²]
Stress resistance:	N_{Rd} =	**473,8**	[kN/m]

Layer [-]	[mm]	Building Material (description)	area-% b/e in [%]	thickness [mm]	V [m³]	ρ [1] [kg/m³]	m [kg]	λ [1] [W/mK]	R [m²K/W]	μ [1] [-]	V-% [%]	M-% [%]
exterior									0,04			
1	20,0	Timber Cladding		20,0	0,020	500,0	10,00				5,9%	11,4%
2	30,0	Timber Battens (50, e=800)	6,3%	30,0	0,002	500,0	0,94				0,6%	1,1%
3	30,0	Timber Battens (50, e=625)	8,0%	30,0	0,002	500,0	1,20				0,7%	1,4%
4	22,0	Wood Fibre Insulation Board		22,0	0,022	173,0	3,81	0,045	0,49		6,5%	4,4%
5	200,0	Construction Timber (80/...; e=625)	12,8%	200,0	0,026	500,0	12,80	0,130	1,54		7,5%	14,7%
		Cellulose Cavity Insulation	87,2%	200,0	0,174	65,0	11,34	0,040	5,00		51,4%	13,0%
6	0,2	Vapour Retarder		0,2	0,000	1000,0	0,15				0,0%	0,2%
7	93,0	Solid Timber (e.g. CLT)		93,0	0,093	500,0	46,50	0,130	0,72		27,4%	53,2%
		Metal Joints, Screws, etc.	1,0%	8,0	0,000	7850,0	0,63				0,0%	0,7%
interior					0,340 m³/m²		87,4 kg/m²		0,13		100%	100%

Dimensions of the Building Component

[m]		Area [m²]	Volume [m³]	Mass [kg/m²]	U-value [W/m²K]	R-value [m²K/W]
0,40	component's thickness	**1,00**	**0,395**	**87,4**	**0,19**	**5,39**
1,00	component's length					
1,00	component's height					

Annotations

[1] if specific information is missing: material information according to DIN EN ISO 10456:2010-05

Graphic: made by Marco Krechel
Source: THG-Holzbau
Examples: Wohnungsbau Kalkbreite in Zürich | Schittich, Christian (Hg.) (2017): Urbanes Wohnen = Urban Housing. München: Detail (Best of Detail), S.88ff
Wohn- und Geschäftshaus c 13 | Kaufmann, Winter et al (2017): Atlas mehrgeschossiger Holzbau, S.170ff

Ökobilanzierung

Ökobilanzielle Berechnung* der Umweltauswirkungen und des Ressourceneinsatzes

Berechnung nach DIN EN 15804 & 15978 basierend auf DIN EN ISO 14040 & 14044

Umweltwirkungen
alle Werte bezogen auf 1 m² Konstruktionsfläche
Über den gesamten Lebenszyklus (cradle-to-gate m. Optionen):

Stoffliche Nutzung:	Verbaute Menge an nawaros:		**85,1**	[kg]	
Biogener Kohlenstoff:	Biogener Kohlenstoff in kg CO_2-äq.:		**121,6**	[kg CO_2]	
Energetische Nutzung:	Einsatz an Primärenergie:	**PEET**	**810,81**	[MJ]	
(Benötigte Primärenergie)	davon Anteil erneuerbar:	**rs-PEET**	**51,44**	[%]	
Bauteil:	Bauteil Eigengewicht:		**86,13**	[kg/m²]	*Rohdichte gemäß ÖKOBAUDAT*
	Bauteildicke:		**395**	[mm]	
	Bauteilfläche:		**1,0**	[m²]	

Datenbank
ÖKOBAUDAT BMUB, Version: 2019-III vom 29.05.2019

Baustoffangaben zur Konstruktion, Schichtaufbau

(von außen nach innen, Maße in mm)

Schicht	Deklar. Einheit	Baustoff / Schicht	Datensatz-ID (ÖKOBAUDAT)	Austausch (B4)	nawaro	Lebenszyklusphasen A1-A3	A4-A5	B1-B7	C1-C4	Potential Modul D
1	m3	Timber Cladding	2103d7e9-529e-45da-8549-892598dba5f3	1	x	x		x	x	x
2	m3	Timber Battens (50, e=800)	76c249ab-1481-4af8-9e98-39c3073eda6f	1	x	x		x	x	x
3	m3	Timber Battens (50, e=625)	76c249ab-1481-4af8-9e98-39c3073eda6f	1	x	x		x	x	x
4	m3	Wood Fibre Insulation Board	40b5bfc6-83b6-43e3-8852-567822c56729		x	x			x	x
5	m3	Construction Timber (80/...; e=625)	b6f81ab5-4055-4597-afae-b1462dcfc128		x	x			x	x
	m3	Cellulose Cavity Insulation	adbef3b8-9350-48e2-9f1c-e164793fcdd5		x	x			x	x
6	qm	Vapour Retarder	95a4f4b3-b354-4e2c-9046-0a36175cd768			x				
7	m3	Solid Timber (e.g. CLT)	954a286e-36e6-4ceb-9ab9-ec4270b618aa		x	x			x	x
	kg	Metal Joints, Screws, etc.	1b45f4e3-74c9-4d00-9a45-136ca36d37c8			x			x	x

Ökologische Bewertung im Detail

Ökologische Bewertung der Umweltindikatoren

Lebenszyklus (Phasen)	GWP [kg CO_2 -äq.]	AP [kg SO_2 -äq.]	EP [kg PO_4 -äq.]	ODP [kg R11 -äq.]	POCP [kg Ethen-äq.]	ADPE [kg Sb-Äq.]	ADPF [MJ]
Herstellung A1-A3	-109,620	0,098	0,020	1,13E-07	0,018	7,98E-04	348,55
Errichtung A4-A5	0,000	0,000	0,000	0,00E+00	0,000	0,00E+00	0,00
Nutzung/Austausch B	1,863	0,011	0,002	4,29E-09	0,002	2,32E-05	20,48
Entsorgung C1-C4	135,870	0,005	0,006	2,13E-08	0,001	9,34E-07	11,47
Lebenszyklus A/B/C	28,113	0,113	0,029	1,39E-07	0,021	8,22E-04	380,50

Ökologische Bewertung des Ressourceneinsatzes

Lebenszyklus (Phasen)	PERE [MJ]	PENRE [MJ]	PERM [MJ]	PENRM [MJ]	PERT [MJ]	PENRT [MJ]
Herstellung A1-A3	356,02	356,29	1402,38	39,27	1758,38	395,47
Errichtung A4-A5	0,00	0,00	0,00	0,00	0,00	0,00
Nutzung/Austausch B	57,34	23,67	0,00	0,00	57,34	23,67
Entsorgungsphase C	3,71	13,78	-1258,33	-12,75	-1189,50	6,62
Lebenszyklus A/B/C	417,07	393,74	144,05	26,52	626,22	425,76

Recyclingfähigkeit

Berechnung* der Stoff- und Abfallströme

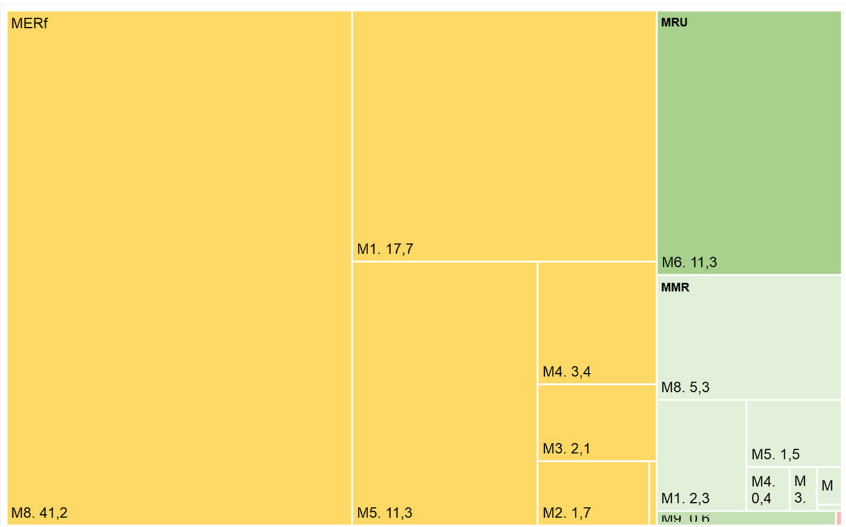
Berechnung mit Modellansatz aus dem Projekt DBU Ressourcennutzung Gebäude

Ressourcen und Recyclingfähigkeit
alle Werte bezogen auf 1 m² Konstruktionsfläche
Über den gesamten Lebenszyklus (cradle-to-gate m. Optionen):

			Masse		Anteil
Material zur ...	Wiederverwendung:	**MRU**	**11,3**	[kg]	**11,4%**
	gleichwertigen stofflichen Verwertung:	**MSM**	**0,6**	[kg]	**0,6%**
	minderwertigen stofflichen Verwertung:	**MMR**	**10,1**	[kg]	**10,1%**
	endgültigen stoflichen Verwertung:	**MMRf**	**0,0**	[kg]	**0,0%**
	endgültige energetischen Verwertung:	**MERf**	**77,4**	[kg]	**77,8%**
	Deponierung / therm. Beseitigung:	**MWD**	**0,0**	[kg]	**0,0%**
Bauteil:	Ausgangs-Eigengewicht des Bauteils:		**87,36**	[kg/m²]	
	Summe an Stoffströmen über den Lebenszyklus:		**99,50**	[kg/m²]	**114%**

Baustoffangaben zur Konstruktion, Schichtaufbau
(von außen nach innen, Maße in mm)

Schicht	Baustoff / Schicht	Masse m [kg]	Masse-% [%]	1 [kg]	2 [kg]	3 [kg]	4 [kg]	5 [kg]	6 [kg]
1	Timber Cladding	20,00	20%		0,00	2,30	0,00	17,70	0,00
2	Timber Battens (50, e=800)	1,88	2%		0,00	0,22	0,00	1,66	0,00
3	Timber Battens (50, e=625)	2,40	2%		0,00	0,28	0,00	2,12	0,00
4	Wood Fibre Insulation Board	3,81	4%		0,00	0,44	0,00	3,37	0,00
5	Construction Timber (80/...; e=625)	12,80	13%		0,00	1,47	0,00	11,33	0,00
	Cellulose Cavity Insulation	11,34	11%	11,34					
6	Vapour Retarder	0,15	0%		0,00	0,04	0,00	0,11	0,00
7	Solid Timber (e.g. CLT)	46,50	47%		0,00	5,35	0,00	41,15	0,00
	Metal Joints, Screws, etc.	0,63	1%		0,61	0,00	0,00	0,00	0,02
		99,50	100%	11,34	0,61	10,09	0,00	77,44	0,02
				11,4%	0,6%	10,1%	0,0%	77,8%	0,0%



Kostenrechnung

Berechnung* der Bauteilkosten

Abschätzende Berechnung anhand der BKI Baukosten

Kosten
alle Werte bezogen auf 1 m² Konstruktionsfläche
Herstellungskosten

Herstelllungskosten …	oberer Kostenwert:	bis <	**304,18 €**
	mittlerer Kostenwert:	Mittel Ø	**271,00 €**
	unterer Kostenwert:	> von	**247,74 €**

Kostenstand
1. Quartal 2019, Bundesdurchschnitt, inkl. 19% MwSt. **BKI** Baukosteninformationszentrum, Stuttgart

Baustoffangaben zur Konstruktion, Schichtaufbau
(von außen nach innen, Maße in mm)

Schicht	Baustoff / Schicht	Daten-Grundlage (BKI)	Faktor	Austausch	BKI-Nr.
1	Timber Cladding	Fassadenbekleidung, Holz-Stülpschlaung	1,00	1,00	335.38.P14
2	Timber Battens (50, e=800)	Unterkonstruktion, Holz, Lattung 30/50 od. 40/60	1,00	1,00	335.38.P01
3	Timber Battens (50, e=625)	Unterkonstruktion, Holz, Lattung 30/50 od. 40/60	1,00	1,00	335.38.P01
4	Wood Fibre Insulation Board	Dämmung Holzfaserplatte, d=80mm, N+F	1,00		364.16.P62
5	Construction Timber (80/…; e=625)	KVH Konstruktionsvollholz, MH, Nadelholz	0,03		361.16.P04
	Cellulose Cavity Insulation	Einblasdämmung, Zellulose, DZ, 180mm	1,10		363.16.P57
6	Vapour Retarder	Dampfbremse, feuchteadaptiv, sd-variabel	1,00		364.16.P47
7	Solid Timber (e.g. CLT)	BSH, Nadelholz, GL24h, Industriequalität	0,09		361.16.P06
	Metal Joints, Screws, etc.				