Enhancing the Sustainability Assessment: A Multi-Criteria Decision Making Framework for Assessing Building Elements

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Abstract

The building sector plays a significant role in environmental impacts, underscoring the importance of minimizing its negative effects. One strategy for reducing the environmental impact of buildings is by reducing the negative effects of the building's components through the selection of environmentally friendly building elements. However, this task is often complex, due to the involvement of various stakeholders with diverse areas of expertise and perspectives. In such cases, where numerous criteria need to be considered and various alternatives are to be evaluated, the complexity of decision-making increases. To address this challenge, this research proposes a multi-criteria decision-making framework (MCDM) to facilitate the selection process of the most sustainable ceiling for a project in Nuremberg, Germany. The Analytic Network Process (ANP) was the selected method in this thesis. The model assesses the sustainability of various ceiling options, including conventional reinforced concrete, solid wood concrete, wood-beam ceilings, and timber-concrete composite systems by considering the global warming potential, abiotic depletion potential (fossil and non-fossil), harmful emissions, share of renewable primary energy, thermal mass, circularity potential in the pre-use phase and in the post-Use phase as relevant sustainability parameters to assess sustainability at a building element level. Two variants are analyzed separately in the decision-making model: variant 1 assumes equal weighting for all criteria, while variant 2 prioritizes the GWP and Emissions cluster to align with the innovative and sustainable design principles of the research project. The results of the ANP model reveal that the board-stacked ceiling and the cross-laminated timber ceiling perform the best for both variants. Reinforced concrete shows the worst performance for both variants. The timber-concrete composite system demonstrates superior performance in variant 1 but performs poorly in variant 2. These findings highlight the importance of considering different weighting approaches and prioritizing specific criteria to properly use the ANP method. Furthermore, the application of the ANP in a case study revealed that defining interdependecies among sustainability criteria is still challenging. By utilizing the ANP methodology, this research contributes to the field of sustainable construction by providing a method to evaluate and select the most sustainable ceiling option. The results offer insights into the environmental performance of different ceiling structures and inform decision-making processes, facilitating the adoption of sustainable design practices in the building sector.

Kurzfassung

Die Baubranche hat eine erhebliche Auswirkung auf unsere Umwelt. Um die globalen Nachhaltigkeitsziele zu erreichen, ist es von großer Bedeutung, die Auswirkungen dieser Branche zu minimieren. Eine Strategie zur Reduzierung der Umweltauswirkungen von Gebäuden besteht darin, die Auswirkungen der einzelnen Bauteile durch die Auswahl umweltfreundlicher Bauteile zu verringern. Diese Aufgabe ist jedoch oft äußerst komplex, da verschiedene Projektbeteiligte mit unterschiedlichen Fachkenntnissen und Perspektiven in Bauprojekte involviert sind. In Projekten, in denen zahlreiche Kriterien berücksichtigt werden müssen und aus mehreren Alternativen die beste ausgewählt werden muss, steigt die Komplexivität des Entscheidungsprozess. Um dieser Herausforderung zu begegnen, schlägt die vorliegende Arbeit ein multikriterielles Modell (Multi-Criteria Decision Making - MCDM) vor, um die Nachhaltigkeit auf Bauteilebene von Bauprojekten zu bewerten und den Entscheidungsprozess zu unterstützen. Der Analytic Network Process (ANP) wurde als Methode gewählt, um die Nachhaltigkeit von Deckenkonstruktionen im Rahmen eines Forschungsprojekts zu bewerten. Sieben Deckenaufbauten wurden ausgewählt, darunter konventioneller Stahlbeton, Massivholzdecken, Holzbalkendecken und Holz-Beton-Verbundsysteme. Als relevante Nachhaltigkeitsparameter zur Bewertung auf Bauteilebene wurden die Kriterien des Globales Erwärmungspotenzials, Potenzial für den abiotischen Abbau (fossil & nicht fossil), Schadstoffe, Anteil erneuerbarer Primärenergie, thermische Masse und Kreislauffähigkeit (in der Pre-Use & Post-Use Phasen) ausgewählt. Zwei Varianten wurden im Rahmen dieser Arbeit analysiert: Variante 1 geht von einer gleichmäßigen Gewichtung aller Kriterien aus, während Variante 2 den GWP- und Emissionsclustern als Priorität setzt, um sie mit den innovativen und nachhaltigen Designprinzipien des Forschungsprojekts in Einklang zu bringen. Die Ergebnisse des ANP-Modells zeigen, dass die Massivholzdecken (Brettstapeldecke und Brettsperrholzdecke) in beiden Varianten am nachhaltigsten sind. Die konventionelle Stahlbetondecke zeigt die schlechteste Leistung im Modell für beide Varianten. Die Holz-Beton-Verbundsystemdecke zeigt in Variante 1 eine bessere Leistung als in Variante 2. Diese Ergebnisse verdeutlichen die Bedeutung verschiedener Gewichtungsansätze in dem Analytic Network Process. Durch den Einsatz der ANP-Methode leistet diese Forschung einen Beitrag zum Bereich des nachhaltigen Bauens, indem sie eine Methode zur Bewertung und Auswahl von nachhaltigen Bauteilen unterstützt. Die Ergebnisse bieten Einblicke in die Nachhaltigkeit verschiedener Deckenkonstruktionen und erleichtern die Einführung nachhaltiger Designpraktiken im Bausektor.

List of abbreviations

ADPe	Abiotic Depletion Potential of elements
ADPf	Abiotic Depletion Potential of fossil fuels
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CR	Consistency Ratio
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DIN	Deutsches Institut für Normung
EoL	End of Life
EPD	Environmental Product Declaration
GHG	Greenhouse Gas Emissions
GWP	Global Warming Potential
LCA	Life Cycle Assessments
LEED	Leadership in Energy and Environmental Design
MCDM	Multi-Criteria Decision Making
nZEB	Nearly zero-emission building
PERT/PET	Share of renewable primary energy
SDG	Sustainable Development Goals
UMI	Urban Mining Index
VOC	Volatile Organic Carbon

1. Introduction

1.1. Motivation

The building sector is one of the foremost contributors to environmental impacts. Statistics show that 26,1% of the final energy consumption (Klumbytė et al., 2021), 40% of all the greenhouse gas emissions (United Nations Environment Programme, 2021), 40% of material resource use (Heinrich & Lang, 2019), and 40% of the waste production (Heinrich & Lang, 2019) are associated nowadays with the construction and operation of buildings.

Significant for these impacts are not only new buildings but also the current and aged building's construction. Around 75 % of existing buildings do not comply with current standards, being considered inadequate and insufficient (Amorocho & Hartmann, 2022). Buildings have a substantial impact on material consumption, energy consumption, and emissions and have a lifespan that can last over 100 years. If planners and designers don't consider sustainability already in early project's phases, buildings can be associated for a long time with high energy demand, resource consumption and greenhouse gas emissions.

Many ways to facilitate the enhancement of sustainability in the building sector have been developed over the last years. Certification systems, such as the German rating system DGNB, the U.S. American system LEED, or the Japanese system CASBEE strengthen the relevance of sustainability at the building level, nonetheless in many cases only in advanced planning phases of the project. Eco-labels, such as Eurovent, Blauer Engel, or FSC/PEFC also augment sustainability, though at the material level. (Bruckner & Strohmeier, 2018)

Nevertheless, concerning sustainability in the early planning phases of projects is much more important, as it has more influence on the overall output of the building's sustainability (Balcomb & Curtner, 2000). Early identification of sustainable design strategies is crucial for creating future sustainable buildings (Balcomb & Curtner, 2000). However, how to design, and construct buildings with the goal of minimizing the environmental impacts is a challenging task. Many measures and fields of action play a role in this decision process. The prioritization of all possible actions is due to its complexity and interdependencies a demanding process - does the reduction of the primary energy demand, the reduction of greenhouse gas emissions or perhaps the increase of the circularity potential carry more advantages for a certain project? Considering these parameters, which design option would be the most appropriate selection from the numerous possibilities available in order to minimize the environmental impacts of buildings?

The multi-criteria decision making (MCDM) framework is a method that helps address this challenge and facilitate decision-making processes. MCDM is a method that promotes the ranking of the most beneficial and advantageous actions to be taken in a project. (Saaty & Vargas, 2001). Furthermore, it is particular beneficial for evaluating projects in cases where many fields of action and criteria play a role (Klumbytė et al., 2021), such as the interdisciplinary field of sustainability and building sector.

1.2. Goal definition and research questions

There are mainly three goals to be addressed in this thesis. Firstly, the thesis aims to provide a comprehensive overview of the criteria associated with environmental protection at the building element level. This involves identifying and analyzing the key parameters that contribute to the environmental impact of building elements. By examining the relevance of these parameters, a deeper understanding can be gained of their relevance in achieving environmentally friendly building elements.
Secondly, the thesis aims to provide an extensive overview of various MCDM methods used in the construction and sustainability sector. This includes reviewing the different methods utilized in decision making processes related to sustainability and building sector. By examining different publications regarding MCDM and sustainability in the building sector, valuable insights can be gained regarding their strengths, limitations, and suitability in the sustainability sector.
Both goals serve as basis for the main goal of this thesis, which is to investigate how environmental criteria can be evaluated in building elements using a multi-criteria decision making framework. This involves applying one specific MCDM method in a case study, allowing a comprehensive analysis of the results and providing insights to the current state-of-art. By achieving these goals, this research aims to augment sustainable practices in the building sector by facilitating decision making in this sector.

With this in mind, this work aims to answer three key research questions:

1. *What are the most relevant criteria for climate and environmental protection when evaluating building elements?*

2. *Which methods exist for the development of multi-criteria decision making frameworks, and which one is the most applicable when evaluating sustainable buildings?*

3. *How can building elements be evaluated with the help of this method?*

1.3. System boundaries

This thesis establishes three primary boundary conditions. Firstly, the focus is solely on the environmental and climate protection aspects of sustainability, disregarding the social and economic pillars. While sustainability includes all three pillars, this work limits its scope to the environmental dimension.
Secondly, the focus is placed exclusively on sustainability at the building element level. Consequently, criteria such as building water consumption or final energy demand are not included within the scope of this thesis. The attention is directed towards analyzing and addressing sustainability considerations that are specifically relevant to building elements.
Furthermore, this study takes a comprehensive approach by examining the entire lifecycle of building elements. This includes the environmental impacts linked with the production and construction phases (Phase A, Pre-Use), the continuous impacts during the

use phase of building materials (Phase B, Use), and the impacts related to the end-of-life phase (Phase C, D, Post-Use). By addressing the whole building element's lifecycle, the research provides a comprehensive understanding of the environmental impacts of building elements, contributing to the sustainable decision making processes throughout all lifecyle phases.

1.4. Methodology

This thesis can be divided into five main work phases, presented in the following Figure:

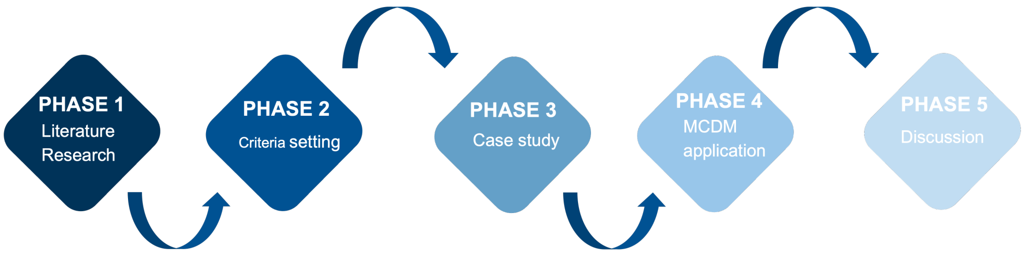


Figure 1 Work phases of the thesis

Phase 1: The basis of this thesis is a systematic comprehensive literature research on multi-criteria decision making methods in the building/sustainability sector and on criteria for environmental and climate protection in building elements. Here, different international and national rating systems, regulations, norms, guidelines, and publications on the topic are going to be deeply researched and the state of art of environmental criteria is going to be created. Furthermore, the researched state of the art is demonstrated and summarized in tabular form.

Phase 2: Based on the findings of phase 1, a limited number of criteria for environmental and climate protection of building elements are going to be selected. Furthermore, an appropriate method to apply the multi-criteria decision making framework at building element level is going to be selected.

Phase 3: In this phase, the application of the defined criteria on different ceiling structures of a research project in Germany. The research project is the new construction of a university building in the campus of the Technical University of Nuremberg in Bavaria, Germany. Exemplary ceiling structures of this project are going to be selected and each of the selected criteria is going to be individually assessed for each ceiling element.

Phase 4: To be able to measure which of the selected ceiling structures of the research project brings the most environmental benefits, a multi-criteria decision making framework is going to be developed with the selected criteria in phase 2. Core of this work is the development of a decision matrix, that serves to evaluate and prioritize the different ceiling structures. The basis for this development lies in the literature review on various multi-criteria decision making methods, enabling the identification and selection of the most suitable approach for the application. The calculations are going to be performed with the help of the software SuperDecisions.

Phase 5: The last phase concludes the work with a critical review and analysis of the results, limitations of the approach and future research recommendations on the topic.

The phases are again presented in form of a flow chart for better visualisation of the steps in this thesis.

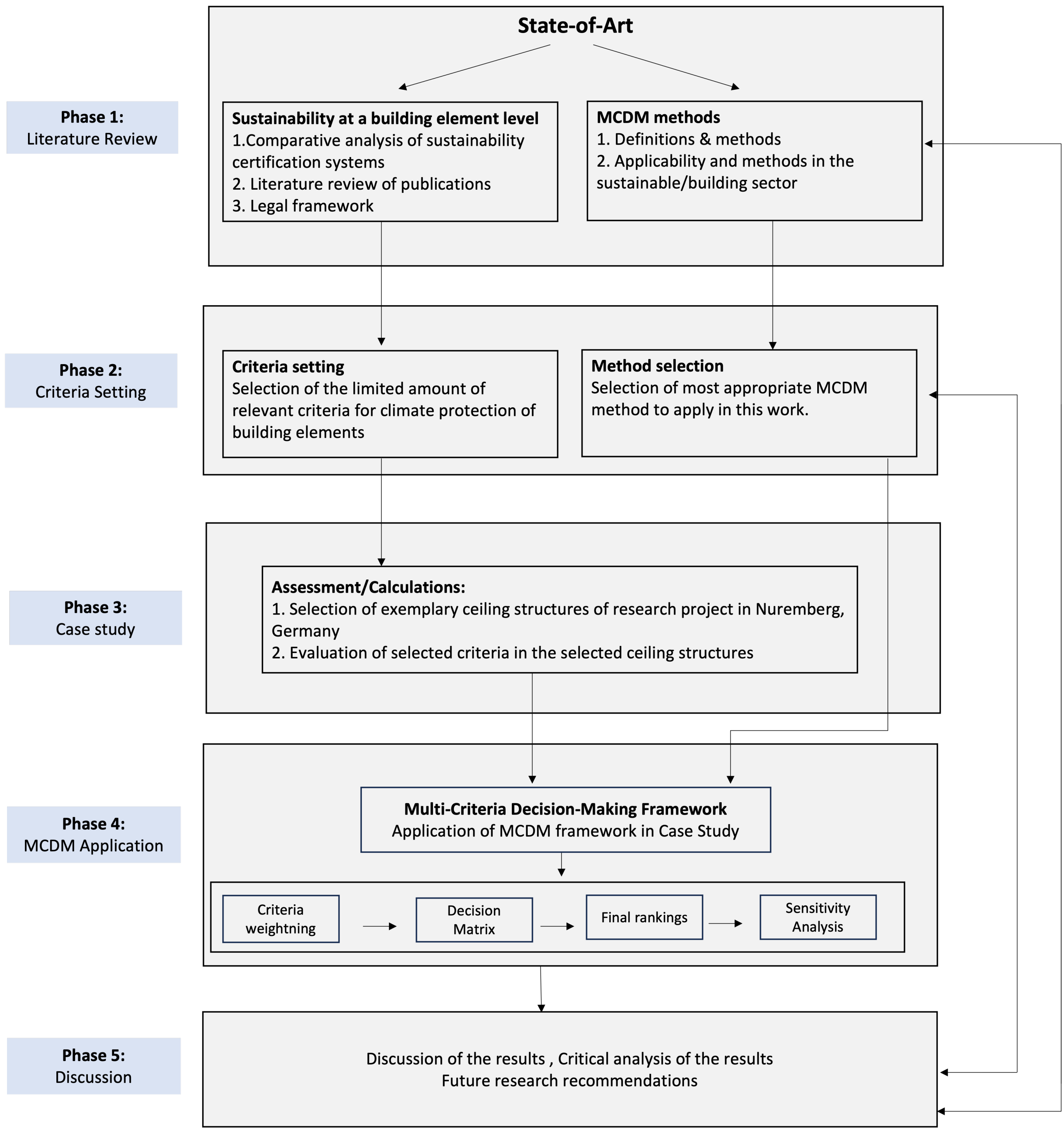


Figure 2 Flowchart of work phases of the thesis

2. State-of-art

This section provides a theoretical background for the following chapters. Section 2.1 provides an overview of the state-of-art in multi-criteria decision making and presents the connection between MCDM and the building and sustainability sector. While this study primarily examines sustainability at the building element level, Section 2.1 provides an extensive analysis of the various methods and applications of multi-criteria decision making (MCDM) frameworks within the broader context of sustainability. In Section 2.2 the state-of-art on environmental and climate protection criteria at a building element level is presented, presenting a comprehensive overview of the most relevant criteria for environmental protection in tabular form.

2.1. Basics of multi-criteria decision making

The multi-criteria decision making (MCDM) framework is a mathematical method utilized to address challenges that emerge when multiple actors with diverse expertise, perspectives, and preferences need to come to a final decision. Challenges can arise when multiple criteria are considered during decision making and when the task involves selecting the best solution from a range of alternatives. In those cases, one of the main challenges of the decision making is the presence of conflicting preferences and areas of expertise. Different stakeholders or project participants may have varying opinions, making it really complex to come to a final decision to select the most appropriate alternative for a certain decision.(Sangiorgio et al., 2022)

One further challenge of decision making emerges from the different assessment approaches that the criteria used in the decision making problem can have. Certain criteria can only be subjectively evaluated, while others can be measured numerically. This adds further complexity to the task of deciding the relative importance of parameters, complicating the selection of the optimal solution among various alternatives even more. (Sangiorgio et al., 2022)

One method to deal with this challenge and facilitate decision making is the multi-criteria decision making (MCDM) framework. Multi-criteria decision making is a mathematical method used to determine the optimal alternative among a set of alternatives. It is used in situations, where several criteria are simultaneously considered. MCDM integrate all possible options and actors of a decision in the calculation, being a method to solve complex decision making problems. (Saaty & Vargas, 2012)

Result of the MCDM is the identification of the best alternative among a set of options, in which a ranking of these alternatives is created (Saaty and Vargas, 2001; Sangiorgio et al., 2022). Furthermore, this method is especially suitable for sectors, where many participants contribute simultaneously in a project (Klumbytė et al., 2021). This is particularly applicable in the sustainability and building sector, as decision making in projects in this field often involves numerous stakeholders.

Multi-criteria decision making frameworks are capable to process both qualitative and quantitative criteria. Qualitative criteria are non-measurable factors, that are derived from

diverse social perspectives and the preferences of various stakeholders, such as the well-being and comfort of users. Quantitative criteria are measurable factors with quantifiable metrics like greenhouse gas emissions. This feature of the MCDM framework makes the method a really facilitator for decision makers, as it allows the simultaneous evaluation of criteria with diverse typologies and evaluation strategies. (Sangiorgio et al., 2022)
To better understand and assess MCDM frameworks, a three-level hierarchy is used as a simple and straightforward method for organizing a decision problem. The highest level involves the definition of the decision-making objective. The second level should include the criteria that will be analyzed in the decision making problem. Finally, the third level consists of the alternatives that will be evaluated based on the criteria defined in the second level. (Saaty & Vargas, 2001)

Sangiorgio et al., 2022 outlines following steps needed typically in multi-criteria decision making frameworks:

1. **Problem and goal definition:** decision makers have to define the problem clearly and establish a clear goal they want to achieve with the multi-criteria decision making framework.
2. **Identifying the alternatives:** alternatives for a decision solving need to be determined. Outcome of the MCDM framework is the selection of the best alternative among the established ones.
3. **Identifying criteria:** defining criteria, that are related to the goal of the problem and builds basis for the solving of the decision making problem.
4. **Performance of each alternative:** evaluating the performance of each alternative against each criteria to determine their importance in the decision making problem.
5. **Assigning local weights:** weighting of each criteria to calculate their importance in the decision making problem.
6. **Combining local weights and alternatives:** local weights have to be calculated with each of the alternatives to generate final weights of the alternatives.
7. **Examining the results**: critical analysis of the final weights and rankings.
8. **Sensitivity Analysis:** perform a sensitivity analysis of the results to better understand the final results.

2.1.1. Overview of classical multi-criteria decision making methods

There are two primary classifications of multi-criteria decision making: multi-attribute decision making (MADM) and multi-objective decision making (MODM) (Figure 3). MADM is applied in cases of a limited amount of criteria and alternatives, while MODM is more appropriate for dealing with decision making problems concerning infinite criteria and alternatives. Since this work involves a decision making problem with a limited number of criteria and alternatives, analysing MADM methods and applications is more appropriate. In the current state-of-art, MADM and MCDM (Multi-Criteria Decision Making) are considered the same.(Jorge-García and Estruch-Guitart, 2022; Zhu et al., 2021; Ogrodnik, 2019; Zavadskas et al., 2015)

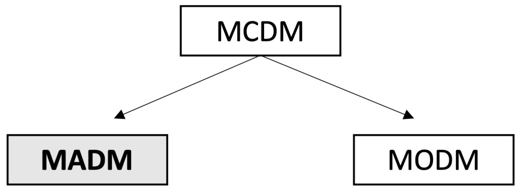


Figure 3 Classification of MCDM methods after Zavadskas et al., 2015

Various methods are available for developing multi-criteria decision making frameworks, each one being more appropriate at certain conditions, sectors and type of decision involved. Zhu et al., 2021 performs a systematic literature review of the most common MCDM methods in the construction sector, where 530 construction articles published between 2000-2019 on the topic of MCDM and construction were analysed. The study categorizes the MCDM methods into six main groups: multiple attribute utility (value) functions, pairwise comparison methods, distance (ratio) to reference point methods, outranking based MCDM methods, fuzzy set methods and their variants, and other MCDM methods (Zhu et al., 2021). Figure 4 provides an overview of these categories with diverse examples of methods in each category.

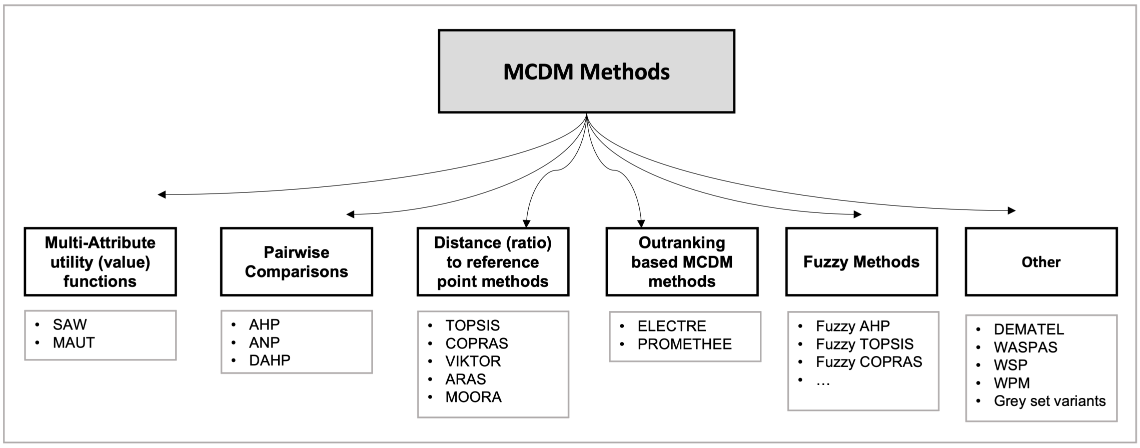


Figure 4 Overview of different MCDM methods (own elaboration)

In the category of multi-attribute utility values, common methods are the Simple Additive Weighting (SAW) and Multi-Attribute Utility Theory (MAUT). The principle behind this cat-

egory is that the preference of decision makers and the methods' calculation are based on utility/value functions. The methods in this category can deal with both quantitative and qualitative criteria and the methods assume, that the criteria in the decision making model are independent. Essential for the final evaluation of the alternatives in this category is the weighting of the criteria. (Zhu et al., 2021)
In the category of pairwise comparisons, the most reoccurring methods in the state-of-art are the *Analytic Hierarchy Process (AHP)* and the *Analytic Network Process (ANP)*. Both methods utilize pairwise comparisons to develop the priority of the criteria. The Analytic Hierarchy Process (AHP) simplifies complex problems by organising the decision problem in a hierarchy, where the goal, criteria, and alternatives are linearly connected. (Saaty and Vargas, 2001, Saaty and Vargas, 2012)
However, the method does not consider cases of interdependence between criteria and alternatives, thus this limits its effectiveness in solving real-world decisions in diverse sectors (Sangiorgio et al., 2022). Saaty and Vargas, 2006, p. 1 describes the Analytic Network Process (ANP) as "a generalization of the Analytic Hierarchy Process (AHP)", specifically created to handle the interdependencies among criteria in decision-making processes.
Distance (ratio) to reference point methods selects the best alternative by utilizing a function that calculates how distant one alternative is to a certain reference point. In this category, the criteria in the model are normalized to eliminate the different units present in the criteria. Furthermore, the weighting of the criteria can be done by various other methods, such as the pairwise comparison method utilized in the AHP and ANP (Zhu et al., 2021). The most used method in the building sector is TOPSIS (technique for order of preference by similarity to ideal solution)(Lindfors, 2021). This method calculates how distant each alternative is from the ideal and from the non-ideal reference point (Zhu et al., 2021). Other methods using this calculation method are the methods COPRAS, VIKTOR, ARAS, MOORA. (Zhu et al., 2021)
The key concept of outranking based MCDM methods is that a certain alternative can have a certain level of superiority over another alternative. In the building sector, the methods ELECTREE and PROMETHEE methods have been effectively applied (Lindfors, 2021). The method ELECTREE has also been intensively researched and developed. The ELECTRE family embraces many different types of methods, such as ELECTRE I,ELECTRE II,ELECTRE III, ELECTRE IV, ELECTRE TRI, ELECTRE TRI-C, and ELECTRE TRI-C-nC. PROMETHEE method also consists of a family of diverse methods. (Zhu et al., 2021)
Fuzzy methods in MCDM are used to handle situations where data is uncertain. Fuzzy AHP, Fuzzy TOPSIS, and Fuzzy VIKOR are some of the used fuzzy methods in MCDM. There are other methods, that do not fit in the above mentioned categories, such as DEMATEL and WASPAS, two methods commonly used in the building sector. Combining various MCDM methods is also a possible and common approach to enhance effectiveness and attain better results. This can be done by reinforcing methods by integrating them with others. For instance, combining the ANP with DEMATEL has proven to deliver effective results and has been applied in many publications in the state-of-art. Another example involves the combination of WASPAS with WSM and WPM.(Zhu et al., 2021)

2.1.2. Applications of multi-criteria decision making in building and sustainability sector

The use of multi-criteria decision making for the sustainability assessment of buildings has gained the attention of researchers already at the beginning of the century with publications such as Balcomb and Curtner, 2000. Nevertheless, great importance to the topic and its application to sustainability has been given only in recent years. Klumbytė et al., 2021 shows an overview of the research's development on the topic. Concerning the keywords "MCDM" and "Sustainability", the year 2016 encloses only 50 publications on the topic, while the year 2020 holds over 150 publications, revealing that the demand for this research had tripled over a period of four years. Another study of Mardani et al., 2015 shows, that 13,5% of the MCDM applications between the years 2000 and 2014 are in the field of energy, environment and sustainability, showing thus the relevance of MCDM frameworks in the sustainable building sector.

Multi-criteria decision making has been applied in many fields of the construction sector. In building projects, for example, the use of multi-criteria decision making can be applied in different phases of a project: design, construction, management, and dismantling phases. MCDM can be utilized during the design phase, for example, to select the best material supplier to be used in a project among a set of alternatives, and during the construction phase to assess and rank various construction strategies and practices. During management and commissioning of a project, MCDM can be utilized by facilitating and selecting the most appropriate maintenance activities throughout the building's service life or perhaps to select which green building certification system suits better for a certain project. In the dismantling phases, MCDM can enable and augment circularity in the building sector, by considering environmental and economic aspects in the design of the different EoL scenarios. (Sangiorgio et al., 2022)

In the field of sustainability, MCDM has been researched and applied in the selection of passive designs with publications such as Kuzman et al., 2013. In the field of low-carbon and energy-efficient constructions, publications such as Zavadskas et al., 2017 and Pana, 2015 analyse how multi-criteria decision making can be applied to design and achieve nearly zero-energy buildings (nZEB). The use of multi-criteria decision making framework has also been applied in the sustainable urban planing of cities and neighborhoods in publications such as Ogrodnik, 2017, Spina et al., 2019, Zinatizadeh, 2017, Masoumi and Genderen, 2019.
The growing number of laws and regulations addressing thermal and sustainability aspects of buildings (see Chapter 2.2.3) has led to an increased interest in utilizing multi-criteria decision making (MCDM) frameworks for evaluating building renovation options. Several publications, including Sioinytė et al., 2014, Seddiki et al., 2016, and Amorocho and Hartmann, 2022, have demonstrated the effectiveness in selecting the most suitable renovation options with the help of multi-criteria decision making. These studies highlight the importance of MCDM approaches to assess and prioritize diverse renovation alternatives.

Zavadskas et al., 2015 conducts a comprehensive analysis of 113 articles in the field of Civil Engineering, published between 1995 and 2015 in 32 different countries. The study concluded that the most frequently utilized methods in Civil Engineering were as follows: Analytic Hierarchy Process (AHP) with 37 publications, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) with 22 publications, Fuzzy sets with 14 publications, Elimination and Choice Expressing Reality (ELECTREE) with 13 publications, Analytic Network Process (ANP) with 8 publications, Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) with 7 publications, Complex Proportional Assessment (COPRAS) with 7 publications, and Weighted Aggregated Sum Product Assessment (WASPAS) with 6 publications. Building upon these findings, this thesis conducted a literature review on these methods and their application in the field of sustainability. Table 1 provides an overview of these methods along with an overview of the sustainability-related publications.
Further studies identifying the most relevant and appropriate application methods in the sustainability sector include Ogrodnik, 2019, Lindfors, 2021, Stojić et al., 2019 and Ziemba, 2022. Ogrodnik, 2019 performs an extensive literature review on the application of multi-criteria decision making methods in the field of Architecture, Urban Planing and Energy-Efficient Construction. The study shows several examples of publications applying different methods of MCDM in these fields, showing that the methods *AHP* (Analytic Hierarchy Process), *TOPSIS* (Technique for Order of Preference by Similarity to ideal solution), and *COPRAS* (complex proportional assessment) were the most used ones.
Another study of Lindfors, 2021 analyses the different applications of MCDM in the sustainability sector, showing that the *AHP* and different fuzzy methods were the most reoccurring methods in the sustainability sector, being applied in the fields of sustainable construction, energy systems, environmental protection and raw material extraction.
Furthermore, Stojić et al., 2019 performs a literature review between the year of 2008 and 2018, analysing the most applied MCDM methods in the field of Sustainability Engineering. As a result of the study, the *AHP* method was also found to be the most frequently applied in civil engineering. The study also highlights that, when applying MCDM methods in the construction sector, it is common to merge the AHP methods with other different methods or with other theories, such as fuzzy or grey theories.
The study conducted by Ziemba, 2022 gives valuable insights for this work.The research focused to analysis how different MCDA methods can solve decision-making problems related to sustainability.The study shows similar results, revealing that the AHP method was the most utilized method in the sustainability sector, accounting for nearly 30% of the analyzed publications.The study also highlights the methods WAM/SAW, TOPSIS, VIKOR as commonly used methods to assess decisions in the sustainability sector and also the increasing interest in fuzzy sets in assessing sustainability-related decisions nowadays.

Table 1 Overview of the sustainability-related publication on MCDM methods (own elaboration)

Method	Methods' name	Sustainability-related publications
AHP	Analytic Hierarchy Processs	Sangiorgio et al., 2022, Erdogan et al., 2019, Kuzman et al., 2013, Yang et al., 2010,Sioinytė and Antucheviienė, 2013, Guzmán-Sánchez et al., 2018, Moghtadernejad et al., 2018, Jalilzadehazhari et al., 2019, Sioinytė et al., 2014, Sánchez-Garrido et al., 2021
ANP	Analytic Network Process	Khoshnava et al., 2018, Mahmoudkelaye et al., 2018, Xu et al., 2015, Jayakrishna et al., 2015, Deniz, 2017, Spina et al., 2019
TOPSIS	Technique for order preference by similarity to an ideal solution	Amorocho and Hartmann, 2022, Escrig-Olmedo et al., 2017, Sioinytė and Antucheviienė, 2013, Zavadskas et al., 2013, Guzmán-Sánchez et al., 2018 Moghtadernejad et al., 2018, Beltrán and Martínez-Gómez, 2019, Sedláková et al., 2015, Sánchez-Garrido et al., 2021
COPRAS	Complex proportional assessment	Klumbytė et al., 2021, Sioinytė and Antucheviienė, 2013, Zolfani et al., 2017, Motuzienė et al., 2016, Sánchez-Garrido et al., 2021
ELECTRE	Elimination et coix traduisant la realité	Cinelli et al., 2014, Li et al., 2021
PROMETHEE	Preference ranking organization method for enrichment evaluation	Seddiki et al., 2016, Vujoević and Popovic, 2016, Cinelli et al., 2014
WASPAS	Weighted aggregated sum product assessment	Klumbytė et al., 2021, Zavadskas et al., 2013, Zavadskas et al., 2017, Sioinytė and Antucheviienė, 2013, Medineckienė and Diugaitė-Tumėnienė, 2014

2.2. Environmental criteria for evaluating building elements

This chapter aims on giving an overview of the state-of-art on environmental criteria at a building element level. This chapter serves as the foundation for selecting the appropriate criteria in Chapter 4.

2.2.1. Analysis framework

To evaluate the current state of the art regarding environmental criteria at a building element level, the following components will be examined: certification systems, relevant publications, and a review of the legal framework related to the topic.

Firstly, this work selected five national certification systems in the field of sustainability to perform a comparative analysis. The analysis focused only on five certification systems, allowing a deep examination of their content. The systems selected were the British BREEAM (BREEAM, 2018), the US LEED system (USGBC, 2013), the German DGNB system (DGNB, 2018), the Australian Green Star (also utilized in New Zealand and South Africa) (GBCA, 2019), and the Japanese CASBEE (IBEC, 2020). The selection of these certification systems was influenced by diverse factors, including their many version updates, the quantity of certified projects and citations, and their global presence, as presented in Table 2.

Table 2 Comparative data on certification systems after Polli, Biju, et al., 2022

Certification system	Country	Number of projects 2022	Number of citations 2022
BREEAM	UK	> 594.000	101
LEED	USA	> 131.000	614
DGNB	Germany	1889	21
Green Star	Australia	828	89
CASBEE	Japan	530	34

Furthermore, also part of the literature research was the analysis of relevant publications in the field of sustainability at a building element level. To ensure a comprehensive and extensive literature search on publications, the following databases were used in the research: Web of Science, Scopus, Research Gate, OPAC, and Google Scholar.

The time frame used in the literature search was set between 2014 and 2023, allowing an appropriate time frame to obtain recent developments in the field of environmental and climate protection criteria at the building element level.

To find relevant publications, a set of keywords was utilized. The selected keywords were: *sustainability building materials, building sustainable assessment, cradle-to-cradle, impact categories, low-emission building materials,low-carbon construction, energy-efficient materials and climate protection.*

Certain inclusion and exclusion criteria were applied during the literature selection process. Inclusion criteria involved selecting publications that specifically addressed the

criteria for environmental and climate protection at a building element level. Non-English/ non-German articles were excluded unless they contained an English abstract providing sufficient information for the understanding of the results.
The identified publications were analyzed aiming on extracting pertinent criteria related to the research topic.

In the field of laws, norms, and regulations, the literature research was focused rather on European norms and standards. Reason for that is the large number of different standards and guidelines worldwide and at the same time the limited available time planed for the literature review, since it is not the main focus of this thesis. Furthermore, rating systems also contain a strong background on national laws, standards, and guidelines (Ali-Toudert et al., 2020). Therefore, analysing certification systems from different regions around the world, such as Australia and Japan, embraces also – indirectly – the analysis of different regulations and norms of those countries. Thirdly, the project to be considered in this thesis is in Germany and therefore the relevance to German and European standards is significantly higher for this work.

2.2.2. Sustainability criteria at building element level

This section provides an overview of the findings derived from the comparative analysis of the certification systems and publications. Section 2.2.3 describes the legal framework of the criteria for environmental protection.
Tables 3 - 5 provide an overview of the criteria identified through the literature review. The findings of the extensive literature research were categorized into four main groups: Emissions, Energy, Resources, and Materials. The tables present the identified criteria, the corresponding publications, and their presence in certification systems. The certification systems were represented with the help of the following color scale:

DGNB	LEED	BREEAM	CASBEE	GreenStar
■ (yellow)	■ (light grey)	■ (blue)	■ (orange)	■ (green)

The block Emissions includes criteria related to the release of pollutants, greenhouse gases, and other harmful emissions during the life cycle of building elements.The most significant criterion identified across various publications and certification systems is greenhouse gas (GHG) emissions. It is consistently considered in the analysis of all certification systems, carrying a weight of 40% in the Life Cycle Assessment after the German rating system (DGNB, 2018). Additionally, indoor pollutants (such as VOCs, formaldehyd, biocides) and sound emissions emerged as highly relevant topics in the literature research, being confirmed by the presence of these topics in all certification systems. Although not explicitly addressed in certification systems, ecological and human toxicity, particulate matter formation and radioactivity of building materials were also observed as relevant in the literature.

The Energy block focuses on criteria associated with energy consumption and efficiency during the different life cycle phases of building elements. This includes factors such as the primary energy demand and the embodied energy of construction materials. Within the field of the building envelope, specific thermal parameters hold significant importance in designing energy-efficient building structures. Parameters such as air tightness, heat transfer coefficient, thermal conductivity, heat protection, U-values, and R-values are important energy-related parameters found in many certification systems. The thermal passive design of building elements was also found to be an effective strategy to ensure the energy-efficient design of building elements.

The Materials block includes criteria related to processed building materials and their environmental impacts throughout the entire lifecycle of building materials. This involves evaluating the processed materials and considering criteria that pertain to the pre-Use, Use and post-Use phase of these building elements. The pre-use phase embraces criteria such as the use of secondary or renewable raw materials. Additionally, the block includes criteria such as material regionality (which is closely related to greenhouse gas emissions resulting from material transportation (USGBC, 2013)) and responsible sourcing (which addresses impacts such as groundwater contamination and biodiversity loss). The use-phase includes for example materials' durability and maintainability. The end-of-life (EoL) stage of materials is also considered within this block, covering aspects such as the ease of deconstruction of processed building materials, as well as material recyclability, reusability, and other EoL scenarios associated with these processed materials.

The Resources block addresses criteria related to the conservation of natural resources, aiming on avoiding deteriorating primary raw resources, such as water and soil. This involves water consumption, metal depletion and resource consumption of fossil fuels and non-fossil fuels resources. Other impacts categories, such as eutrophication potential, acidification potential, photochemical ozone creation potential were also identified as relevant in mitigating the environmental impacts at a building element level.

2.2.3. Reference to sustainability-related legislation

At a global scale, the United Nations' 2030 Sustainable Development Goals (SDGs) established high-level goals to achieving sustainability. Omer and Noguchi, 2020 analyses to which extent green buildings' materials contribute to achieving the goals of the Agenda 2030. Table 6 illustrates the potential of the building sector, specifically at a building element level, to help achieve the UN Sustainable Development Goals (SDGs).

The Paris Agreement holds immense importance as an environmental milestone nowadays. By setting limits on the global average temperature rise to maximal 1.5 or 2 degrees Celsius, the Paris Agreement plays an essential role in combating climate change nowadays. To attain this objective, it becomes crucial to limit the greenhouse gas emissions. Considering that the building sector contributes significantly to greenhouse gas emissions, this sector bears a great responsibility in achieving the goals presented in the

Table 3 Emissions Category

Emissions		
Criteria	**Publications**	**Certification system**
Greenhouse gas emissions	Huang et al., 2020, Krídlová-Burdová and Vileková, 2012, Sabnis and Pranesh, 2017, Omer and Noguchi, 2020,Zari, 2019, Thiel et al., 2013, Attia, 2016, Kröhnert et al., 2022, Alptekin and Çelebi, 2018, Huang et al., 2018,Theilig et al., 2021, Kamali and Hewage, 2015,Theilig and Lang, 2022, Heinrich and Lang, 2019, Brambilla et al., 2019	
Indoor pollutants	Omer and Noguchi, 2020, Zari, 2019, Thiel et al., 2013, Jang et al., 2022,Rodrigo-Bravo et al., 2022, Rodrigo-Bravo et al., 2022,Alptekin and Çelebi, 2018,Theilig et al., 2021,Kamali and Hewage, 2015,Theilig and Lang, 2022,Heinrich and Lang, 2019	
Sound emissions	Theilig et al., 2021, Theilig and Lang, 2022,Heinrich and Lang, 2019	
Particulate matter formation	Huang et al., 2020, Jang et al., 2022, Kröhnert et al., 2022, Huang et al., 2018	-
Radioactivity of building materials	Krídlová-Burdová and Vileková, 2012, Theilig et al., 2021	-
Ecological toxicity	Huang et al., 2020,Zari, 2019, Thiel et al., 2013, Kröhnert et al., 2022, Alptekin and Çelebi, 2018, Huang et al., 2018	-
Human toxicity	Huang et al., 2020, Thiel et al., 2013, Jang et al., 2022, Huang et al., 2018	-

Resources		
Criteria	**Publications**	**Certification system**
Water consumption	Zari, 2019, Thiel et al., 2013, Rodrigo-Bravo et al., 2022, Alptekin and Çelebi, 2018, Kamali and Hewage, 2015	
Resource consumption (fossil and non-fossil)	Huang et al., 2020, Jang et al., 2022, Rodrigo-Bravo et al., 2022, Alptekin and Çelebi, 2018, Huang et al., 2018,Brambilla et al., 2019	
Metal depletion	Huang et al., 2020, Rodrigo-Bravo et al., 2022, Kröhnert et al., 2022, Huang et al., 2018,Brambilla et al., 2019	-
Acidification, Ozone depletion, Eutrophication	Krídlová-Burdová and Vileková, 2012, Thiel et al., 2013, Jang et al., 2022,Rodrigo-Bravo et al., 2022, Alptekin and Çelebi, 2018,Huang et al., 2020, Jang et al., 2022, Huang et al., 2018	

Energy		
Criteria	**Publications**	**Certification system**
Primary Energy Demand	Huang et al., 2020, Sabnis and Pranesh, 2017, Krídlová-Burdová and Vileková, 2012, Omer and Noguchi, 2020, İzzet Yüksek, 2015, Thiel et al., 2013, Attia, 2016, Rodrigo-Bravo et al., 2022, Kröhnert et al., 2022, Kamali and Hewage, 2015, Heinrich and Lang, 2019,Brambilla et al., 2019	
Thermal Passive Design (Thermal Mass)	Heinrich and Lang, 2019, Hussein et al., 2021, Sharaf, 2020, Kamal and Arabia, 2011	
Embodied energy	Krídlová-Burdová and Vileková, 2012, Omer and Noguchi, 2020, Zari, 2019, Kröhnert et al., 2022, Kamali and Hewage, 2015, Heinrich and Lang, 2019,Cottafava and Ritzen, 2021	-
Building envelope parameters	Heinrich and Lang, 2019	

Table 5 Material Category

Materials		
Criteria	**Publications**	**Certification system**
Recycled/recovered content	Krídlová-Burdová and Vileková, 2012, İzzet Yüksek, 2015, Zari, 2019,Heinrich and Lang, 2019,Adams et al., 2017,Eberhardt et al., 2020, Campbell, 2019,Eberhardt et al., 2018,Cottafava and Ritzen, 2021,Mhatre et al., 2021,Eberhardt et al., 2021	
Virgin/Renewable raw materials	İzzet Yüksek, 2015, Kamali and Hewage, 2015, Campbell, 2019,Cottafava and Ritzen, 2021,Eberhardt et al., 2021	
Material Regionality	Krídlová-Burdová and Vileková, 2012, Omer and Noguchi, 2020, İzzet Yüksek, 2015, Kamali and Hewage, 2015,Campbell, 2019	
Responsible sourcing	Omer and Noguchi, 2020, Heinrich and Lang, 2019	
Materials' Durability	Omer and Noguchi, 2020, İzzet Yüksek, 2015, Heinrich and Lang, 2019, Eberhardt et al., 2020,Campbell, 2019,Mhatre et al., 2021,Eberhardt et al., 2021	
Maintainability	Adams et al., 2017, Eberhardt et al., 2020,Campbell, 2019,Mhatre et al., 2021	
Reusability/Recyclability	Zari, 2019, Rodrigo-Bravo et al., 2022,Heinrich and Lang, 2019, Adams et al., 2017, Eberhardt et al., 2020,Campbell, 2019,Eberhardt et al., 2018,Cottafava and Ritzen, 2021,Eberhardt et al., 2021	
Ease of deconstruction	Heinrich and Lang, 2019, Adams et al., 2017, Eberhardt et al., 2020,Eberhardt et al., 2018,Cottafava and Ritzen, 2021	
Other EoL scenarios > Upcycling, Downcycling, Biodegrab. Energy recov.	Zari, 2019, Eberhardt et al., 2020, Campbell, 2019,Eberhardt et al., 2018,Mhatre et al., 2021	

Table 6 Contribution of the building sector on achieving the SDGs (own elaboration after (Omer & Noguchi, 2020))

SDG	Name	Building sector contribution	Criteria
	SDG3: Good health and well-being	Elimination of toxic chemicals in materials	Indoor pollutants
	SDG7: Affordable and clean energy	Choosing building materials that rely on renewable energy sources	Primary Energy Demand
	SDG12: Responsible consumption and production	Enhance and embrace materials' circularity	Circularity Potential
	SDG13: Climate Action	Reduction of greenhouse gas emissions associated with building elements	Greenhouse gas emissions
	SGD15: Life on Land	Responsibly sourced materials reduced use of water, and conservation of biodiversity	Resource consumption

Paris Agreement. (Theilig and Lang, 2022;UNFCCC, n.d.)
The European Union's Green Deal has also the reduction of greenhouse gas emissions as one of its main goals. The ambition here is of achieving net-zero emissions by the year of 2050. Specially in the building sector, buildings must eliminate carbon emissions associated with fossil fuels and non renewable energy production to help achieve this goal.(Theilig & Lang, 2022)
Also at a European level, the framework called LEVEL(S) is of great relevance nowadays to establish sustainability in the building sector. This framework, established by the European Commission, provides guidance for achieving sustainable buildings within the European Union. It includes various parameters necessary for evaluating and promoting buildings sustainability. Key aspects considered in this framework at a building element level include *greenhouse gas emissions, the share of primary energy demand, circularity of materials (including construction materials and end-of-life scenarios), and indoor air quality.* (European Commission, 2017)
At the national level, the German legislation known as Klimaschutzgesetz (KSG) establishes a target to reduce greenhouse gas emissions by a minimum of 65% in 2030 compared to the baseline year of 1990.("Bundes-Klimaschutzgesetz", 2019; Theilig and Lang, 2022). Germany has implemented the Gebäudeenergiegesetz (GEG), a federal law aimed at promoting energy efficiency in buildings and at embracing the use of renewable energy sources in the building sector (Theilig & Lang, 2022).
Other forms to promote and augment sustainability at a building level are incentives provided by the German state, such as the QNG (Qualitätssiegel Nachhaltiges Gebäude). For a building to become this incentive, some benchmarks have to be fullfilled. The limitation of greenhouse gas emissions and of nonrenewable primary energy are keys parameters for the funding. Also of great importance is the exclusion of materials pollu-

tants in building elements and the environmental impacts caused in the EoL scenarios. (Bundesministerium des Innern, für Bau und Heimat, n.d.-b)
The circular economy action plan strives to minimize waste and optimize resource utilization by augmenting the circularity in many different sectors. Among the many objectives of this plan, the integration of recycled materials as well as the durability, reusability, and reparability of materials can be applied in the building sector at a building element level. Furthermore the circular economy action plan aims to increase the energy and resource efficiency, address harmful substance of materials as well to reduce the carbon emissions with material production and consumption. (European Commission, 2020)
In addition, the Waste Framework Directive plays a crucial role in providing a legal framework for waste management in the European Union, aiming to protect the environment from the environmental impacts from waste generation. Given that the building sector is currently one of the major contributors to waste production (Heinrich & Lang, 2019), setting target goals becomes essential in transitioning towards to a more circular economy. This directive establishes a waste hierarchy that prioritizes waste prevention, material reusability, recyclability, and recoverability as preferred approaches to waste management. (European Commission, n.d.)
The field of indoor pollutants also embraces many laws and regulations such as: europäischen Chemikalienverordnung REACH, Europäische BiozidRichtlinie und Biozid-Verordnung, europäische DecopaintRichtlinie 2004/42/EG, showing the relevance of this parameter in achieving sustainable building materials. (Umweltbundesamt, n.d.)

Considering these regulations, the current legal framework highlights a set of parameters that hold significant relevance. These parameters are greenhouse gas emissions, primary energy demand, indoor pollutants, and circularity of building materials. These criteria are essential in effectively mitigating the environmental impacts emerging from building elements, being therefore also essential for achieving the goals and national laws in Germany.

3. Fundamentals of the Analytic Network Process (ANP)

This chapter provides an explanation for selecting the Analytic Network Process as the multi-criteria decision making (MCDM) method in this work. Additionally, the fundamental concepts of the ANP method are outlined, providing a solid foundation for its application and understanding in this study in Chapter 4.

3.1. Key elements of ANP

The main goal of the development of the multi-criteria decision making framework in this work is to evaluate and rank the different ceiling elements of the a project regarding sustainability. For this, the most appropriate MCDM method has to be firstly selected. The basis for the choice of the multi-criteria decision making method lies in Section 2.1, where many methods and approaches to develop multi-criteria decision making were researched.

The findings of the studies shown in Section 2.1.2 demonstrate the suitability of the Analytic Hierarchy Process (AHP) as a method for application in this research. Studies have proven that the Analytic Hierarchy Process was the most used method when applying multi-criteria decision making frameworks in the building and sustainability sector. The AHP consists of mainly three elements: goal, criteria and alternatives, being structured in a hierarchy (see Figure 5 (left)). The Analytic Hierarchy Process (AHP) assumes, however, that the criteria present in the model are independent and thus have no interaction with each other. (Saaty and Vargas, 2001;Saaty and Vargas, 2006; Saaty and Vargas, 2012)

In the context of sustainability, it is possible that the criteria may have interdependencies, thus applying the AHP in this work would be inappropriate. While the study of Ziemba, 2022 also identifies the AHP as the most commonly used method in the sustainability sector, the study also raises concerns about its application in cases where sustainability criteria are interconnected. The study highlights that the AHP may not always be the most appropriate method in such scenarios. In such cases, where criteria in the model are correlated, the weighting with the AHP would be lead to an overvaluation of the alternatives, and the model would not show reliable and realistic results (Ishizaka & Nemery, 2013).

To deal with this problematic in the sustainability sector and to model the interdependencies among criteria in the decision making problem, the Analytic Network Process (ANP) is a solution. It is a generalization of the AHP, where criteria interdependencies are considered, and therefore showing more accurate and reliable results, that are closer to reality in the field of the sustainability sector. (Ishizaka and Nemery, 2013;Saaty and Vargas, 2006)

On the one hand, the AHP consists of a linear structure, where defined elements are structured into levels/hierarchies (Figure 5 left). The goal, being the highest hierarchy in

the decision making problem is directly connected to the criteria, which again are correlated to the different alternatives to be considered in the model. On the other hand, the ANP assesses the criteria and alternatives not in a hierarchy anymore, but in a network structure. The different elements of the decision making can have interdependencies, building therefore a network structure of elements and interconnections.(Ishizaka & Nemery, 2013)
The ANP consists of mainly two key elements: clusters and nodes. One cluster can be defined as a “parent classification” of a group of nodes and the nodes represent the different elements of the decision making problem (criteria and alternatives). The criteria and the alternatives are compared to each other at the same level. Figure 5 (right) shows an exemplary network structure in the ANP model. In this case the model consists of five clusters. Cluster C1 consists of four nodes and C2 consists of two nodes. (Ishizaka & Nemery, 2013)
The lines connecting the clusters represent the correlation between the different clusters (Saaty & Vargas, 2006). Ishizaka and Nemery, 2013 defines two types of dependency in the ANP: inner and outer dependencies. The inner dependency describes a correlation within one cluster, meaning that two elements in one cluster are correlated. That is evident for clusters C4 and C5, where a loop is shown in Figure 5 (right) describing the inner dependency present in each of the clusters. The outer dependency (or feedback) describes a correlation between two different clusters, meaning that one element present in one cluster is connected to another element present in another cluster. That is evident for clusters C1 and C2. (Ishizaka & Nemery, 2013)

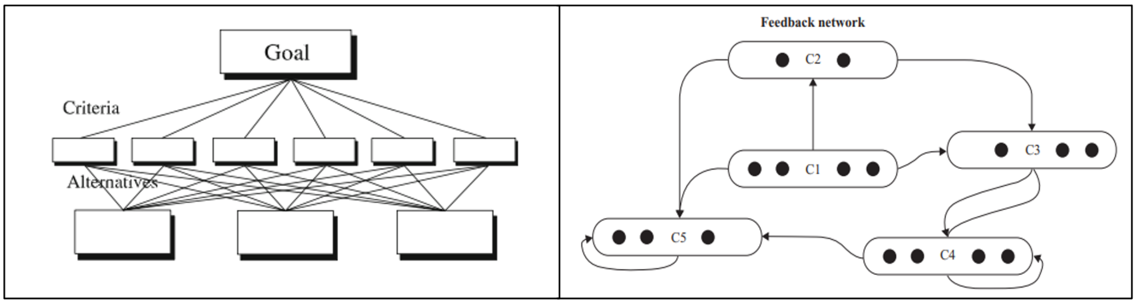


Figure 5 Analytic Hierarchy Process (left) (Saaty & Vargas, 2001) and Analytic Network Process (right) (Ishizaka & Nemery, 2013)

3.2. Pairwise comparisons, eigenvectors and consistency test

Pairwise comparison is the method used in the Analytic Network Process to derive the local weights of the elements (criteria and alternatives) in the decision-making problem (Saaty & Vargas, 2006). For that, the elements are pairwise compared to each other with respect to a specific parent element in the model (control criterion) (Saaty & Vargas, 2006). The question that needs to be asked by doing pairwise comparisons is:

“Given a parent element (control criterion) and comparing elements A and B under it, which element has greater influence on the parent element?” (Akaa, 2017, p. 214)

The 1-9 scale of Saaty is used in the ANP to describe the degree of relevance of one element in comparison to another element. Scale 9 shows that one element has *absolute importance* over another, while scale 1 describes that two elements have *equal importance*. (Saaty & Vargas, 2001) The 1-9 scale after Saaty is shown in Table 7.

Table 7 Saaty's scale (Saaty & Vargas, 2006)

Numerical value	Description
1	Equal importance
3	Moderate of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Extreme importance of one over another
2,4,6,8	Intermediate values

As described in chapter 3.1, the ANP divides the problem into two different elements: nodes and clusters. With this in mind, following pairwise comparisons need to be done:
1. Comparisons at a cluster level: Comparing how more important one cluster is over another when analysing each cluster (Kadoić, 2018).
2. Comparisons of criteria with respect to other criteria: Comparing how more important one criterion is over another when analysing each criterion (Kadoić, 2018)
3. Comparisons of alternatives with respect to each criterion: Comparing how more important one alternative is over another when analysing each criteria (Kadoić, 2018). Here, raw data can also be used and computed in the software SuperDecisions.
4. Comparisons of criteria in each cluster with respect to each alternative: Comparing how more important one criterion is over another when analysing each alternative (Kadoić, 2018).

One generic example of how pairwise comparisons are performed using the Saaty's scale can be seen in Table 8 (left), where *n* elements are being compared with regard to the control criterion C. If element 1 is "moderately more important" than element 2 with regard to the control criterion C, the entry $a_{1,2}$ in Table 8 will be assigned a 3 using the Saaty's scale. In contrast, the value in $a_{2,1}$, will be assigned 1/3. The diagonal elements of a matrix always equal to 1 because it is not meaningful to compare one element to itself.

Table 8 Generic pairwise comparison matrix after Sangiorgio et al., 2022 and resulting eigenvector

C	1	2	$\dots$	n
1	1	$a_{1,2}$	$\dots$	$a_{1,n}$
2	$\frac{1}{a_{1,2}}$	1	$\dots$	$a_{2,n}$
$\vdots$	$\dots$	$\dots$	$\dots$	$\dots$
n	$\frac{1}{a_{1,n}}$	$\frac{1}{a_{2,n}}$	$\dots$	1

Column sum $\longrightarrow$

C	1	2	$\dots$	n
1	$\frac{1}{\Sigma_1}$	$\frac{a_{1,2}}{\Sigma_2}$	$\dots$	$\frac{a_{1,n}}{\Sigma_n}$
2	$\frac{a_{2,1}}{\Sigma_1}$	$\frac{1}{\Sigma_2}$	$\dots$	$\frac{a_{2,n}}{\Sigma_n}$
$\vdots$	$\dots$	$\dots$	$\dots$	$\dots$
n	$\frac{a_{n,1}}{\Sigma_1}$	$\frac{a_{n,2}}{\Sigma_2}$	$\dots$	$\frac{1}{\Sigma_n}$

Row average $\longrightarrow$

$$\begin{bmatrix} \mathrm{EV}_1 \\ \mathrm{EV}_2 \\ \vdots \\ \mathrm{EV}_n \end{bmatrix}$$

To define the relevance of the elements pairwise compared, eigenvectors are utilized. Eigenvectors describe the weights of the compared elements. In this work, the eigenvalues are calculated by dividing each entry of a column of the pairwise comparison matrix by the sum of each column and then building the average of each row, resulting in the eigenvector. This process is shown Table 8. (Saaty & Vargas, 2006)

Important in the pairwise comparisons is to ensure the consistency ratio of the pairwise comparison is *CR < 0.10* (Saaty & Vargas, 2006).The Consistency Ratio (CR) is an important parameter in the Analytic Network Process, since it ensures the accuracy of the performed pairwise comparisons. First step is to calculate the consistency measure vector (CM vector). It is calculated by multiplying the pairwise comparison matrix with the eigenvector (EV) resulted from that pairwise comparison. The formulas are also shown below. (Farman et al., 2017; Saaty and Vargas, 2006)

$$\begin{bmatrix} 1 & a_{1,2} & \dots & a_{1,n} \\ a_{2,1} & 1 & \dots & a_{2,n} \\ \vdots & & \ddots & \vdots \\ a_{n,1} & & \dots & 1 \end{bmatrix} \times \begin{bmatrix} \mathrm{EV}_1 \\ \mathrm{EV}_2 \\ \vdots \\ \mathrm{EV}_n \end{bmatrix} = \begin{bmatrix} \mathrm{CM}_1 \\ \mathrm{CM}_2 \\ \vdots \\ \mathrm{CM}_n \end{bmatrix} \tag{3.1}$$

Following that, λ_{max} is calculated by averaging the CM vector.The Consistency Index (CI) value and the Consistency Ratio (CR) are then calculated with the following formulas, where *n* is the number of elements in the decision making problem and RI are the random index after Table 9.(Farman et al., 2017; Saaty and Vargas, 2006)

$$CI = \frac{\lambda_{\mathrm{max}} - n}{n-1}$$

$$CR = \frac{CI}{RI}$$

Table 9 Random Index (RI) (Saaty & Vargas, 2006)

Order n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
R.I.	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

3.3. ANP methodology

With the theoretical background presented in Chapters 3.1 and 3.2, the Analytic Network Process can be facilitated by utilizing the software *SuperDecisions*. Chapter 4 applies the Analytic Network Process in a case study following the subsequent steps. The following steps need to be performed in the ANP and were described in Saaty and Vargas, 2006.

Step 1: Creating a network structure, where the criteria and alternative clusters are defined. The clusters contain the different criteria and alternatives, also known as nodes. (Chapter 4.3)

Step 2: The calculated values for the alternatives are inserted as raw data into SuperDecisions. These values are normalized, generating local priority vectors for the alternatives. (Chapter 4.5)

Step 3: Performing pairwise comparisons and calculating priority vectors among the different elements of the decision making problem. The pairwise comparisons consider the impact of each element over another and are conducted with the help of the 1-9 scale proposed by Saaty. It is essential to maintain a consistency ratio (CR) of $CR < 0.10$ in the pairwise comparison process. (Chapter 4.6)

Step 4: Calculation of the unweighted supermatrix. The supermatrix in the ANP is a nxn matrix, where *n* is the number of nodes in the model. Each column of the unweighted supermatrix is filled with the priority vectors obtained from the pairwise comparisons in Step 2 & 3, and the supermatrix indicates the significance of each element of the decision making problem. (Chapter 4.7)

Step 5: Calculation of the weighted supermatrix by multiplying the unweighted supermatrix by the cluster weights (determined in Step 2, by pairwise comparing the different clusters). (Chapter 4.7)

Step 6: Synthesizing the results by raising the weighted supermatrix to powers of a high number, resulting in the limit matrix. The values of each row are identical and represent the weight of each of the alternatives on achieving the defined goal (Chapter 5.1-5.2)

Step 7: Perform a sensitivity analysis of the results to better understand the final results (Chapter 5.3)

For better visualisation, Figure 6 illustrates a more detailed step-by-step methodology in the form of a flowchart.

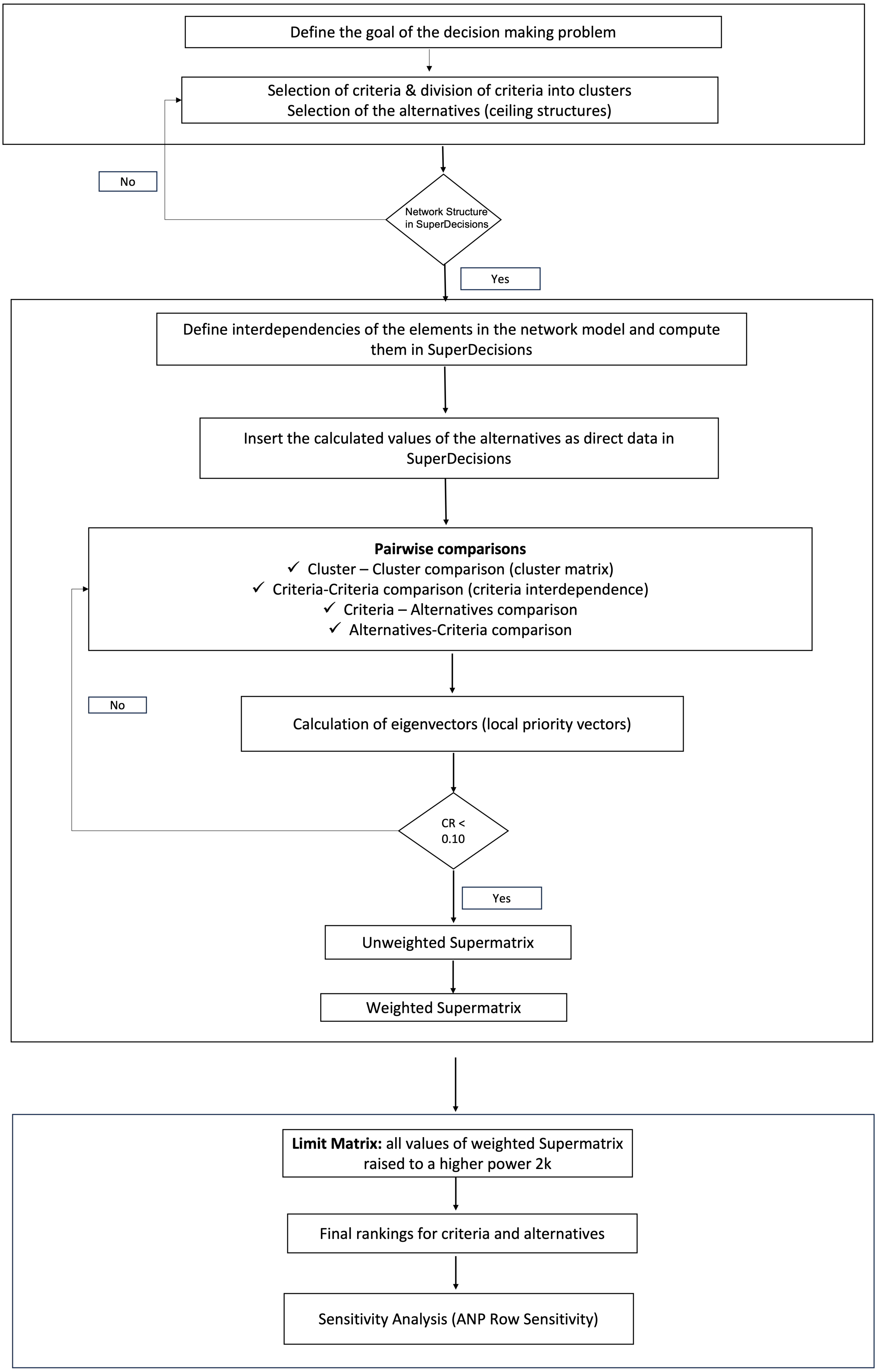


Figure 6 Flowchart of the Analytic Network Process (own elaboration)

4. Case study: Proposed ANP model for selection of building elements

4.1. Project description and selection of building elements

The Analytic Network Process is going to be applied in a project in Nuremberg, Germany. The project is called EDUwood and consists of a new university campus at an available area of ca. 37 hectare. The project sets important topics, such as mobility, carbon neutrality and sustainability as central issues in the design. The new campus includes a new university building, other many research facilities, and living spaces for estimated 900 students. ((Stadtportal Nürnberg, 2023))
Ceiling structures (cost group 350 after DIN 276) were the selected structure type in the scope of this work. They are separated into conventional concrete ceilings, solid wood ceilings, wood beam ceilings, and timber-concrete composite systems. Table 10 - 11 show an overview of the selected ceiling structures and their materials. The ceiling structures were given a designation, which is going to be utilized in the following chapters.

4.2. Criteria setting

Based on the literature research performed in section 2.2, goal of this chapter is to define a limited number of environmental criteria, so that these criteria can be used in the Analytic Network Process. The selection of a limited number of criteria should consolidate the extensive literature research findings into a concise summary of the state-of-art. As a strategy to narrow down the criteria, three key factors were considered to select the most appropriate criteria (Sangiorgio et al., 2022):

- Completeness: Have all primary groups (presented in the literature research) and significant topics been included at some degree in the selection process? If not, are there reasons for the exclusion of certain criteria?
- Redundancy: Are there some topics, that are unnecessary and redundant? Are there some topics, that can be regarded as part of other topics and therefore selecting them could result in criteria redundancy?
- Operationally: Does the selected criterion have a clear and defined evaluation strategy? Criteria that cannot evaluated due to insufficient expertise and calculation methods should be excluded.

Considering these three factors, following criteria were chosen for the scope of this study:

Table 10 Selected ceiling structures

Conventional ceiling			
Ceiling	**Designation**	**[mm]**	**Layer**
Reinforced concrete	B-konv_-DE_StB	5.0	Flooring Linoleum
		50.0	Cement screed (wet screed)
		0.4	Polyethylene (PE) film, separation layer
		20.0	Polystyrene - rigid foam 20-2 (Footfall sound insulation), EPS 040
		200.0	Reinforced concrete
Solid wood ceilings			
Board stacked ceiling	B_DE_-BST_tE	5.0	Flooring Linoleum
		36.0	Dry screed from gypsum fibreboard 2 x 18mm (EI90)
		30.0	Footfall sound insulation mineral wool (s' $\leq$ 30)
		60.0	Chippings fill elastically bound (m' $\geq$ 90 kg/m2) on trickle protection fleece (PP)
		240.0	Board stacked wood, glued, Gl24h
		90.0	CD-profile (center distance e = 400mm)
		80.0	Wood fibre insulation board
		25.0	Gypsum plasterboard 2 x (m' $\geq$ 14,5 kg/m2)
Laminated timber ceiling	B_DE_-BSP_nE	5.0	Flooring Linoleum
		50.0	Cement screed (m' $\geq$ 120 kg/m2)
		40.0	Footfall sound insulation mineral wool (s' $\leq$ 7)
		60.0	Chippings fill elastically bound (m' $\geq$ 90 kg/m2) on trickle protection fleece (PP)
		200.0	Cross laminated timber 5-layers (CL24)
Wood-beam ceilings			
Ribbed ceiling	B_DE_R_nE	5.0	Flooring Linoleum
		50.0	Cement screed (m' $\geq$ 120 kg/m2)
		20.0	Footfall sound insulation mineral wool (s' $\leq$ 8)
		60.0	Chippings fill elastically bound (m' $\geq$ 90 kg/m2) on trickle protection fleece (PP)
		28.0	Three-layer board, glued to carrier
		220.0	Laminated timber, carrier Gl24h (120/200, e=0,625m)
		220.0	Compartment insulation, mineral wool
		36.0	Gypsum board fireproof panels 2 x

Table 11 Selected ceiling structures (continued)

Hollow box ceiling	B_DE_HK_-nE	5.0	Flooring Linoleum
		50.0	Cement screed (m' $\geq$ 120 kg/m2)
		20.0	Footfall sound insulation mineral wool (s' $\leq$ 8)
		60.0	Chippings fill elastically bound (m' $\geq$ 90 kg/m2) on trickle protection fleece (PP)
		28.0	Three-layer board, glued to carrier
		180.0	Glued laminated timber, Gl24h (80/180, e=0,3125m)
		180.0	Compartment insulation, mineral wool
		28.0	Three-layer board, glued to carrier
		36.0	Gypsum board fireproof panels 2 x
Timber-concrete composite systems			
Timber-concrete composite systems (beam)	B_DE_-HBV(HTB)	5.0	Flooring Linoleum
		50.0	Cement screed (m' $\geq$ 120 kg/m2)
		40.0	Footfall sound insulation mineral wool (s' $\leq$ 7)
		100.0	Reinforced concrete C30/37
		280.0	Glued laminated timber, Gl24h (140/280, e=0,94m)
Timber-concrete composite systems (board stack)	B_DE_-HBV(BST)	5.0	Flooring Linoleum
		50.0	Cement screed (m' $\geq$ 120 kg/m2)
		40.0	Footfall sound insulation mineral wool (s' $\leq$ 7)
		80.0	Reinforced concrete C30/37
		120.0	Dowel laminated timber, Gl24h

a. Global Warming Potential

The Global Warming Potential calculates the changes in the greenhouse effect resulting from human-related emissions (Bayer et al., 2010). It is calculated with the help of Life-Cycle-Assessments (LCA) and the unit is kg CO2-eq. The reduction of greenhouse gas emissions is a crucial parameter in addressing the environmental impacts of climate change at a building element level, as presented in Section 2.2. Since the the construction sector accounts for 40% of the total greenhouse gas emissions (United Nations Environment Programme, 2021), this sector holds great responsibility in mitigating its environmental impacts. The importance of this criterion is confirmed by the numerous legislation and regulations focusing on limiting GHG emissions, as well as its recurring significance in certification systems and publications. This criterion carries a weight of 40% in the LCA after the German certification system DGNB, further emphasizing its relevance (DGNB, 2018).

b. Abiotic Depletion Potential (fossil & elements)

The abiotic depletion potential describes the use of natural resources and thus its scarcity for future generations. Jang et al., 2022, p. 7 describes "the prolonged use of natural resources, such as groundwater and fossil fuels as the cause of abiotic depletion". This impact category is separated into two types: ADP of elements (ADPelem) with the unit kg Sb-eq and ADP of fossil fuels (ADPfossil) with the unit MJ. Both criteria are going to be assessed separately in this work and are calculated with the help of Life-Cycle-Assessments (LCA).

Studies show the relevance of resource depletion in the field of building materials. Jang et al., 2022 analyses which LCA impact categories show the most informative and meaningful results for building materials, concluding that the global warming potential and the abiotic depletion potential were the most relevant environmental impacts categories. Another study of Alptekin and Celebi, 2018, also analyzing the environmental impacts of building materials, concludes that the resource depletion is one of the most important impact categories in building materials. The same results were found in the study of Huang et al., 2018.

c. Harmful Emissions

Many indoor pollutants, such asbestos, formaldehyde, mercury and volatile organic carbons) have been found in diverse building materials. These pollutants not only decrease the indoor air quality and comfort but also pose health risks, leading to severe illnesses and contributing to sick building syndromes (SBS)(Heinrich and Lang, 2019;Theilig and Lang, 2022) . Buildings can last up to 100 years (depending on building type and location) and therefore the use of healthy materials is essential. Furthermore, building products containing pollutants have no recycling potential and any concentration of a indoor pollutant can compromise the circularity potential of a building material (Rosen, 2021).

The goal 3 of the 2030 Agenda of the United Nations describes the increased awareness of human health, well-being and productivity. Applying this in the building sector, SDG3 encourages the use of non- toxic and healthy building materials. The reason for selecting this criteria is the substantial presence of federal laws and national regulations in Germany addressing this issue (e.g. LEVELs, QNG). The significance of this topic is recognized by all certification systems, as it carries substantial weight in their evaluation process.

Given that the research project is located in Germany, the evaluation of this criterion will utilize the assessment methodology of the German rating system DGNB, aligning thus closely with the specific context and requirements in Germany.

d. Share of Renewable Primary Energy

Primary energy is the energy that comes naturally and directly from raw energy resources (“Energiewende”, 2015). It can come from renewable sources (e.g. solar, wind, hydro and biomass) or from non-renewable sources (e.g. coal, oil or natural gas) (“Energiewende”, 2015). The primary energy demand of building elements is calculated with the help of Life Cycle Assessments and the unit is MJ.

The primary energy is particularly important at a national level in Germany. It holds sig-

nificance in the German certification system, as it is included in the LCA balancing rules following the DGNB guidelines (DGNB, 2018). Additionally, the limitation of primary energy for building materials is considered for federal funding under the QNG program and also by the European LEVEL(s) framework , highlighting its relevance. Building materials contribute significantly to the overall primary energy demand during the various stages of their life cycle (production/construction, repair, operation, and disposal). Therefore, energy efficient building materials hold great relevance when aiming to reduce the environmental impacts.
To deliver more expressive information and to enable a better comparison between the ceiling structures, the share of renewable primary energy (PERT/PET) in % was selected here.

e. Thermal Mass

Building materials with high thermal mass have the capacity to absorb and retain heat (e.g. coming from sunlight), and release it slowly over time (Hussein et al., 2021;Rüdisser, 2018). There are many methods to calculate the thermal mass, being a tool, designed after and by the ISO 13986 the selected method to calculate the thermal mass at a building element level(Rüdisser, 2018). The parameter calculated to describe the thermal mass of building elements is the external areal heat capacity in kJ/m2K.
Ceilings possess a significant capacity for heat storage, making them an ideal element for effectively absorbing and retaining heat within a building. Selecting building elements with high thermal mass can contribute to the sustainability of a building by reducing the need for mechanical heating and cooling systems, lowering the overall energy demand of a building and promoting indoor thermal comfort (Reilly & Kinnane, 2017).
The environmental benefits of thermal mass are not immediately apparent at a building element level. It only becomes noticeable when the buildings' energy consumption is reduced or when the indoor thermal comfort of users is increased. However, to achieve these environmental benefits, planers must consider the thermal mass of building elements early in the design process by selecting materials with high thermal mass potential.

f. Circularity Potential: Pre-Use & Post-Use

The field of materials was extensively researched in Section 2.2. Trying to create a strategy to cover all those criteria and aiming to reduce topics' redundancy, the topics presented in Section 2.2 were divided up into two primary categories: circularity potential in the pre-use and post-use phase. Materials' circularity is not only addressed in SDG 12 of the United Nations but also holds significance in various other crucial regulations, including LEVELs, QNG, and the Circular Economy Action Plan. Consequently, it holds great relevance within the scope of this work. For both phases, pre-use and post-use, the Urban Mining Index (Rosen, 2021), developed by Dr. Anja Rosen, was the selected evaluation method in this study.
The pre-use circularity potential takes into account the origin and use of building materials before to their utilization. It embraces following quality levels in the evaluation of the materials' circularity potential: reuse; recycling (in both forms, pre-consumer and

post-consumer (Rosen, 2021)); renewable raw material(e.g.wood); downcycling (materials' recycling, however with quality loss (Helbig et al., 2022)); primary raw materials (e.g. concrete). All of these quality levels, except for primary raw materials, encompass a certain level of circularity potential. It is important to avoid the use of nonrenewable primary raw materials like concrete, as they contribute to significant environmental impacts in the construction of buildings. (Rosen, 2021)
The post-use circularity potential examines various end-of-life scenarios for building materials. The method evaluates the following criteria: the reusability of materials, their recyclability, the potential for downcycling (recycling with some loss in quality), the suitability of materials for energy recovery, and the options for disposal.(Rosen, 2021)
In the context of this work, the pre-use and post-use circularity potential will be evaluated individually, treating them as distinct and separate criteria.

Criteria excluded from the analysis in this work:
The topic of sound emissions is highly relevant in the context of this work. All certification system consider this topic of great relevance, when designing sustainable buildings elements. In fact, later in the study in Chapter 4.5, sound insulation will be evaluated as the functional unit of the life cycle assessment. In this work, the topic sound emissions will not be considered as an independent criterion. This is because sound insulation is already regulated by law in Germany through the norm DIN 4109, and all building elements are required to meet the standards of this law by providing sufficient sound insulation.
Water consumption has become a significant topic of concern nowadays with worldwide water scarcity. However, when examined at the level of individual building element level, the importance of this topic seem to be small. While water is consumed during the entire lifespan of building materials, the extent to which the water consumption of building elements contributes to the current water scarcity is relatively insignificant.
The consideration of responsible resource extraction is also significant within the context of this study. Irresponsible resource extraction can lead to many environmental impacts, such as groundwater contamination by chemicals, soil degradation, and biodiversity loss, acting as an obstacle for the sustainable development practices (Umweltbundesamt, 2019). However, at the current project stage, this criterion cannot be evaluated due to insufficient information and evaluation strategies. Similarly, the topic "Material Regionality," which relates mostly to the emissions of building materials associated with transporting (USGBC, 2013), was neglected for this same reason. Furthermore, criteria, such as the durability and maintainability of materials, were excluded of the assessment, because they are indirectly evaluated in the Life Cycle Assessment (LCA) of building elements, which directly influences the results of GWP, ADP and, PERT/PET.

An overview of the selected criteria can be seen in the Table 12, where the eight criteria, their unit and evaluation strategy are presented. Furthermore, Table 13 shows an overview of the seven ceiling structures with the corresponding used designation in further calculations.

Table 12 Overview of selected criteria

Category	Abbrev.	Criteria	Unit	Evaluation strategy
Emissions (Em)	Em1	Global Warming Potential	kg CO2-eq	Life Cycle Assessment
	Em2	Abiotic Depletion Potential (fossil fuels)	MJ	Life Cycle Assessment
	Em3	Abiotic Depletion Potential (elements)	kg Sb -eq	Life Cycle Assessment
	Em4	Harmful Emissions	-	DGNB rating system/matrix
Energy (En)	En1	Share of renewable primary energy	%	Life Cycle Assessment
	En2	Thermal Mass	kJ/m2K	ISO 13986
Circularity Potential (CP)	CP1	Circularity Potential Pre-Use	%	Urban Mining Index
	CP2	Circularity Potential Post-Use	%	Urban Mining Index

Table 13 Overview of the ceiling structures

Ceiling	Abbreviation
A1: Reinforced concrete ceiling	B-konv_DE_StB
A2: Board stacked ceiling	B_DE_BST_tE
A3: Laminated timber ceiling	B_DE_BSP_nE
A4: Ribbed ceiling	B_DE_R_nE
A5: Hollow box ceiling	B_DE_HK_nE
A6: Timber-concrete composite system (beam)	B_DE_HBV (HTB)
A7: Timber-concrete composite system (board stacked)	B_DE_HBV (BST)

4.3. Network structure

In order to apply the Analytic Network Process, the primary stage is to create a network structure with all elements of the decision making problem. For that, these elements firstly have to be defined. The decision making problem in this work consists of three criteria clusters: Emissions (Em), Energy (En) and Circularity Potential (CP). The specific criteria within each cluster are shown in Table 12. All alternatives (ceilings A1-A7, summarized in Table 13) are grouped together in one alternative cluster. Figure 7 shows the network structure, which includes the four clusters and illustrates the interdependencies among them. The interdependencies among the criteria are deeply explained in Chapter 4.6, where quantitative values for these interactions are calculated.
Figure 8 shows the same network model, however extended at a node level, where all nodes of the decision making problem are presented. The solid arrows describe the connection between the criteria and the alternatives. The interactions between the criteria are shown qualitatively with the dotted arrows in Figure 8. These can be mainly divided into two types – inner dependency and outer dependency (Ishizaka and Nemery, 2013;Saaty and Vargas, 2006).

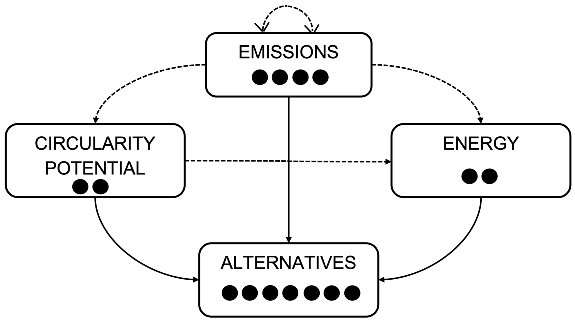


Figure 7 Network structure at a cluster level (own elaboration)

The inner dependency occurs when one criterion is interconnected to other criteria within one cluster (Ishizaka and Nemery, 2013;Saaty and Vargas, 2006). One example is an inner dependency between the GWP (Em1) and the ADP(f) (Em2). That is also illustrated in Figure 7 with a loop in the emissions cluster.
The outer dependency occurs when one criterion depends on at least one criterion of another cluster (Ishizaka and Nemery, 2013;Saaty and Vargas, 2006). That is the case for the GWP (Em1) and the share of renewable primary energy (En1). This outer dependency is illustrated in Figure 7 with an arrow connecting both clusters emissions and energy. There is no loop in the Alternatives cluster in Figure 7 and no arrows connecting the alternatives in Figure 8, since the alternatives do not interact or depend on each other in this model.

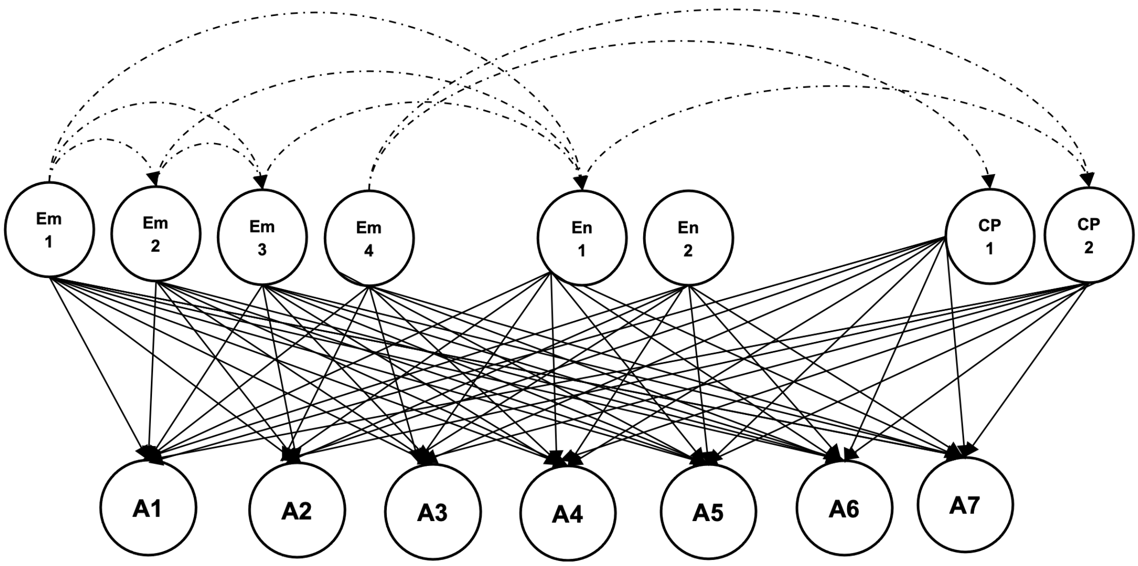


Figure 8 Network structure at a node level (own elaboration)

4.4. Goal definition and weighting scenarios

The primary goal of the ANP model is to select the most sustainable ceiling element when analysing the eight selected criteria for environmental and climate protection. In the scope of this work, two different weighting variants are going to be analyzed. The first variant (ANP Variant 1) describes the case, where all criteria in the model are equally

weighted and are thus equally relevant for the sustainability of the ceiling elements. The second variant (ANP Variant 2) describes an ecological variant for the case of the global warming potential (GWP) and the cluster Emissions being the most relevant cluster and criteria among the others. The project sets the environmental performance and the reduction of greenhouse gas emissions as one of the top priorities and thus assigning a greater weight to the global warming potential provides an accurate representation of a potential real-life scenario for this project.
The results of these two variants are going to be presented later in this chapter, giving the possibility of comparison between the results. Goal here is a comparative analysis between the results: does overweighting the global warming potential change the final results of the alternatives, when compared to equally weighted criteria?
The software SuperDecisions will be utilized to implement the Analytic Network Process in the case study. This software facilitates decision-making in both AHP and ANP methodologies and has been extensively employed in ANP applications.

4.5. Evaluation of alternatives

In this chapter, the selected ceiling structures in Section 4.1 and the selected criteria in Section 4.2 are going to be individually assessed and then local priority vectors for the seven ceilings are going to be derived, as described in Chapter 3.

4.5.1. Emissions

A Life-Cycle Assessment was performed in order to determine the global warming potential GWP (Section 4.5.1.1), the share of renewable primary demand PERT/PET (Chapter 4.5.2.1), the abiotic depletion potential fossil ADPfossil (Chapter 4.5.1.2) and elementary ADPelem (Chapter 4.5.1.3). The goal here is to analyze and compare the seven construction types and evaluate the environmental impact of each ceiling regarding the above-mentioned impact categories. The used software for the LCA was eLCA, the used database for the calculation was Ökobau.dat, and the used dataset OBD_2021_II_A1. In most cases, using the generic database was sufficient. The values for the impact categories were calculated for 1 m2 ceiling structure. The life cycle assessment was done for the following lifecycle phases of the building: A1- A3 (Raw material supply, Transport, Manufacturing), B4 (Refurbishment), C3-C4 (Waste processing, Disposal), and D (Recyclingpotential). The other lifecycle phases, such as A4-A5 (Construction process stage), B1-B3, B5, B7 (Use), C1-C2 (Deconstruction, Transport) were not evaluated due to insufficient data. For this project, the functional unit selected is the sound insulation [dB]. All ceiling structures are complied with the minimal requirements on sound insulation after the German norm DIN 4109 and therefore the sound insulation was chosen as a meaningful and suitable functional unit. The lifespan of the building was determined as 100 years and the net floor area (NGF) and the Gross Floor Area (GFA) were determined as 1m2 for the calculations.

4.5.1.1 Global Warming Potential

The results of the global warming potential for all the seven ceiling structures and for the different analyzed lifecycle phases are summarized in the Table 14 and a graphic representation can be seen in Figure 9. The results show that the reinforced concrete ceiling (B-konv_DE_StB) has the highest GWP of all ceiling structures, with a value of 111.10 kg CO2-eq. The highest amount can be seen in the production phase (73.65 kg CO2-eq), due to the extensive use of concrete. The recycling potential of the reinforced concrete ceiling is quite low with only -6.2 kg CO2-eq. There is a direct correlation between the presence of concrete and the high GWP values of the analyzed ceilings. The three ceilings with concrete have the worst performances in the impact category global warming potential. After the reinforced concrete, the timber-concrete-composite ceilings (B_DE_HBV(HTB) & B_DE_HBV(BST)) are, respectively the second and third worst ceilings. The board-stacked ceiling (B_DE_BST_tE) shows the best performance with a value of 4.64 kg CO2-eq, almost 25 times lower than the reinforced concrete ceiling. Main responsible for this great results is the extensive use of timber and wood fiber insulation boards, both renewable raw materials capable of absorbing CO_2 during the material's lifecycle.

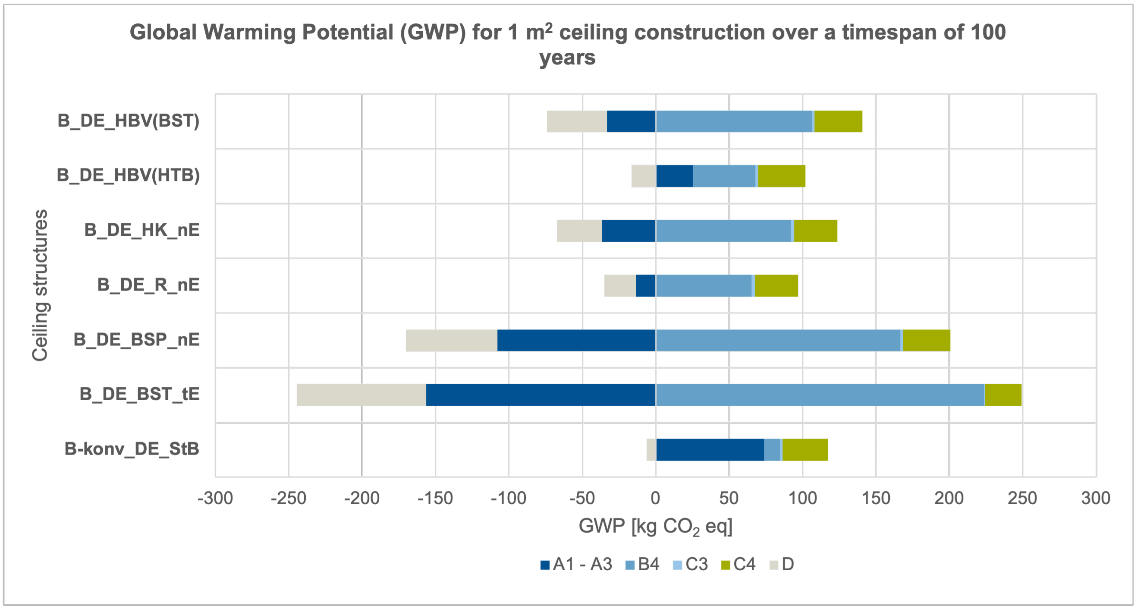


Figure 9 Results of Global Warming Potential

The next step involves obtaining the local priority vectors (eigenvector) by utilizing the values obtained from the calculations. The calculate the local priority vectors, the values in the last column of Table 14 are normalized by dividing each value by the sum of that column. However, when aiming to select the most sustainable ceiling, higher local weights for the alternatives indicate better rankings. On the other hand, lower values for GWP, ADP_{fossil}, and ADP_{elem} indicate greater sustainability of the ceiling. Therefore, the values for these three criteria need to be inverted so that the ANP method can appropriately calculate the weightings of each ceiling with respect to each criterion.
Table 15 shows the obtained results for global warming potential, their corresponding in-

verted values, and the resulting final priorities for each alternative with regard to GWP. The final priorities are calculated by dividing the values by the column sum (Saaty and Vargas, 2012;Sánchez-Garrido et al., 2022). The GWP weights strongly for the board stacked ceiling (B_DE_BST_tE) (0.678), since it has the lowest values for GWP, contributing positively to the final results. The reinforced concrete, however, due to its high values for GWP should contribute minimally to the results, weighting therefore weakly (0.028).

Table 14 Results of Global Warming Potential, separated in the lifecycle phases

Global Warming Potential [kgCO2 eq]						
Ceiling structure	A1-A3	B4	C3	C4	D	Total
B-konv_DE_StB	73.65	30.85	10.89	1.80	-6.09	111.10
B_DE_BST_tE	-156.55	24.79	223.47	0.86	-87.93	4.64
B_DE_BSP_nE	-108.04	32.36	166.60	1.85	-62.24	30.53
B_DE_R_nE	-13.47	29.61	65.12	2.34	-21.69	61.89
B_DE_HK_nE	-36.74	29.61	91.87	2.31	-30.60	56.44
B_DE_HBV(HTB)	25.09	32.36	42.59	1.85	-16.38	85.51
B_DE_HBV(BST)	-33.30	32.36	106.38	1.85	-40.86	66.43

Table 15 Final priorities for the Global Warming Potential (GWP)

Ceiling structures	**GWP**	**1/GWP**	**Eigenvector (EV)**
B-konv_DE_StB	111.103	0.009	0.028
B_DE_BST_tE	4.641	0.215	0.678
B_DE_BSP_nE	30.520	0.033	0.103
B_DE_R_nE	61.895	0.016	0.051
B_DE_HK_nE	56.446	0.018	0.056
B_DE_HBV(HTB)	85.510	0.012	0.037
B_DE_HBV(BST)	66.431	0.015	0.047

4.5.1.2 Abiotic Depletion Potential - fossil fuels

The impact category ADP_{fossil} in the life cycle assessment is an efficient method to evaluate the resource consumption of fossil fuels of building elements. The results of the LCA with the impact category ADP_{fossil} of the seven analyzed ceiling structures are shown in the Table 16. A graphic representation of the results separated in the different lifecycle phases can be seen in Figure 10.

The reinforced concrete ceiling (B-konv_DE_StB) is the structure with the highest consumption of fossil fuels, with a value of 1659.51 MJ. 53.70% (excl. D) of this value is

caused individually in the buildings' use phase (B4). The production phase has also great relevance in the overall resource consumption of the reinforced concrete ceiling, being responsible for almost 45% of the total results. Following the reinforced concrete ceiling, the ribbed ceiling (B_DE_R_nE) is the second major fossil fuel consumer among the analyzed structures. This ceiling consumes in total 1356.78 MJ, in which the biggest amount comes from the production phases (50.04% (excl. D)), followed by the use phase with 41.57%. The least fossil fuel consumer is the board-stacked ceiling structure (B_-DE_BST_tE), with an ADP_{fossil} of 949.33 MJ.
Similarly to the approach of the GWP, the local priority vectors were calculated here by first inverting the total results and then dividing the values by the column sum, resulting in the eigenvalues presented in Table 16.

Table 16 Results of Abiotic Depletion Potential fossil and corresponding eigenvector

Abiotic Depletion Potential- fossil fuels [MJ]							
Ceiling structure	A1-A3	B4	C3	C4	D	Total	**EV**
B-konv_DE_StB	768.98	944.65	19.89	25.53	-99.58	1659.51	**0.107**
B_DE_BST_tE	1116.60	1083.10	22.45	12.19	-1167.90	1066.40	**0.168**
B_DE_BSP_nE	748.61	958.91	26.45	26.27	-810.97	949.33	**0.188**
B_DE_R_nE	697.97	924.06	23.87	33.04	-322.24	1356.78	**0.132**
B_DE_HK_nE	742.91	924.06	24.11	32.75	-452.08	1271.82	**0.140**
B_DE_HBV(HTB)	678.97	958.91	17.97	26.27	-233.74	1448.35	**0.123**
B_DE_HBV(BST)	787.86	958.51	19.93	26.27	-544.90	1254.10	**0.142**

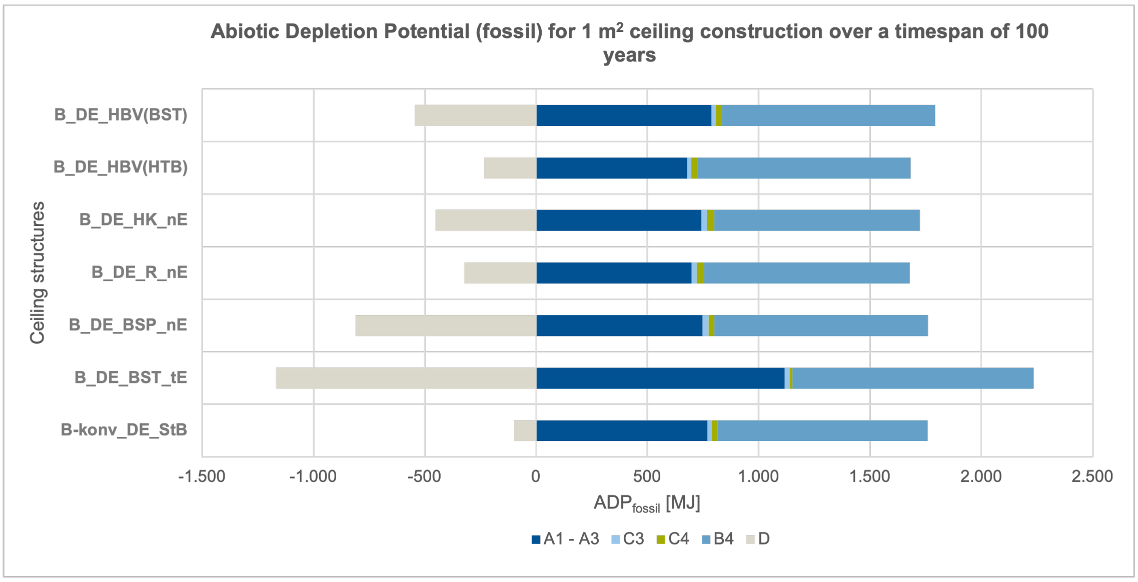


Figure 10 Results of Abiotic Depletion Potential(fossil)

4.5.1.3 Abiotic Depletion Potential - elements

Table 17 and Figure 11 present the results of the Life Cycle Assessment for the impact category abiotic depletion potential(elements). The worst performance is again the reinforced concrete ceiling with a value of 3.19E-02 kg Sb-eq and the best performance is the board-stacked ceiling structure (B_DE_BST_tE) with a value of 6.31 E-05 kg Sb-eq. The ratio between the best and the worst ceiling is 505.32, which shows how different the results can be for ceiling structures with similar purposes. Although the difference between the best and worst ceiling is extremely high, the ceilings in between have quite similar values for the ADP_{elem}. While ranking number 2 (B_DE_BSP_nE) has a value of 6.38E-05 kg Sb-eq, ranking number 4 has a value of 6.59E-05 kg Sb-eq, suggesting that the evaluation of this criterion on ceiling structures do not deliver significant comparative information.
A graphic representation of the results for all ceilings does not give meaningful and significant information since the results for the reinforced concrete are very high (order of magnitude E-02) and the results for the board-stacked- ceiling are very low (order of magnitude E-05). Therefore a graphic representation for the ceilings ranked number 2 - 6 is shown in Figure 11.

Table 17 Results of Abiotic Depletion Potential (elements) and corresponding eigenvector

Abiotic Depletion Potential- elements [kg Sb-eq]							
Ceiling structure	A1-A3	B4	C3	C4	D	Total	**EV**
B-konv_DE_StB	1.60E-02	1.59E-02	7.58E-07	1.83E-07	-2.71E-06	3.19E-02	**0.000**
B_DE_BST_tE	3.61E-05	5.74E-05	7.26E-07	8.71E-08	-3.12E-05	6.31E-05	**0.209**
B_DE_BSP_nE	3.23E-05	5.26E-05	1.02E-06	1.88E-07	-2.23E-05	6.38E-05	**0.209**
B_DE_R_nE	2.15E-07	5.20E-05	8.01E-07	2.36E-07	-8.59E-06	6.59E-05	**0.179**
B_DE_HK_nE	2.29E-05	5.20E-05	8.54E-07	2.34E-07	-1.21E-05	6.39E-05	**0.209**
B_DE_HBV(HTB)	9.11E-05	5.26E-05	6.50E-07	1.8E-07	-6.47E-06	1.38E-04	**0.090**
B_DE_HBV(BST)	8.10E-05	5.26E-05	7.48E-07	1.88E-07	-1.53E-05	1.19E-04	**0.104**

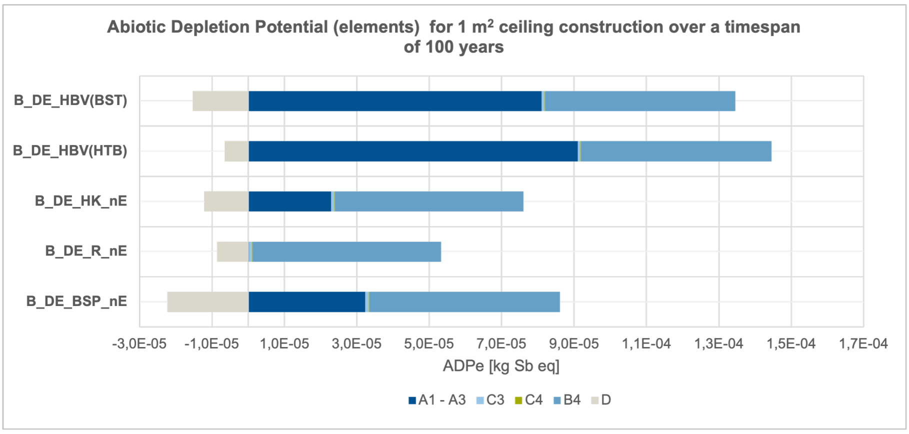


Figure 11 Results for Abiotic Depletion Potential (elem) of five ceiling structures

4.5.1.4 Harmful emissions

The evaluation of material's harmful emissions is carried out the help of datasheets, such as product data sheet, safety data sheet, or sustainability datasheet, where information on different pollutant's concentration is given. Material's pollutants are not fixed numbers for a certain material type, but they vary according to the product's manufacturer. (Theilig & Lang, 2022)
To assess the material's pollutant, datasheets provided by manufactures are required. However, neither information on the material's manufacturer nor datasheets are available for the assessment of the building materials' emissions. The project is still in early project stages and therefore the manufacturers were perhaps not even determined. The assessment of certain emissions, such as Volatile Organic Carbon (VOC) can be done with the help of generic environmental product declarations (EPD) for standard building elements, such as concrete and some types of timber. However, assessing only few materials of a ceiling component results in incomplete results, leading to an unreliable and distorted comparative analysis between the different ceiling structures.
Furthermore, emissions from interior designs of building users, such as furniture, buildings' cleaning, cleaning products, fenin dust from inkjet printers (relevant here due to academic usage of building) were at the present time of the evaluation not determined.
Although the relevance of this criteria is quite high in the state-of-art, being of extreme relevance for the achievement of the UN Agenda 2030 and other sustainability goals, the assessment of this criteria is not possible in this work due to the above-mentioned reasons. In later project stages, datashets of all materials used in the project must be documented for a complete and reliable assessment. This way, harmful emissions of building materials, such as VOCs, formaldehyde and biocide can be determined more precisely. Further on this work, all seven ceiling structures are rated equally with the highest quality level on harmful emissions after the German rating system DGNB (quality level 4) and have thus the same ranking in the assessment. With this in mind, all ceiling are equally weighted, showing an importance of 0.143 (see Table 22).

4.5.2. Energy

The results for the calculations of the share of primary energy demand (Section 4.5.2.1) and thermal mass (Section 4.5.2.2) are going to be presented, as well as the corresponding local priority vectors.

4.5.2.1 Share of renewable primary energy demand (PERT/PET)

The performed Life Cycle Assessment, described in section 4.5.1, was also used to calculate the share of renewable primary energy demand. The LCA was performed for the impact categories renewable (PERT) and nonrenewable (PENRT) primary energy for 1m² over a service life of 100 years. The ratio between renewable primary energy (PERT) and the total primary energy (PET) results in the share of renewable primary energy [%]. The results can be seen in Table 18.

The board stacked ceiling (B_DE_BST_tE) shows the highest share on primary energy demand, in which 78.38% of its primary energy demand come from renewable sources. Following this ceiling structure, the cross laminated timer (B_DE_BSP_nE) with 73,68% renewable primary energy and the timber-concrete composite (B_DE_HBV(BST)) are the second and third best ceilings. The worst performer is the conventional reinforced concrete, where only 33,94% of its primary energy comes from renewable sources. Concrete, cement, and steel are materials that consume a high amount of fossil fuels and therefore is this value high for this ceiling structure. The results are also shown in Figure 12, where the amount of nonrenewable primary energy demand (PENRT), the amount of renewable primary energy demand (PERT), and the share of renewable primary energy demand (PERT/PET) for all the seven different ceiling structures are shown.

Table 18 Results of share of renewable primary energy and corresponding eigenvector

Share of renewable primary energy [%]				
Ceiling structure	PENRT [MJ]	PERT [MJ]	PERT/PET[%]	**EV**
B-konv_DE_StB	1786.78	935.70	34.37	**0.085**
B_DE_BST_tE	949.9	3442.60	78.38	**0.195**
B_DE_BSP_nE	899.84	2519.10	73.68	**0.183**
B_DE_R_nE	1393.14	1479.82	51.51	**0.128**
B_DE_HK_nE	1279.58	1755.85	57.85	**0.144**
B_DE_HBV(HTB)	1527.29	1280.48	45.60	**0.113**
B_DE_HBV(BST)	1263.32	1991.45	61.19	**0.152**

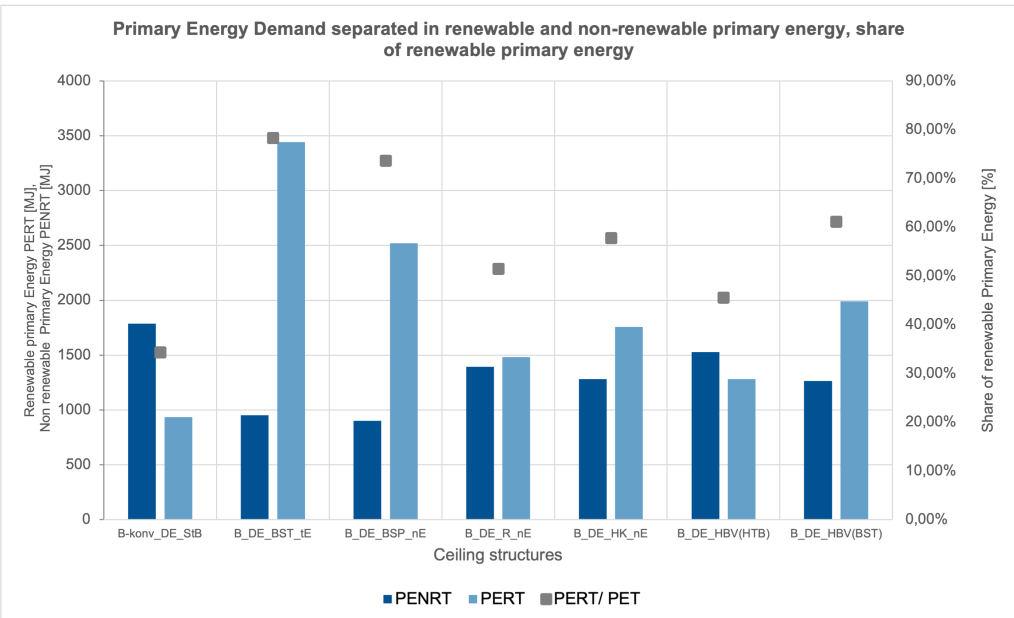


Figure 12 Results for share of renewable primary energy

4.5.2.2 Thermal mass

The thermal mass of each of the seven ceiling structures was calculated after the norm ISO 13986 (Rüdisser, 2018). For the calculation of the thermal mass with the help of this tool, following information of the building materials are required:

- Thermal conductivity [W/m^{2}K]
- Gross density [kg/m^3]
- Specific heat capacity c [J/kgK]

Also required for the calculation are the internal and external heat transfer resistance R_{si} and R_{se}. Here, the internal heat transfer resistance concerns the ceiling, and the external heat transfer resistance concerns the flooring. Since the ceilings are interior ceilings and thus the heat-flux are mostly generated by temperature fluctuations indoor, the values for R_{si} and R_{se} are both 0,13 m^{2}K/W (Rüdisser, 2018).
The most relevant parameter to determine and evaluate the thermal mass is the *external areal heat capacity* [kJ/m^{2}K] (Rüdisser, 2018), which calculates how much energy [kJ] is needed to increase the temperature of a surface [m2] by one Kelvin degree [K] (Rüdisser, 2018). Table 19 presents the results for the thermal mass of the seven ceiling structures. Wood has low heat storage potential and low heat conductivity, making it unfavorable for timber building structures to have great thermal mass (Sharifi & Murayama, 2013). The results confirm this tendency, since the worst performance in regard to thermal mass is for the board stacked ceiling (B_DE_BST_tE), due to the use of timber and glass wool, both bad thermal conductors with thermal conductivities of, respectively 0.13 and 0.035 W/m2K. Concrete, on the contrary, has great potential for thermal mass (Sharifi & Murayama, 2013), being also visible in the results, as the reinforced concrete and the timber-concrete composite system (B_DE_HBV(HTB)) have respectively the best thermal performances, both showing more than three times the thermal capacity than the board-stacked ceiling.

Table 19 Results of the thermal mass and corresponding eigenvector

Ceiling structure	Thermal Mass [kJ/m2K]	**EV**
B-konv_DE_StB	87.866	**0.281**
B_DE_BST_tE	24.983	**0.080**
B_DE_BSP_nE	29.261	**0.094**
B_DE_R_nE	31.692	**0.101**
B_DE_HK_nE	30.548	**0.098**
B_DE_HBV(HTB)	78.90	**0.253**
B_DE_HBV(BST)	29.03	**0.093**

4.5.3. Circularity potential

This chapter presents the results of the calculations of the Circularity Potential in the Pre-Use Phase (Section 4.5.3.1) and in the Post-Use Phase (Section 4.5.3.2). The method selected to calculate the Circularity Potential was the Urban Mining Index (UMI), developed by Dr. Anja Rosen in the University of Wuppertal, Germany (Rosen, 2021).
The method can be applied at different levels: raw material, material, component layer, construction element, building component, and building level. In the scope of this work – since ceiling structures are being analyzed – the urban mining index is going to be calculated at a building component level. The dissertation of Dr. Anja Rosen builds basis for the assessment of this work. Detailed information, formulas, and boundary conditions of method are described in the dissertation *„Urban Ming Index: Entwicklung einer Systematik zur quantitativen Bewertung der Kreislaufkonsistenz von Baukonstruktionen in der Neubauplanung“* (Rosen, 2021).
To apply this method in seven ceiling structures, the following information and tools were required. For the calculation, Excel was used to select and collect all gained data. Data on the different building materials and its circularity potential were found mostly in the documents Atlas Recycling (Hillebrandt et al., 2018), the dissertation Urban Mining Index (Rosen, 2021), database Ökobaudat and in Environmental Product Delarations (EPD). The detailed process of the Urban Mining Index will not be presented in the scope of this work, as it is not the primary focus. The results for both categories are presented in the following chapters.

4.5.3.1 Circularity potential: Pre-use

To divide and better assess and compare different building structures, the Urban Mining Index divides the pre-use circularity potential into 6 main categories, illustrated in Figure 13. All the categories contribute for the circularity potential in the pre-use phase, except the use of primary raw materials, such as concrete or natural stone (Rosen, 2021).

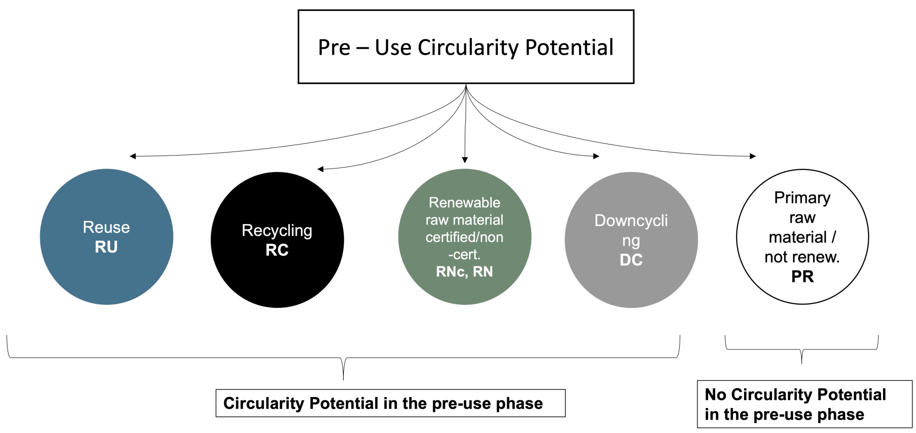


Figure 13 Categories of the Pre-Use Circularity Potential (own elaboration after (Rosen, 2021))

For the assessment of the Pre-Use Circularity Potential, following information of each building material is required: thickness of each component layer, raw density [kg/m3], mass [kg/m2], material's service life [year] (after German system BNB). These material's parameters build basis for the calculation of the Urban Mining Index in the pre-use phase. The calculation occurs separately for every material of a building element and thus data on the share of recycled, reuse, primary renewable/nonrenewable raw materials must be collected for each material. Figure 14 shows the different circularity potential of the most reoccurring materials in the seven ceiling structures. The diagram shows that gypsum fiberboards, concrete and cement screed are the worst circular materials in the pre-use phase since they contain almost exclusively nonrenewable primary materials. Materials such as wood fiber insulation, linoleum and different types of timber consist of high shares of renewable raw materials and materials such as glass wool and reinforced steel great shares of recycling content in their composition.

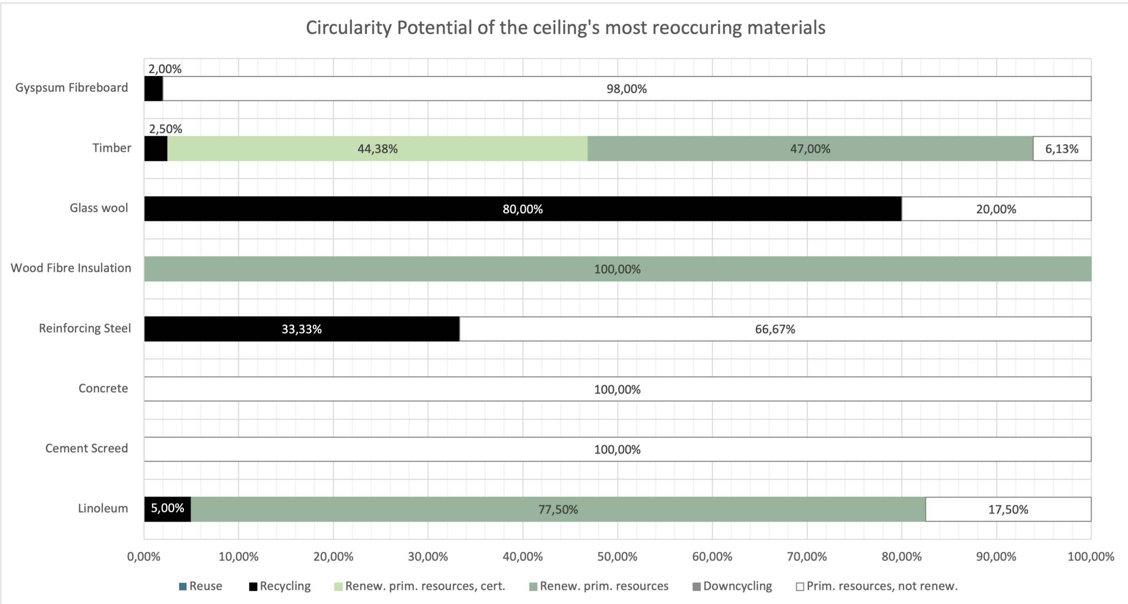


Figure 14 Circularity Potential of the most reoccurring materials in the ceilings (own elaboration after (Rosen, 2021))

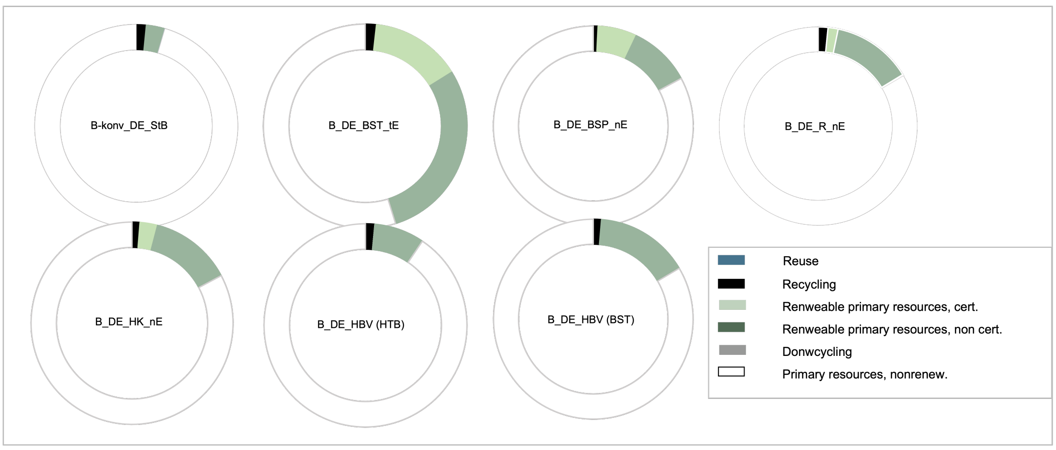


Figure 15 Categories of the Pre-Use Circularity Potential

The results for the seven ceiling structures can be seen in Figure 15 and Table 20. The results show that the reinforced concrete is the worst ceiling in this category. 95% of the reinforced concrete is nonrenewable primary raw material. This is due to the extensive use of use concrete, and the presence of cement screed, EPS insulation and polyethylene (PE- Folie). The timber-concrete composite systems (beam) (B_DE_HBV (BST)) also shows bad performance, one of the reasons also being the use of concrete and cement screed. The difference to the reinforce concrete ceiling lies in the use of wood in its composition, which causes an increase in the share of renewable materials and a decrease in the share of primary raw nonrenewable materials. This doubles the circularity potential in the Pre-Use Phase for this ceiling (9.55%) in comparison with the reinforced concrete ceiling.
The board-stacked ceiling with dry screed (B_DE_BST_tE) is the most circular ceiling among the analyzed ceilings, due to the presence of wood, glass wool and wood fiber insulation. All these materials have great circularity potentials and therefore influence positively the results. Important to mention here, is that dry screed was not included in the calculations in this ceiling due to lack of data.

Table 20 Results of the Circulatiry Potential in the Pre-Use Phase and corresponding eigenvector

Ceiling structure	CP Pre-Use [%]	**EV**
B-konv_DE_StB	4.55	**0.036**
B_DE_BST_tE	45.19	**0.357**
B_DE_BSP_nE	17.11	**0.135**
B_DE_R_nE	16.42	**0.130**
B_DE_HK_nE	17.22	**0.136**
B_DE_HBV(HTB)	9.48	**0.075**
B_DE_HBV(BST)	16.52	**0.131**

4.5.3.2 Circularity potential: Post-use

The results for the Post – Use Circularity Potential are going to be presented in this section. For the calculation, three levels are considered:

a. Material level
There are two prerequisites for the assessment at the material level: the absence of harmful emissions in the building materials and the consideration of the different types of End-of-Life scenarios. The circularity potential can be impeded by any concentration of harmful substances in materials. With this in mind, the absence of harmful emissions in building materials is prerequisite for the circularity potential of materials. (Rosen, 2021)
The assessment of this criterion was done in section 4.5.1.4, where all ceiling structures were assumed to be pollutant – free. For the assessment of the End-of-Life Scenarios, the categories presented in Figure 16 are possible in the Urban Mining Index.

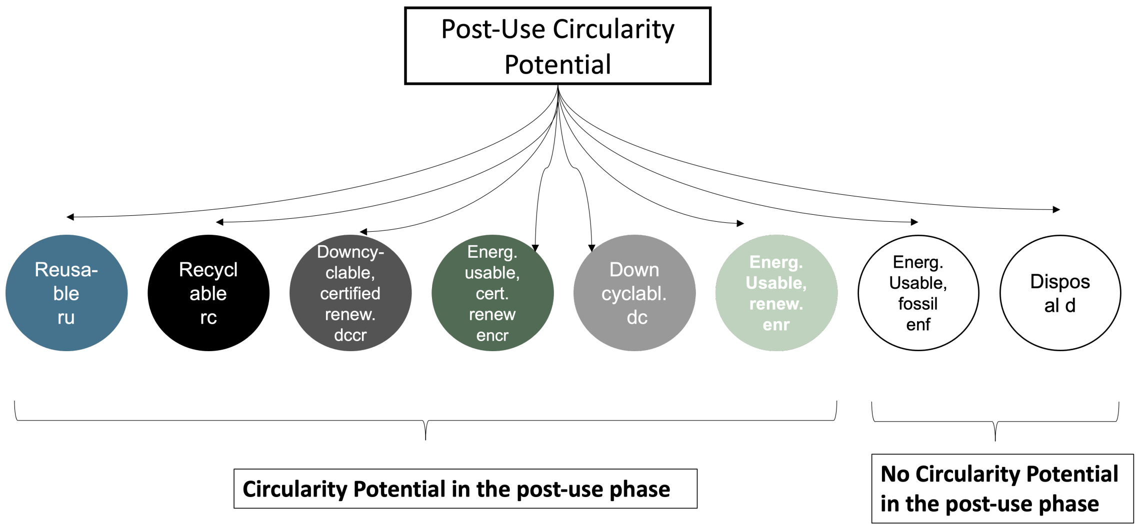


Figure 16 Categories of the Post-Use Circularity Potential(own elaboration after (Rosen, 2021)

b.Constructive level

Two key parameters play a crucial role in determining the circularity potential during the post-use phase. Firstly, the building element should have detachable connection types, which is important solely for reusable materials. For materials with other EoL, such as recyclable, downcyclable, or suitable for energy recovery, the connection type becomes less significant, since the material will be dissolved during recycling. Secondly, the materials within the building element must possess a certain level of purity to facilitate successful recycling.(Rosen, 2021)

c. Economic level

In this category, the economic level is determined by calculating the labor effort of people and machines for the deconstruction of the building elements (Rosen, 2021). The economic level is divided up into two subcategories:

- *Factor work fw:* effort for deconstruction and separation of people and machines. Describes how much energy pro square meter building element is needed to deconstruct the building materials. The unit to describe this parameter is [MJ/m2]
- *Factor value fv:* describes the material value, the disposal costs and recycling revenues of the building materials. The unit here is €/ton and the higher the material values per ton, the higher is the value for fv

Data for the factors fw and fv for different building materials are shown in the Atlas Recycling (Hillebrandt et al., 2018) and in the dissertation Urban Mining Index (Rosen, 2021). The calculation occurs separately for each material and embraces – at some degree – all three levels mentioned above.

The results for the seven ceiling structures are presented in Table 21 and Figure 17. The ceilings show similar results for the Post-Use Circularity Potential. The best performance is the board-stacked ceiling ((B_DE_BST_tE), being only 6.13% better than the second-best ceiling – the timber-concrete composite system ceiling (beam). The rein-

forced concrete ceiling is the third best ceiling in this category and the cross-laminated timber ceiling the worst one.
Interesting to mention is that the share of recycled materials is the highest for ceilings with concrete in their composition (reinforced concrete and timber-concrete compositive systems). Concrete can be recycled up to 100% and the reinforced steel up to 40%, leading to high recycling rates in the concrete ceilings (Hillebrandt et al., 2018). Glass wool is also responsible for some share of the recycling rate, as it can be up to 80% recycled at the end of its lifecycle (Hillebrandt et al., 2018). The other ceilings show high values for downcycling and energetically usage due to the presence of timber in their structure.

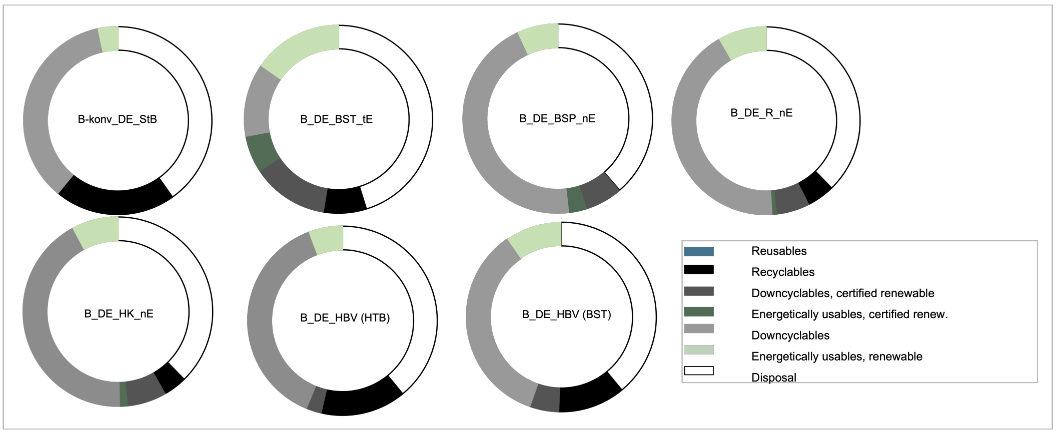


Figure 17 Categories of the Post-Use Circularity Potential

Table 21 Results of the Circulatiry Potential in the Post-Use Phase and corresponding eigenvector

Ceiling structure	CP Post-Use [%]	**EV**
B-konv_DE_StB	42.06	**0.141**
B_DE_BST_tE	49.39	**0.165**
B_DE_BSP_nE	38.57	**0.131**
B_DE_R_nE	40.61	**0.138**
B_DE_HK_nE	40.86	**0.138**
B_DE_HBV(HTB)	41.75	**0.141**
B_DE_HBV(BST)	43.27	**0.145**

The local priorities vectors of the alternatives with regard to each criterion of the model are summarized in Table 22 and 23. The values from Table 15 (local priorities for GWP) correspond to the first column of Table 22. Due to lack of data of the research project, the criterion harmful emissions was assumed to be equally important for all ceilings, weighting therefore 0.143 for each ceiling. The value for abiotic depletion potential (elements) for the reinforced concrete is so high, that its weighting with regard to this criterion tends to zero.

Table 22 Overview of local priorities (eigenvectors) for the criteria in the emissions cluster

Ceiling structures	GWP	ADP(f)	ADP(e)	Harmful Emissions
B-konv_DE_StB	0.028	0.107	0.000	0.143
B_DE_BST_tE	0.678	0.168	0.209	0.143
B_DE_BSP_nE	0.103	0.188	0.209	0.143
B_DE_R_nE	0.051	0.132	0.179	0.143
B_DE_HK_nE	0.056	0.141	0.209	0.143
B_DE_HBV(HTB)	0.037	0.123	0.090	0.143
B_DE_HBV(BST)	0.047	0.142	0.104	0.143

Table 23 Overview of local priorities (eigenvectors) in the Energy and Circularity Potential Cluster

Ceiling structures	PERT/ PET	Thermal Mass	CP Pre-Use	CP Post-Use
B-konv_DE_StB	0.085	0.281	0.036	0.141
B_DE_BST_tE	0.195	0.080	0.357	0.165
B_DE_BSP_nE	0.183	0.094	0.135	0.131
B_DE_R_nE	0.128	0.101	0.130	0.138
B_DE_HK_nE	0.144	0.098	0.136	0.138
B_DE_HBV(HTB)	0.113	0.253	0.075	0.141
B_DE_HBV(BST)	0.152	0.093	0.131	0.145

4.6. Pairwise comparisons

Considering all elements of the decision making problem shown in Figure 7-8, following pairwise comparisons need to be performed within the framework of this decision making problem: (Kadoić et al., 2017)

- Cluster comparisons with regard to each cluster (chapter 4.6.1)
- Comparisons of criteria with regard to each criteria (chapter 4.6.2)
- Comparisons of criteria with regard to each alternative (chapter 4.6.3)

These three levels of pairwise comparisons are going to be explained and performed in the following sections.

4.6.1. Cluster comparisons

The four clusters must first be compared to each other to establish their relative importance. The pairwise comparisons at cluster level compares the different clusters with

regard to - separately - each of them. Example here is represented in Table 24, where all the clusters of the decision making problem are compared with regard to the cluster "Emissions" for the case of variant 2. The question to be asked is: *Regarding the cluster “Emissions”, which cluster is more relevant, the cluster “Energy” or the cluster “Circularity Potential”?*
For Variant 1, all clusters were assumed to be equally important (scale 1 after Saaty). For the case of Variant 2 (ecological variant), the Emissions cluster was defined as extremely more important than the other clusters (scale 9, see Table 24). As a result of the pairwise comparisons for Variant 2, the eigenvector were calculated, showing that the cluster Emissions has a priority of 0.750, whereas the other clusters a priority of each 0.083 over the cluster Emissions.
This approach was performed with regard to each cluster separately for the two different variants. After checking if the consistency rate of every pairwise comparison has been <0.10, the cluster matrix was generated for variant 1 (Table 25) and for variant 2 (Table 26). The results of the pairwise comparison, presented in Table 24 correspond to the first column of the cluster matrix for variant 2, shown in Table 26. An interpretation of the cluster matrix for variant 1 in the last column would be, that Emissions, Energy and Circularity Potential have all same impact (0.33) on the Alternatives.

Table 24 Pairwise comparisons wrt. to emissions for variant 2

Emissions	Em	En	CP	Altern.	EV
Emissions (Em)	1	9	9	9	0.750
Energy (En)	1/9	1	1	1	0.083
Circularity Potential(CP)	1/9	1	1	1	0.083
Alternatives	1/9	1	1	1	0.083

CR = 0.000

Table 25 Cluster matrix for variant 1

Variant 1	Em	En	CP	Altern.
Emissions (Em)	0.250	0.333	0.333	0.333
Energy (En)	0.250	0.000	0.333	0.333
Circularity Potential (CP)	0.250	0.333	0.000	0.333
Alternatives	0.250	0.333	0.333	0.000

Table 26 Cluster matrix for variant 2

Variant 2	Em	En	CP	Altern.
Emissions (Em)	0.750	0.818	0.818	0.818
Energy (En)	0.083	0.00	0.091	0.091
Circularity Potential (CP)	0.083	0.091	0.000	0.091
Alternatives	0.083	0.091	0.091	0.000

4.6.2. Criteria interdependence

This chapter outlines the interdependencies between the criteria examined in this thesis and proposes a method for measuring these relationships. The initial stage involves identifying any potential interdependencies among the criteria, which will then be validated later in this chapter. Initially, the decision making problem was assumed to have the following interdependencies:

- **GWP, ADPfossil, ADPelem, PERT/PET:**
  The calculation method for these four criteria is the life cycle assessment, suggesting here already a correlation among them. For the use of non-renewable primary energy, fossil fuels are consumed, causing the share of greenhouse gas emissions to increase. That means, that an increase of the share of renewable primary energy could suggest a decrease of the greenhouse gas emissions and therefore a decrease in the values for global warming potential. Furthermore, nonrenewable primary energy is also mostly generated by fossil fuels, establishing direct relation between the consumption and extraction of fossil fuels and the use of nonrenewable primary energy. Thus, the increase of the share of renewable primary energy, or the decrease the share of nonrenewable primary energy, could suggest a decrease of the values for ADP.
- **Harmful Emissions and Circularity Potential (Pre-Use & Post- Use):**
  The absence of harmful substances in building materials is a prerequisite for the materials' circularity potential, being this relation of extreme relevance (Rosen, 2021).
- **PERT/PET and Circularity Post Use:**
  For the calculation of the Post-Use Circularity potential, the energy demand for the machine use in the deconstruction of buildings elements makes a great part of the calculation. That is expressed in the form of a factor (factor work fw) in the calculation of the Urban Mining Index (Rosen, 2021).

The calculated values for the various ceiling structures in Chapter 4.5 are visually presented in Figure 18 for the cases of interdependence between GWP-PERT/PET and PERT/PET-ADP(f). The diagrams have the different ceiling structures plotted on the x-axis and the corresponding values for each criterion on the y-axis. Analysing the relationship between GWP and PERT/PET (Figure 18) it is evident that the GWP and PERT/PET criteria are correlated. For all seven ceiling structures, higher GWP values correspond to lower shares of renewable primary energy, demonstrating here already an inverse relation between these two criteria.

To prove and quantify the degree of interdependence among these criteria, the Pearson correlation coefficient was applied. This coefficient describes the relationship between two different parameters. It ranges between -1 and +1 and values between -1 or +1 denote a strong correlation among two indicators. A positive correlation coefficient describes a positive linear relation, meaning that if values of one indicator increase, the values of the other indicator are also increased. Similarly is for negative values, where if one indicator increases its values, the other indicator decreases its values. (Djordjević et al., 2021)

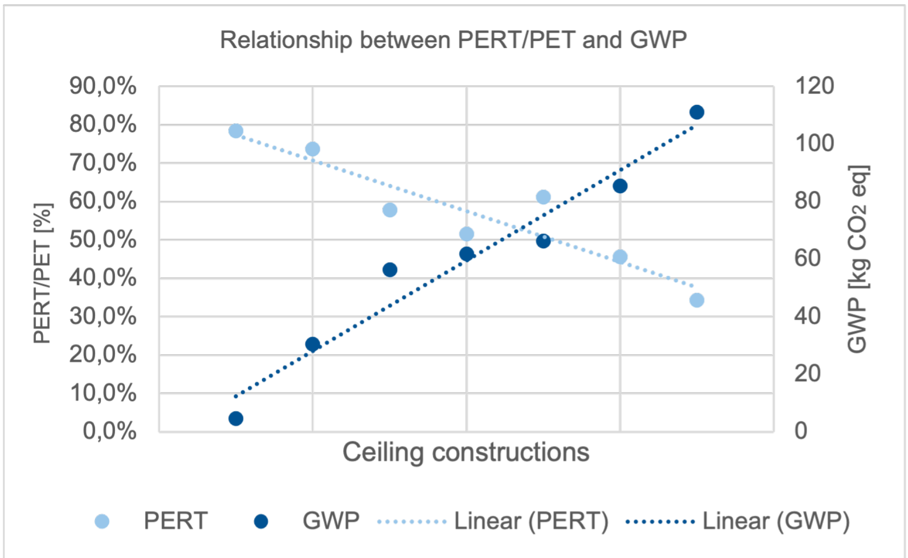


Figure 18 Interdependence between GWP and PERT/PET

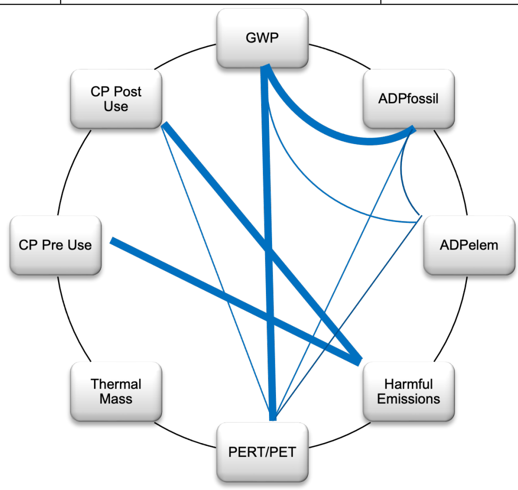
The Pearson correlation coefficients were calculated with the values of the seven ceiling samples obtained in Chapter 4.5 for the mentioned correlation hypothesis. Table 27 show the calculated values for the Pearson correlation coefficient and the Figure in the table shows graphically the criteria interdependencies in the model. Strong correlations are represented with thick arrows, while weak correlations with thin arrows.

The Pearson correlation coefficient calculated between the global warming potential (GWP) and abiotic depletion potential (fossil) provides evidence to support the assumption that these two parameters influence each other. The results indicate a strong, almost linear positive relationship (0.9467, see Table 27) between GWP and ADP(f). Similar relationships were observed between GWP and ADP(e), GWP and PERT/PET, and PERT/PET and ADP(f). For the case of the relationship between the presence of harmful emissions and the circularity potential in the pre-use and post-use phases, the Pearson correlation could not be calculated due to insufficient results (see chapter 4.5.1.4). Since the absence of pollutants is a prerequisite for the circularity of a material, a correlation coefficient of 1.0 was assumed.
Nevertheless, the hypothesis done earlier in this chapter about the correlation between the share of renewable primary energy with the Circularity Potential in the Post-Use phase is not entirely consistent, as the Pearson coefficient of 0.3569 indicates a mild to moderate relation between the two parameters.

Once the correlation among the criteria has been established, the next step involves conducting pairwise comparisons among the criteria to define the degree of importance of one criteria over another. These comparisons are performed *clusterwise*. The pairwise comparisons are differentiated into two types: **inner dependency**, where criteria within the domain of one cluster are compared one to another and **outer dependency**, where

Table 27 Criteria interaction and corresponding Pearson correlation coefficient

Criteria interaction		Pearson coefficient
GWP	ADPfossil	0.9467
GWP	ADPelem	0.6541
GWP	PERT/PET	-0.9669
ADPf	ADPelem	0.6832
PERT/PET	ADPfossil	-0.9851
PERT/PET	ADPelem	-0.6617
PERT/PET	CP Post Use	0.3569
CP Post Use	Harmful Emissions	1.0000
CP Pre Use	Harmful Emissions	1.0000



one criteria is compared with criteria present in the domain of another cluster (Ishizaka & Nemery, 2013). One example of inner dependency is to pairwise compare the global warming potential with the abiotic depletion potential (fossil) - both criteria present in the Emissions cluster. An example of outer dependency is to compare the share of primary energy demand with the global warming potential.

Some of the pairwise comparisons are represented in Table 28 - 30. The Pearson correlation coefficient between the GWP and the ADPf corresponds to 0.947 and between GWP and ADPe corresponds to 0.654, as it is presented in Table 28.This implies that the ADPf is 1.447 times (ratio between 0.947 and 0.654) more relevant than the ADPe with respect to GWP. As a result, the pairwise comparison matrix was set to reflect this relevance factor of 1.447. The corresponding eigenvalue was calculated, indicating that - within the Cluster Emissions - ADPf has 59.1% influence on the GWP, whereas ADPe has a 40.9% influence.

For all cases where a criterion is related to multiple criteria within a cluster, the above mentioned approach was applied. In such situations, pairwise comparisons were conducted to determine the weightings of each criterion within the cluster (Kadoić et al., 2017). However, when a criterion is associated with only one other criterion in a cluster, no pairwise comparisons were necessary as the cluster is solely influenced by that criterion (100%) (Kadoić et al., 2017). This is evident for the case for the relation of the global warming potential in the cluster Energy, where the GWP depends exclusively on the share of renewable primary energy.

Table 28 Pairwise comparisons in the Emissions cluster wrt. to Global Warming Potential

Global Warming Potential			Pairwise comparison		
	Pearson Coef.	Absol. ratio	ADPf	ADPe	**EV**
ADPf	0.947	1.447	1	1.447	**0.591**
ADPe	0.654		1/1.447	1	**0.409**

Table 29 Pairwise comparisons in the emissions cluster wrt. to Abiotic Depletion Potential (fossil)

Abiotic Depletion Potential (fossil)			Pairwise comparison		
	Pearson Coef.	Absol. ratio	GWP	ADPe	**EV**
GWP	0.947	1.386	1	1.386	**0.581**
ADPe	0.683		1/1.386	1	**0.419**

Table 30 Pairwise comparisons in the Circularity Potential cluster wrt. to Harmful Emissions

Harmful Emissions			Pairwise comparison		
	Pearson Coef.	Absol. ratio	Pre-Use	Post-Use	**EV**
Pre-Use	1.000	1.000	1	1	**0.500**
Post-Use	1.000		1	1	**0.500**

After using this approach for all proposed interdependencies in this work, the results for the eigenvalues can be summarized in one table (Table 31). The local priority values presented in Table 28, for instance, can be seen in the second and third entry of the first column in Table 31. For cases with only one interdependence within on cluster, the matrix was filled with 1.0 and for cases of no interdependence, with zero.

Table 31 Overview of local priorities (eigenvectors)

	Em1	**Em2**	**Em3**	**Em4**	**En1**	**En2**	**CP1**	**CP2**
Em1:GWP	0.000	**0.581**	**0.489**	0.000	**0.369**	0.000	0.000	0.000
Em2:ADP(f)	**0.591**	0.000	**0.511**	0.000	**0.376**	0.000	0.000	0.000
Em3:ADP(e)	**0.409**	**0.419**	0.000	0.000	**0.253**	0.000	0.000	0.000
Em4:Harm.Em.	0.000	0.000	0.000	0.000	0.000	0.000	**1.000**	**1.000**
En1:PERT/PET	**1.000**	**1.000**	**1.000**	0.000	0.000	0.000	0.000	**1.000**
En2:Therm.Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CP1:Pre-Use	0.000	0.000	0.000	**0.500**	0.000	0.000	0.000	0.000
CP2:Post-Use	0.000	0.000	0.000	**0.500**	**1.000**	0.000	0.000	0.000

4.6.3. Criteria comparison

An essential aspect of the ANP is to evaluate the significance of one criterion over another criterion with regard to each alternative. This involves determining how much more relevant one specific criterion is compared to another criterion when evaluating a particular ceiling (Fernando, 2020).

The definition of the importance degree for the criteria in the model is difficult to quantify, since benchmarks for all the selected criteria are not yet defined. The German rating system "Bewertungssystem Nachhaltiges Bauen" (BNB), for example, establish a value of 24 kg CO_2eq/m^2NGF*a for the global warming potential and a percentage of at least 37% for the share of renewable primary energy in the building sector (Bundesministerium des Innern, für Bau und Heimat, n.d.-a). Benchmarks limiting and regulating the abiotic depletion potential or the circularity potential in the pre/post -use phase are not available and thus the comparison of the degree of importance of one criterion over another is in the scope of this work not possible. Furthermore, sustainability parameters and their benchmarks strongly depend on climatic boundaries and national and local regulations, being this one one of the reasons for divergences in the weighting of sustainability certification systems.

For these reasons, this work firstly assumes, that all criteria in the model have the same importance degree in the achievement of sustainability in the ceiling samples (Variant 1). This is shown in Table 32, where pairwise comparison in the cluster Emissions with regard to the ceiling reinforced concrete are presented. In this case, each criterion in the Emissions cluster has an equal weight of 25%, and each of the two Energy and Circularity Potential criteria has a weight of 50%, resulting in the values presented in Table 34.

Variant 2 takes a different approach by considering the global warming potential as the most relevant criterion when designing sustainable ceilings. With the building sector contributing for 40% of the world's total greenhouse gas emissions (United Nations Environment Programme, 2021), giving more weight to this criterion in the ANP-model can be an effective strategy to mitigate the environmental impacts of building elements and achieve the environmental goals of the project.

Table 33 illustrates this scenario, where pairwise comparisons within the cluster Emissions with regard to the reinforced concrete were performed. In this case, global warming potential carries a weight of 75% in the sustainability evaluation of the ceiling, while the remaining emissions criteria each carry a weight of only 8.3%. For the clusters "Energy" and "Circularity Potential", the weightings remain the same as in variant 1 since no criteria in these clusters are highly weighted.

Table 32 Pairwise comparisons wrt. to the reinforced concrete for variant 1

B-konv_DE_StB	GWP	ADP(f)	ADP(e)	Harmful Emis.	**EV**
GWP	1	1	1	1	**0.250**
ADPf	1	1	1	1	**0.250**
ADPe	1	1	1	1	**0.250**
Harmful Emissions	1	1	1	1	**0.250**

CR = 0.000

Table 34 and Table 35 present the results obtained for respectively, variant 1 and variant 2. The results for variant 2 highlight the higher weight assigned to GWP in comparison to all other criteria. The resulted eigenvector of the pairwise comparison shown in Table 33 corresponds to the first four entries of column 1 in Table 35.

Table 33 Pairwise comparisons wrt. to the reinforced concrete variant 2

B-konv_DE_StB	GWP	ADP(f)	ADP(e)	Harmful Emis.	**EV**
GWP	1	9	9	9	**0.750**
ADPf	1/9	1	1	1	**0.083**
ADPe	1/9	1	1	1	**0.083**
Harmful Emissions	1/9	1	1	1	**0.083**

CR = 0.000

Table 34 Eigenvalues for Variant 1

Variant 1	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
GWP	0.250	0.250	0.250	0.250	0.250	0.250	0.250
ADPf	0.250	0.250	0.250	0.250	0.250	0.250	0.250
ADPe	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Harm. Em.	0.250	0.250	0.250	0.250	0.250	0.250	0.250
PERT/PET	0.500	0.500	0.500	0.500	0.500	0.500	0.500
Thermal Mass	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP Pre-Use	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP Post-Use	0.500	0.500	0.500	0.500	0.500	0.500	0.500

Table 35 Eigenvalues for Variant 2

Variant 2	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
GWP	0.750	0.750	0.750	0.750	0.750	0.750	0.750
ADPf	0.083	0.083	0.083	0.083	0.083	0.083	0.083
ADPe	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Harm. Em.	0.083	0.083	0.083	0.083	0.083	0.083	0.083
PERT/PET	0.500	0.500	0.500	0.500	0.500	0.500	0.500
Thermal Mass	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP Pre-Use	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP Post-Use	0.500	0.500	0.500	0.500	0.500	0.500	0.500

4.7. Supermatrix

The supermatrix in the Analytic Network Process is a quadratic *nxn* matrix, where *n* is the number of nodes in the decision making problem (Saaty & Vargas, 2006). Since the model consists of eight criteria and seven alternatives, the supermatrix is going to be a 15x15 matrix. The entries of the unweighted supermatrix describe the interaction between the different nodes and they are equal to zero, if there is no interaction between two nodes. (Saaty and Vargas, 2006, Kadoić, 2018). Important steps of the ANP is the calculation of two different supermatrices: *the unweighted and the weighted supermatrices*.

The unweighted supermatrix is an unnormalized matrix with the priority vectors gained from the pairwise comparisons between the elements of the decision making problem, calculated in Chapter 4.6. (Saaty & Vargas, 2006). An example of one supermatrix is represented below.

$$\bar{W} = \overbrace{}^{\text{Criteria}}\overbrace{}^{\text{Alternatives}} \begin{bmatrix} w_{1,1} & w_{1,2} & & \cdots & w_{1,n} \\ w_{2,1} & w_{2,2} & & \cdots & \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \\ w_{n,1} & \cdots & & \cdots & w_{n,n} \end{bmatrix} \begin{matrix} \left.\right\} \textit{Criteria} \\ \left.\right\} \textit{Alternatives} \end{matrix} \tag{4.1}$$

Table 36 shows the unweighted supermatrix for variant 1. The upper-left quadrant of the unweighted matrix (criteria-criteria block in the exemplary matrix above) is filled with the priority values of the pairwise comparisons done in Chapter 4.6.2 (Table 31). The priority values obtained in Chapter 4.6.3 (Table 34 for variant 1) are located in the upper-right quadrant (criteria-alternatives block), while the priority vectors obtained in Chapter 4.5 (Table 22 and 23) are located in the lower-left-quadrant (alternatives-criteria block). Due to the absence of interconnections among the alternatives in this decision making problem, the quadrant in the lower-right corner of the matrix contains only zeros. (Aydogan et al., 2009)
The weighted super matrix is derived from that matrix, where the different entries of the unweighted super matrix are weighted with the different cluster weights, calculated in chapter 4.6.1 (Table 25 for variant 1). For example, the entry $w_{1,1}$ of the cluster matrix (Table 25), which corresponds to 0.25, needs to be multiplied by all the entries of the block Emissions-Emissions $w_{1,1}$ - $w_{4,4}$ of the unweighted supermatrix in Table 36. Analog is the multiplication of $w_{1,4}$ of the cluster matrix (0.33) by all the entries of the block Emissions-Alternatives in the unweighted supermatrix $w_{1,9}$-$w_{4,15}$. (Aydogan et al., 2009)
Note that the weighted supermatrix must be column stochastic, i.e., the sum of each column equals to one (Saaty & Vargas, 2006). That means, that after multiplying the unweighted supermatrix by the entries of the cluster matrix, each entry in a column is divided by the total sum of that column, resulting in the entries of the weighted super matrix in Table 37 (Saaty & Vargas, 2006).
The results for the unweighted and weighted supermatrices for variant 1 and variant 2 are presented in the appendix A. The unweighted supermatrices for both variants are very similar, with the only difference found in the upper-right quadrant where the criteria were compared with respect to the different alternatives (Chapter 4.6.3). The weighted supermatrices strongly differ between the two variants because the clusters in each variant weight differently, leading to significant variations in the resulting weighted supermatrices.

Table 36 Unweighted supermatrix for variant 1

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	...	A7
Em1: GWP	0.000	0.581	0.489	0.000	0.369	0.000	0.000	0.0000	0.250	...	0.250
Em2: ADPf	0.591	0.000	0.511	0.000	0.376	0.000	0.000	0.000	0.250	...	0.250
Em3: ADPe	0.409	0.419	0.000	0.000	0.253	0.000	0.000	0.000	0.250	...	0.250
Em4: Harmful Em.	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.250	...	0.250
En1: PERT/PET	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	0.500	...	0.500
En2:Thermal Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	...	0.500
CP1: CP Pre-Use	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.500	...	0.500
CP2: CP Post-Use	0.000	0.000	0.000	0.500	1.000	0.000	0.000	0.000	0.500	...	0.500
A1: B-konv_DE_StB	0.028	0.107	0.000	0.143	0.085	0.281	0.036	0.141	0.000	...	0.000
A2: B_DE_BST_tE	0.678	0.168	0.209	0.143	0.195	0.080	0.357	0.165	0.000	...	0.000
A3:B_DE_BSP_nE	0.103	0.188	0.209	0.143	0.183	0.094	0.135	0.131	0.000	...	0.000
A4:B_DE_R_nE	0.051	0.132	0.179	0.143	0.128	0.101	0.130	0.138	0.000	...	0.000
A5:B_DE_HK_nE	0.056	0.141	0.209	0.143	0.144	0.098	0.136	0.138	0.000	...	0.000
A6:B_DE_HBV(HTB)	0.037	0.123	0.090	0.143	0.113	0.253	0.075	0.141	0.000	...	0.000
A7: B_DE_HBV(BST)	0.047	0.142	0.104	0.143	0.152	0.093	0.131	0.145	0.000	...	0.000

Table 37 Weighted supermatrix for variant 1

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	...	A7
Em1: GWP	0.000	0.194	0.163	0.000	0.118	0.000	0.000	0.000	0.083	...	0.083
Em2: ADPf	0.197	0.000	0.170	0.000	0.120	0.000	0.000	0.000	0.083	...	0.083
Em3: ADPe	0.136	0.140	0.000	0.000	0.082	0.000	0.000	0.000	0.083	...	0.083
Em4: Harmful Em.	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.333	0.083	...	0.083
En1: PERT/PET	0.333	0.333	0.333	0.000	0.000	0.000	0.000	0.333	0.167	...	0.167
En2:Thermal Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.167	...	0.167
CP1: CP Pre-Use	0.000	0.000	0.000	0.250	0.000	0.000	0.000	0.000	0.167	...	0.167
CP2: CP Post-Use	0.000	0.000	0.000	0.250	0.340	0.000	0.000	0.000	0.167	...	0.167
A1:B-konv_DE_StB	0.009	0.036	0.000	0.071	0.028	0.281	0.018	0.047	0.000	...	0.000
A2:B_DE_BST_tE	0.226	0.056	0.069	0.071	0.065	0.080	0.179	0.056	0.000	...	0.000
A3:B_DE_BSP_nE	0.034	0.063	0.069	0.071	0.061	0.094	0.068	0.043	0.000	...	0.000
A4:B_DE_R_nE	0.017	0.044	0.059	0.071	0.043	0.101	0.065	0.046	0.000	...	0.000
A5:B_DE_HK_nE	0.019	0.047	0.069	0.071	0.048	0.098	0.068	0.046	0.000	...	0.000
A6:B_DE_HBV(HTB)	0.012	0.041	0.030	0.071	0.038	0.253	0.037	0.047	0.000	...	0.000
A7: B_DE_HBV(BST)	0.016	0.047	0.035	0.071	0.051	0.093	0.065	0.049	0.000	...	0.000

5. Results

The Analytic Network Process determines the final weights of the alternatives with the help of a limit matrix. This matrix is calculated by raising the weighted supermatrix (W) to a high power (Saaty & Vargas, 2006), as shown in the formula below.

$$\lim_{k \to \infty} W^k \tag{5.1}$$

The limit matrix was calculated with the help of the software Super Decisions and the results for variant 1 and variant 2 are shown in Appendix A.5 and A.6, respectively. The values of each row in the limit matrix are identical and describe the final weight of each element of the decision making problem (criteria and alternatives). For instance, the final weights of the criteria are described in rows 1-8 of the limit matrix, while the final weights of the alternatives are described in rows 9-15.

There are two approaches to calculate the final weights of the alternatives. As mentioned above, the first approach is to directly read the values from the limit matrix in the rows presenting the alternatives (rows 9-15 in the limit matrix presented in Appendix A.5 - A.6). However, this approach may make it challenging to interpret the results effectively and analyse exactly what is influencing the final weightings/rankings of the ceilings.

To address this challenge, the second approach involves multiplying the final weights of the criteria (presented in the limit matrix, rows 1-8) with the normalized weighted values of the alternatives (lower left quadrant of the weighted supermatrix in Table 37).

The limit matrix determines the final weighting of the criteria by assessing all the interdependencies (as discussed in Section 4.6.2) and assumptions established within the model (as discussed in Section 4.6.3). For instance, when a criterion in the model has numerous interdependencies with other criteria (e.g., the share of renewable primary energy, which depends on four other criteria), its final weighting/relevance in the model increases. Conversely, if a criterion lacks correlation with other criteria (e.g., thermal mass), its final weighting will not be substantial. However, within the scope of this work, it is not feasible to provide a detailed mathematical explanation of how precisely the results of the limit matrix are calculated.

As mentioned before, one of the approaches involves multiplying the criterion's final weighting with the normalized weighted values of the ceilings. Consequently, if a criterion holds a high final weighting, it significantly influences the rankings of the ceilings.

The following chapters present the results of the ANP model separately for variant 1 (Section 5.1) and variant 2 (Section 5.2). This includes the demonstration of the final criteria weighting, followed by the presentation of the final weighting/rankings of the ceiling structures. Subsequently, a sensitivity analysis is conducted for variant 1 to assess the robustness of the model (Section 5.3).

5.1. Variant 1: equally weighted variant

The results of the limit matrix for variant 1 is presented in the Appendix A.5. Table 38 presents the resulted final weightings for the various criteria derived from the limit matrix. The most influential criterion among the eight analyzed criteria is the share of renewable primary energy with a weight of 0.1551, followed by the circularity potential in the post-use phase (0.1276) and harmful emissions (0.1052). The ADP(f) and GWP criteria are ranked 5th and 6th, respectively, with very similar final weightings. The criteria with the lowest weighting on the final results are ADP(e) and thermal mass, respectively. It is interesting to note that the criteria in the Emissions cluster do not have a significant influence in the model, with the exception of the criteria harmful emissions.

Table 38 Final criteria weight for Variant 1 resulted from the limit supermatrix

Criterion	**Final Weight (Limit Matrix)**
GWP	0.0660
ADP(f)	0.0668
ADP(e)	0.0562
Harmful Emissions	0.1052
PERT/PET	0.1551
Thermal Mass	0.0495
CP Pre Use	0.0758
CP Post Use	0.1276

To calculate the final weightings of the seven ceiling structures, the values presented in Table 38 are multiplied by the values of the lower left quadrant of the weighted supermatrix (Table 37). The final calculated weights for the ceilings are presented in Table 39 (raw values). The table also shows the normalized weight results for a better comprehension of the results. For better visualisation of the importance degree of each ceiling, the *Final Weight Ideal* was calculated by dividing the raw result of each ceiling by the raw result of the best ceiling (B_DE_BST_tE), which corresponds to 0.065.

Table 39 Final weights of the alternatives for Variant 1

Alternatives	**Final Weight *Raw***	**Final Weight *Normalized***	**Final Weight *Ideal***
B-konv_DE_StB	0.036	0.122	0.561
B_DE_BST_tE	0.065	0.217	1.000
B_DE_BSP_nE	0.043	0.144	0.660
B_DE_R_nE	0.037	0.126	0.578
B_DE_HK_nE	0.039	0.131	0.604
B_DE_HBV(HTB)	0.040	0.134	0.618
B_DE_HBV(BST)	0.037	0.125	0.576

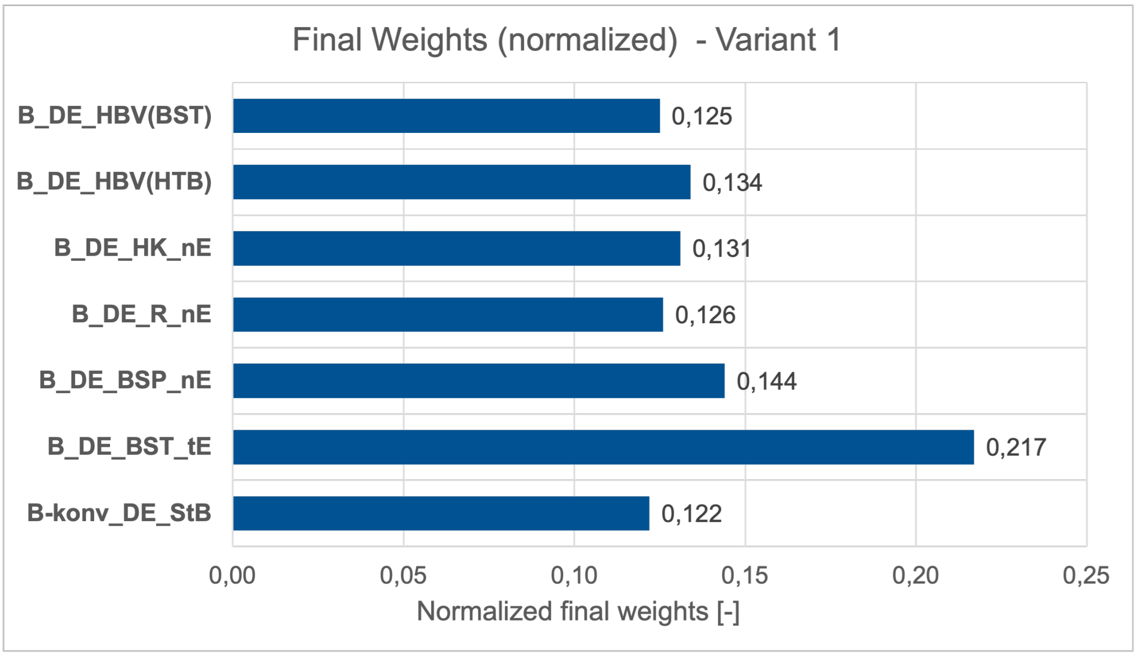


Figure 19 Normalized final weights for the seven ceiling structures

Figure 19 shows the normalized final ranking of the seven ceiling structures for variant 1, which indicate that the board-stacked ceiling (B_DE_BST_tE) is by far the superior solution. This ceiling outperforms all other options for almost every calculated criterion, with the exception of thermal mass. However, given that thermal mass has relatively little weight in the final results (only 0.0495, as shown in Table 38), its inferior performance does not significantly impact the overall performance of this ceiling. In addition, the board-stacked ceiling has the highest share of renewable primary energy of all ceilings, which is the most heavily weighted criterion in the model, also reinforcing its final results. The excellent performance of this ceiling is also supported by its strong pre-use circularity potential, which is another relevant criterion for the final results.

Following this ceiling, the cross-laminated timber ceiling (B_DE_BSP_nE) takes second place with a normalized final ranking of 0.144. This is mainly due to its great performance in criterion share of renewable primary energy, thereby contributing significantly to its high final weighting. The poor performance in thermal mass does not seem to have a significant impact on the overall performance of this ceiling.

The timber-concrete composite system ceiling (B_DE_HBV(HTB)) follows with the third rank. Despite including concrete in its composition, the combination of timber and concrete brings numerous environmental advantages. Notably, this ceiling demonstrates a higher share of renewable primary energy compared to reinforced concrete (34.37% vs. 45.60%) and a higher pre-use circularity potential (4.55% vs. 9.48%), which has a positive influence in the ranking of this ceiling, mainly caused by the presence of timber in the composition. Interestingly, the high GWP values of this ceiling, attributed to the presence of concrete, do not significantly impact its overall ranking, because the GWP do not have an substantial influence in the final results. Furthermore, this ceiling shows great thermal storage capabilities, as demonstrated by its high thermal mass values discussed in Section 4.5.2.2.

The hollow box ceiling (B_DE_HK_nE) and the ripped ceiling (B_DE_R_nE) follow with the fourth and fifth rank with a normalized final weighting of respectively 0.131 and 0.126. In this variant, the timber-composite system ceiling (B_DE_HBV(BST)) and the reinforced concrete ceiling are the two worst options, respectively.

5.2. Variant 2: ecological variant

This chapter presents the results obtained for variant 2 and highlights the main differences between variant 1 and 2. Table 40 presents the final weights assigned to each criterion, showing that the global warming potential is the most significant criteria in this variant, strongly influencing the final ranking of the alternatives. Additionally, the abiotic depletion potential for fossil fuels and elements hold, respectively, the second and third most relevant positions in the decision making model.
The share of renewable primary energy and harmful emissions follow, respectively. Interesting is that, for both models, the thermal mass is the least important criterion for determining sustainable ceiling structures in both models. Figure 21 illustrates a comparison of the eight criteria weighting between the two variants, highlighting the significant emphasis of the emissions criteria in the final results of the model for variant 2.
The final results of the seven ceiling structures, similar as for variant 1, were calculated by multiplying the final criteria weightings (Table 40) by the values of the lower-left quadrant of the weighted supermatrix (Appendix A.4). The resulting final weightings of the alternatives are described in Table 41 (raw weights).The normalized results of the seven ceilings are shown graphically in Figure 20.

Table 40 Final criteria weight for variant 2 resulted from the limit supermatrix

Criterion	**Final Weight (Limit Matrix)**
GWP	0.2886
ADP(f)	0.2558
ADP(e)	0.2065
Harmful Emissions	0.0355
PERT/PET	0.0747
Thermal Mass	0.0046
CP Pre Use	0.0135
CP Post Use	0.0202

The top two ranked ceiling structures in variant 2 are similar to those in variant 1, with the board-stacked ceiling (B_DE_BST_tE) showing the best performance, followed by the cross-laminated timber ceiling (B_DE_BSP_nE). It seems that the divergences in criteria weighting do not significantly impact the performance of these ceilings. Additionally, the reinforced concrete ceiling remains as the poorest performance ceiling option in both variants, highlighting again its significant environmental impact.

Table 41 Final weights of the alternatives for Variant 2

Alternatives	**Final Weight *Raw***	**Final Weight *Normalized***	**Final Weight *Ideal***
B-konv_DE_StB	0.0079	0.0791	0.2601
B_DE_BST_tE	0.0306	0.3043	1.0000
B_DE_BSP_nE	0.0156	0.1553	0.5106
B_DE_R_nE	0.0120	0.1198	0.3937
B_DE_HK_nE	0.0130	0.1296	0.4261
B_DE_HBV(HTB)	0.0103	0.1027	0.3376
B_DE_HBV(BST)	0.0109	0.1088	0.3577

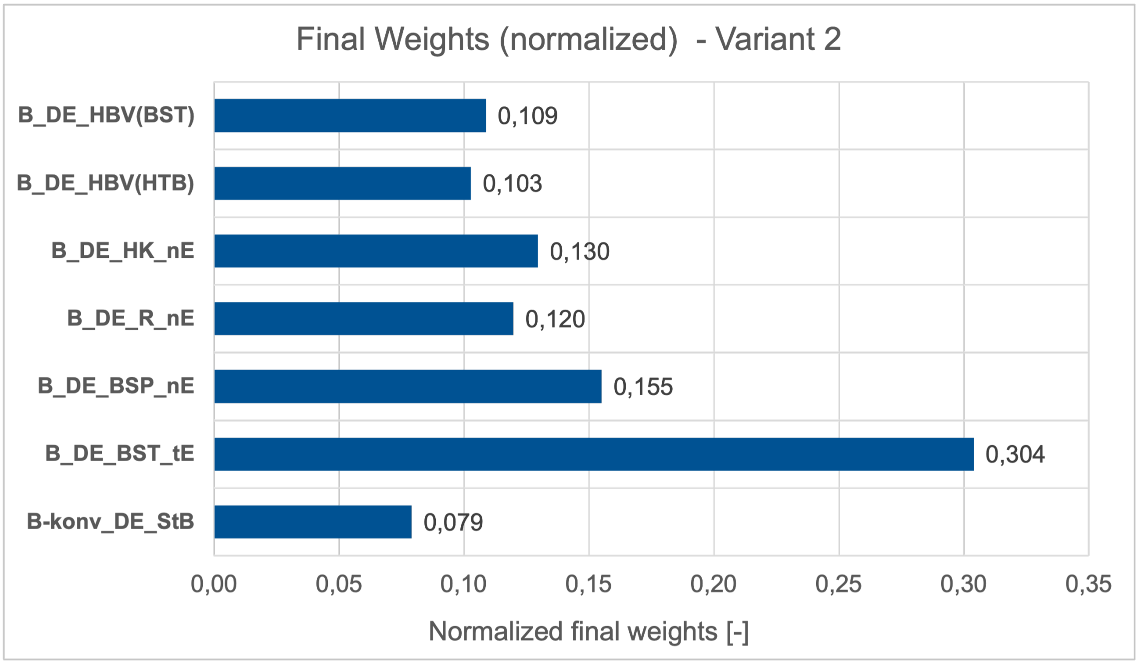


Figure 20 Normalized final weights for the seven ceiling structures - Variant 2

In variant 2, the board stacked ceiling (B_DE_BST_tE) achieves a higher final weighting compared to variant 1 (variant 1 0.217 and variant 2 0.304), mostly due to its excellent performance in the GWP criterion, as discussed in Chapter 4.5.1.1. This is also evident in Figure 22, which compares the final weightings for the alternatives between the two variants. Since GWP is the most heavily weighted criterion in the model (0.2886 as presented in Table 40), the board stacked ceiling's final weighting is accordingly increased.
This tendency is also visible for reinforced concrete ceiling. Despite being the poorest performing ceiling in both variants, the reinforced concrete ceiling exhibits a considerably lower final weighting for variant 2 (0.079) compared to variant 1 (0.122).
The hollow box ceiling (B_DE_HK_nE) takes the third position with a normalized final ranking of 0.1296. In variant 1, this ceiling holds the fourth rank with a very similar normalized final weighting of 0.131. Following closely is the ribbed ceiling, ranking fifth among the available ceiling structures. Next, the two timber concrete composite system ceilings hold the fifth and sixth positions, showing similar weightings in this variant. The B_DE_HBV(BST) ceiling slightly outperforms the B_DE_HBV(HTB) ceiling, which could

potentially be attributed to the reduced amount of concrete used in its composition.
In general, the final weightings/ranking and final rankings between the two variants are very similar. That is also shown in Figure 22, where the normalized final weightings of the two variants are compared. The main difference lies in the fact that in variant 2 the timber-concrete composite system ceiling (B_DE_HBV(HTB)) ranks number 6, while in variant 1 it ranks number 3. The timber-concrete composite system (B_DE_HBV(HTB)) demonstrates high values for GWP, making it the second poorest performing ceiling in terms of this criterion (Section 4.5.1.1). Consequently, when the global warming potential is given excessive weight, the performance of this ceiling is considerably worse.

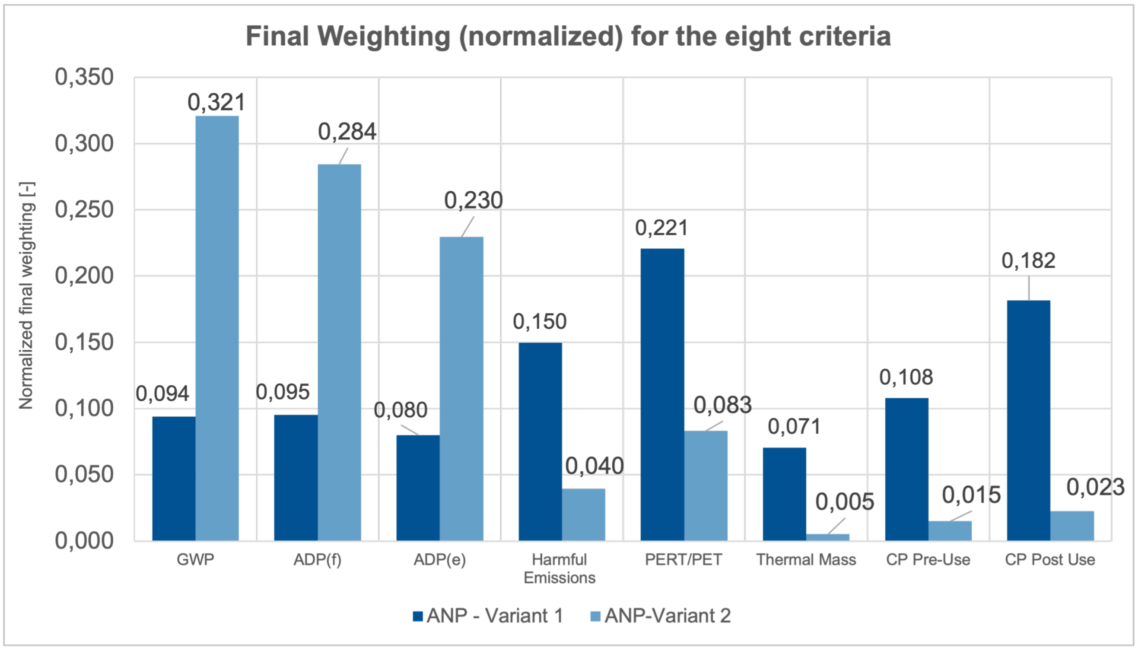


Figure 21 Comparison of variant 1 and variant 2: normalized final weights for the eight criteria

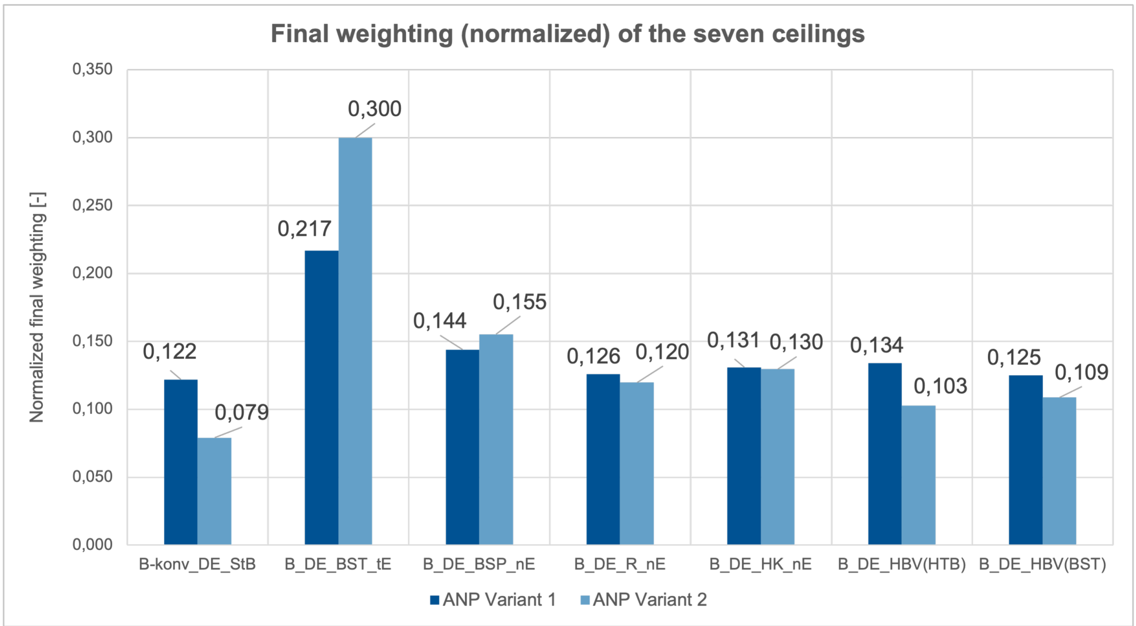


Figure 22 Comparison of Variant 1 and Variant 2: normalized final weights for the seven ceiling structures

5.3. Sensitivity analysis

Sensitivity analysis reveals which criteria are the most influential within the network by investigating how the model corresponds to changes in the criteria weighting. It is commonly used to analyse how the rankings of the alternatives are impacted if the criteria weight is also changed. That facilitates a more comprehensive and precise examination of the reliability of the model. (Adams, 2014)
The Analytic *Hierarchy* Process (AHP) sensitivity alters only one single local weight of the decision making problem (only one entry of the decision matrix) and evaluates the resulting impact on the final results of the alternatives. However, when it comes to network models with many interpendecies, changing only one entry of the decision matrix may not significantly alter the alternative weighting/results. When performing sensitivity analysis for network structures (ANP), the entire row of a given criteria is modified to assess its impact on final outcomes. This involves adjusting all numerical data associated with the node, allowing this way a recalculation of alternative rankings. This approach in the Analytic Network Process is referred to as *Row Sensitivity Analysis.* (Adams, 2014)

The key distinction between variant 2 and the sensitivity analysis (for the GWP) approach lies in the way they handle weighting of the global warming potential criterion. In variant 2, a single entry of the supermatrix is selectively assigned a higher weight, as discussed in Section 4.6.3, while the sensitivity analysis modifies all data in the model that is related to the global warming potential criterion. That includes changing the degree of interdependencies among criteria as well.
To assess the different weighting scenarios in ANP, a parameter p, which represents the importance of a single node, is used. The parameter p lies between 0 and 1. Parameter $p = 0$ means the weakest weighting of the analyzed criterion and $p = 1.0$ means the whole model was designed, so that this criterion becomes the maximal weight it can have. That includes increasing all entries in the supermatrix, that have something to do with this criteria. There is a fixed point (resting parameter) called p_0 that represents the original weight of the nodes. There are 3 ways to define the resting parameter p_0, being the most common used value is $p_0 = 1/2$ and thus for the sensitivity analysis of this model $p_0 = 1/2$ is going to be used. (Adams, 2014)
The sensitivity analysis for variant 1 - where all criteria are equally weighted-, was chosen for further calculations. It is the starting point, to some degree a classic and unbiased model for this decision making problem, where no assumptions and criteria preferences were established. This allows a better comprehension of the different weighting scenarios in the model.
Figure 23 shows the sensitivity analysis for each criterion of the cluster Emissions. The x-axis represents various values for the parameter p, which indicates different weighting scenarios for the analyzed criterion. Meanwhile, the y-axis represents the normalized final results for the different alternatives. The results presented in Chapter 5.1 are represented in the graph for the case $p_0 = 0.50$. The diagrams show, what would happen to the final normalized weight of each of the ceiling alternatives, if the considered criterion's weight is maximized ($p = 1.0$) or minimized ($p = 0.0$). For the global warming potential

(Figure 23 (upper left) for instance, minimizing the weight for GWP in the model gives only a minimal final weighting change, while maximizing the criterion's weight almost triples the ranking for the board-stacked ceiling (B_DE_BST_tE, green line) and halve the weights of the other ceilings.The results align with the results found in the ANP model (presented in Chapters 5.1 and 5.2). Considering the scenario where only one GWP entry in the supermatrix is overweighted (variant 2), the board stacked-ceiling already demonstrated an improvement in the results, as shown in Figure 19 and 20. Taking this into account, it can be inferred that modifying the entire model or adjusting all numerical data associated with the global warming potential would significantly improve the values for the board stacked-ceiling.

Changing the weights of ADP(f) and harmful emissions do not bring many changes to the

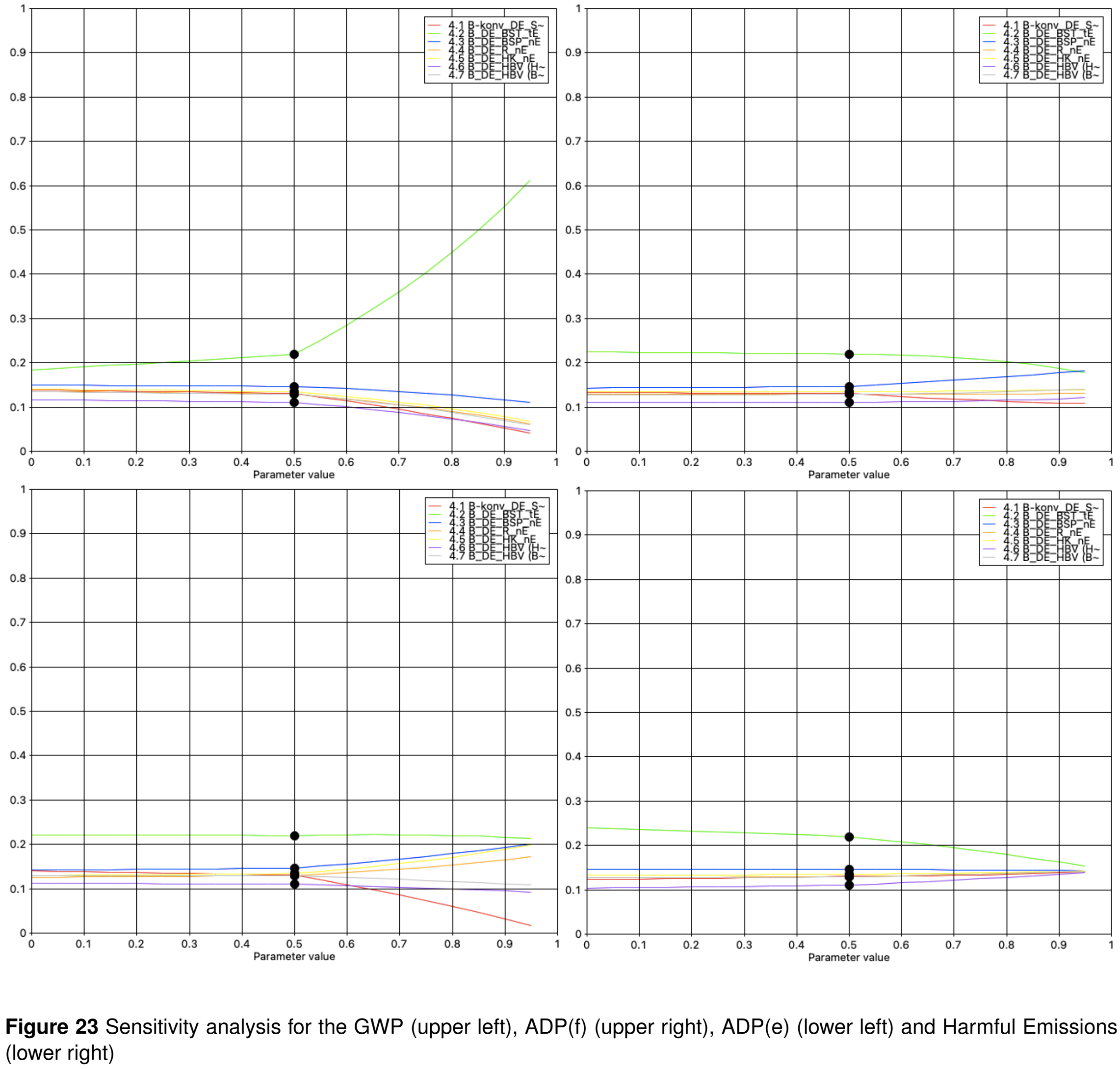


Figure 23 Sensitivity analysis for the GWP (upper left), ADP(f) (upper right), ADP(e) (lower left) and Harmful Emissions (lower right)

final results. The diagram of harmful emissions shows, that all ceilings tend to have the same weight, if the harmful emissions' weight gets maximized. This observation aligns with the assumption made in Chapter 4.5.1.4, where all ceilings are evaluated with the same weight for harmful emissions, thus setting harmful emissions as the most relevant node in the model suggest also equal final rankings of the seven ceilings.

Figure 24 shows the sensitivity analysis for both criteria in the energy cluster. The impact of thermal mass on the ceilings is remarkable. Maximizing the weights of the thermal mass in the model results in an abrupt weight change and rank reversal of the alternatives, where the board-stacked-ceiling (B_DE_BST_tE), which was previously the top-ranked ceiling, is now ranked as the worst. The reinforced concrete ceiling is, on the other hand, the best ceiling for this scenario. The share of renewable primary energy, on the contrary does not show any significant changes.

Maximizing the weight of pre-use circularity potential shows great potential for the board stacked ceiling, since maximizing this criterion's weight increases the importance of this ceiling and decreases the importance of the other ceilings (Figure 25 (left))

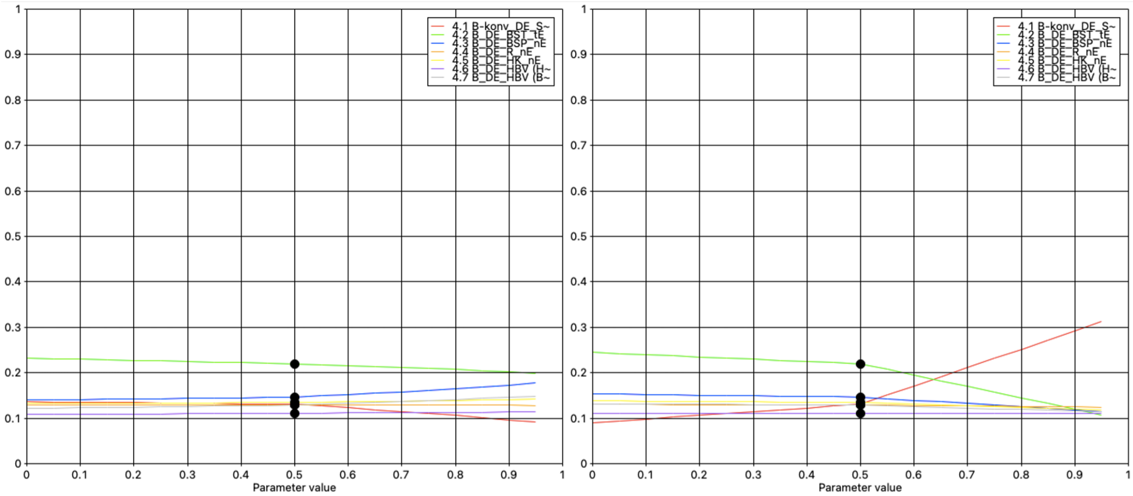


Figure 24 Sensitivity analysis for the share of renewable primary energy (left) and thermal mass (right)

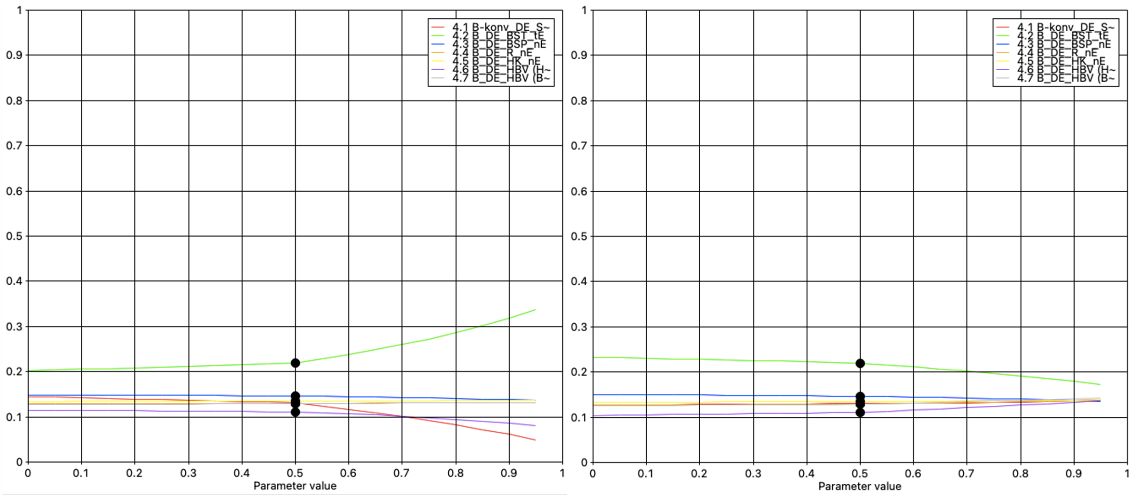


Figure 25 Sensitivity analysis for the circularity potential pre use (left) and post use (right)

6. Discussion

The main purpose of this chapter is to provide a critical review of the results presented in this work. The key advantages and limitations that emerged from the application of the Analytic Network Process are going to be discussed, as well as this work contribution to the current state-of-art, followed by future research suggestions are going to be described.

When comparing the two analysed variants of the ANP method, it becomes evident that there is a substantial difference in the final criteria weighting between the two variants. In variant 1, the criteria of highest relevance was the share of renewable primary energy, followed closely by the circularity potential post-use. The global warming potential was ranked sixth in importance, only slightly less significant than the ADP(e) and the thermal mass. Although - in the model - the circularity potential is much more important than the global warming potential for this variant, there are currently more regulations and laws limiting greenhouse gas emissions than those regarding the circularity potential of materials. This raises questions about the accuracy of the weighting approach used for variant 1 in representing real situations and decisions when designing sustainable ceilings.
Variant 2 aligns more closely with real-world scenarios based on findings from the literature research in Chapter 2. The global warming potential is the most important and influential criterion, followed by other emissions-related criteria in the model. Additionally, the share of renewable primary energy demonstrates significant importance, also reflecting its relevance to real situations.
The assignment of weights of the two variants was mainly based on assumptions. No pairwise comparisons were performed with sustainability experts to determine the relevance of each criteria. Instead, within the scope of this study, two weighting scenarios were chosen. These assumptions weaken the robustness and reliability of the model/method. To enhance the accuracy of results in further works, it is crucial to involve multiple stakeholders who possess a deep understanding of sustainability in the pairwise comparisons of the criteria, allowing a more accurate weighting of the criteria.
Although the two different weighting scenarios had a strong influence on the overall weighting of the criteria (see Figure 21), the final results for the alternatives did not experience substantial changes. While the ranking of the timber-composite system ceiling (HBV) showed a rank change between variant 1 and 2, the rankings of the other ceilings remained unchanged. Additionally, the best and worst ceiling in the model were respectively enhanced and diminished with the overweighting of the GWP criterion. With this in mind, the sensitivity analysis was utilized in this work to gain a better understanding of the various weighting scenarios for criteria weighting.

One limitation of the applied ANP method is its applicability in decision-making problems with many criteria and alternatives. The case study presented in this work considers network of 15 nodes (8 criteria and 7 alternatives), resulting in *n(n-1)/2* number of pairwise comparisons (105 pairwise comparisons). Such a large number of comparisons can lead to confusion regarding the meaning of each of the pairwise comparisons, leading to uncertainties in the evaluation. After a certain point users may find it difficult to understand what is being compared, leading to confusion and uncertainties. This makes the process really complex and time-consuming, when compared to other methods such as AHP or TOPSIS. This topic was also addressed by some authors such as Kadoić, 2018 and Sánchez-Garrido et al., 2022.

Moreover, while the AHP has been widely applied in the building and sustainability sector, it does not consider any interdependencies among the criteria, which can be really questionable in the sustainability sector. The critique here lies in the reliability of the results obtained from previous studies applying the AHP in the sustainability sector. The clear hierarchy structure, the reduced amount of pairwise comparisons and the clear definition of a goal make the AHP more appealing than the ANP, however not always adequate. Within the scope of this work, clear interdependence were found, and therefore making the ANP more adequate. These findings align with the conclusions drawn in the study of Ziemba, 2022. The study emphasizes the absence of a comprehensive sustainability index capable of evaluating the relationships between sustainability indicators, making the application of the Analytic Network Process (ANP) not always easy and straightforward (Ziemba, 2022).
Similar challenges were found in this thesis, where the definition and the quantification of these interconnections were a very complex and unknown process. It was difficult to define whether a interrelation between parameters exist and what degree of interdependence they consist. Trying to quantify these interrelations and apply them in the ANP model, the Pearson correlation method was utilized, using the data from the seven ceiling structures of the case study. However, a sample number of seven is a very small number capable of defining whether a interdependence exists and how strong it is, showing here suggestion of improvement. This is perhaps one of the contributing factors for the higher application of the AHP method compared to the ANP in the current state-of-art.

One additional limitation identified in this study was the challenge of subdividing criteria into clusters. This difficulty was also observed during the literature review in Chapter 2, where it was proved challenging to determine the appropriate categorization of criteria into their respective "parent groups." This clustering is particularly crucial in the Analytic Network Process (ANP) as the criteria are ultimately weighted based on the corresponding cluster weights. For instance, if a criterion belongs to the emissions cluster and this cluster has been assigned high priority, that criterion will consequently carry a significant weight in the final analysis. An example in this study was the criterion of abiotic depletion potential. It was unclear whether this criterion should be included in the Emissions cluster or rather in a separate Resources cluster, potentially with different weighting. Such distinctions would result in different criteria weights and, subsequently, different final results.

Furthermore, creating a decision making tool using Excel, for instance, was not possible for the ANP. Excel lacks the capability to handle limit matrix calculations and cannot efficiently handle the high number of pairwise comparisons involved in ANP method. To support the complexity of pairwise comparisons and the calculation of the limit matrix, the software SuperDecisions was implemented to perform the Analytic Network Process (ANP). The software simplifies the process of conducting pairwise comparisons and automatically calculates the resulting local priority vectors resulted from the pairwise comparisons. Once the user has established and defined the model nodes and dependencies, the software identifies which pairwise comparisons are required for calculation, making it a time-saving tool. The SuperDecisions software also allows to conduct a comprehensive sensitivity analysis for the entire decision making problem. This feature is highly helpful as it allows a deeper understanding of the results and serves as a basis for explaining decisions to project stakeholders.

Concerning future research topics that could be explored in the field of multi- criteria decision making and the sustainability sector, it would be interesting to investigate the impact of criteria interdependence on the final results. That could be done by comparing the same decision making model with the the two different methods: ANP and AHP. While previous studies have examined the differences between the application with AHP and ANP, there is a gap in research regarding their comparative analysis applying it to sustainability criteria. Investigating this aspect can provide valuable insights for decision-making processes in the sustainability sector.

Another interesting research direction would be to analyse the interactions between sustainability parameters, such as the relationship between global warming potential (GWP) and share of renewable primary energy (PERT/PET). To analyse how far some criteria for environmental protection depend on each other could facilitate the application of the Analytic Network Process in the sustainability sector. That could be done by analysing data on different projects and criteria and trying to establish relationship patterns.

Furthermore it would be interesting to apply alternative MCDM methods that take into account interdependencies among criteria and that can be easily applied with a high amount of criteria and alternatives. That could bring also insightful inputs for the decision making in real projects in the sustainability sector.

Lastly, a research recommendation would be to investigate how far multi-criteria decision making frameworks can be implemented in form of a tool (e.g. Excel or web-based), facilitating decision-making processes in the sustainability sector.

7. Conclusion

Aiming on facilitating the decision making process of projects concerning sustainability, this work uses the Analytic Network Process (ANP) to evaluate the sustainability of exemplary ceiling structures of a project in Nuremberg, Germany. For that, this work provides an overview of the key environmental criteria at the building element level, along with a review of the most appropriate multi-criteria decision making methods in the sustainability and building sector (Chapter 2). The literature research serves as a basis for selecting the most appropriate method to be applied in this study (Chapter 3). Subsequently, the Analytic Network Process was selected and applied to eight selected criteria for climate and environmental protection and seven ceiling structures (Chapter 4 and 5).

Firstly, the findings of the literature review performed in this work summarize the key criteria for environmental protection at the *building element level*, categorizing them into four main sustainability aspects that are significant in the design of building elements: emissions, energy, materials, and resources. In the current state-of-the-art, there is a greater focus on analyzing how buildings as a whole can contribute to mitigate the environmental impacts. However, there is a lack of analysis at the building element level, with only a few publications providing a summary of criteria that can be used to assess sustainability at this level. Considering this gap, this study addressed this topic by summarizing the most relevant climate protection criteria at the building element level in a tabular form, providing this way guidance for researchers in their further investigations on the subject.

This work includes a literature review on various MCDM methods used in the sustainability and building sector. Among the commonly applied methods, AHP emerges as the most utilized, followed by TOPSIS, COPRAS, VIKOR and SAW. Furthermore, the application of fuzzy sets has been growing over the years in the construction and sustainability sector. In this study, the Analytic Network Process (ANP) was the selected method of application, as it addresses interdependencies among sustainability criteria.

By applying the ANP, two different weighting scenarios were evaluated. The first scenario assigns equal weight to all criteria, while the second scenario gives higher weight to global warming potential and the Emissions cluster. In both variants, the two solid wood ceilings are ranked as the most sustainable option for the project, while the reinforced concrete ceiling was discovered as the worst ceiling option for both options. The main difference between the two variants was for the timber-composite system ceiling. While this ceiling ranks third for the equally weighted variant, it ranks sixth after the ecological variant.

The results of the application in this study emphasize the relevance of the criteria weighting scenarios in the Analytic Network Process and raises questions whether assuming equal importance for sustainability parameters is entirely appropriate nowadays. When considering the application of the Analytical Network Model at a case study, it was discovered that the quantification of interdependencies between sustainability criteria in the building sector is not yet clearly defined in the current state-of-art. That makes the application of ANP in the sustainability sector challenging, suggesting here ideas for future research to address this gap and improve the understanding and application of ANP in sustainability-related decision-making.

The current state-of-art primarily emphasizes and focus on the application of the Analytic *Hierarchy* Process (AHP) in the construction and sustainability sector. Building upon this, this work contributes to the current state-of-art by presenting an application of the Analytic Network Process (ANP). By employing the ANP, this study expands the scope of research and offers a valuable contribution to the field of decision making in the sustainability sector. This study demonstrates the application of the Analytic Network Process in the sustainable building sector while providing detailed insights into the methodology, boundary conditions, and limitations of the method. The findings presented in this work offer valuable information and knowledge, not only at the building element level as presented here, but also in other fields of sustainable development, such as building renovation and city planning. Based on these conclusions, it is highly recommended that engineers, architects, and sustainability experts integrate multi-criteria decision making methods into their project implementation and decision-making processes within the sustainability sector, augmenting this way sustainable practices in the building sector.

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A. Appendix

A.1. Umweighted supermatrix- variant 1

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	A2	A3	A4	A5	A6	A7
Em1: GWP	0.000	0.581	0.489	0.000	0.369	0.000	0.000	0.0000	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Em2: ADPf	0.591	0.000	0.510	0.000	0.376	0.000	0.000	0.000	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Em3: ADPe	0.408	0.419	0.000	0.000	0.253	0.000	0.000	0.000	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Em4: Harmful Em.	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.250	0.250	0.250	0.250	0.250	0.250	0.250
En1: PERT/PET	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
En2:Thermal Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP1: CP Pre-Use	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP2: CP Post-Use	0.000	0.000	0.000	0.500	1.000	0.000	0.000	0.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
A1: B-konv_DE_StB	0.028	0.107	0.000	0.142	0.085	0.281	0.035	0.141	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A2: B_DE_BST_tE	0.677	0.167	0.208	0.142	0.194	0.080	0.357	0.164	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A3:B_DE_BSP_nE	0.103	0.187	0.208	0.142	0.183	0.094	0.135	0.131	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A4:B_DE_R_nE	0.0508	0.131	0.179	0.142	0.127	0.101	0.129	0.138	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A5:B_DE_HK_nE	0.055	0.140	0.208	0.142	0.143	0.098	0.136	0.138	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A6:B_DE_HBV(HTB)	0.036	0.123	0.089	0.142	0.113	0.253	0.074	0.141	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A7: B_DE_HBV(BST)	0.047	0.142	0.104	0.142	0.151	0.093	0.130	0.144	0.000	0.000	0.000	0.000	0.000	0.000	0.000

A.2. Unweighted supermatrix - variant 2

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	A2	A3	A4	A5	A6	A7
Em1: GWP	0.000	0.580	0.489	0.000	0.369	0.000	0.000	0.0000	0.750	0.750	0.750	0.750	0.750	0.750	0.750
Em2: ADPf	0.591	0.000	0.510	0.000	0.376	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Em3: ADPe	0.408	0.419	0.000	0.000	0.253	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Em4: Harmful Em.	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.083	0.083	0.083	0.083	0.083	0.083	0.083
En1: PERT/PET	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
En2:Thermal Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP1: CP Pre-Use	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
CP2: CP Post-Use	0.000	0.000	0.000	0.500	1.000	0.000	0.000	0.000	0.500	0.500	0.500	0.500	0.500	0.500	0.500
A1: B-konv_DE_StB	0.028	0.107	0.000	0.142	0.085	0.281	0.035	0.141	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A2: B_DE_BST_tE	0.677	0.167	0.208	0.142	0.194	0.080	0.357	0.164	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A3:B_DE_BSP_nE	0.103	0.187	0.208	0.142	0.183	0.094	0.135	0.131	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A4:B_DE_R_nE	0.0508	0.131	0.179	0.142	0.127	0.101	0.129	0.138	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A5:B_DE_HK_nE	0.055	0.140	0.208	0.142	0.143	0.098	0.136	0.138	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A6:B_DE_HBV(HTB)	0.036	0.123	0.089	0.142	0.113	0.253	0.074	0.141	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A7: B_DE_HBV(BST)	0.047	0.142	0.104	0.142	0.151	0.093	0.130	0.144	0.000	0.000	0.000	0.000	0.000	0.000	0.000

A.3. Weighted supermatrix - variant 1

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	A2	A3	A4	A5	A6	A7
Em1: GWP	0.000	0.194	0.163	0.000	0.118	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Em2: ADPf	0.197	0.000	0.170	0.000	0.120	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Em3: ADPe	0.136	0.140	0.000	0.000	0.082	0.000	0.000	0.000	0.083	0.083	0.083	0.083	0.083	0.083	0.083
Em4: Harmful Em.	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.333	0.083	0.083	0.083	0.083	0.083	0.083	0.083
En1: PERT/PET	0.333	0.333	0.333	0.000	0.000	0.000	0.000	0.333	0.167	0.167	0.167	0.167	0.167	0.167	0.167
En2:Thermal Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.167	0.167	0.167	0,.167	0.167	0.167	0.167
CP1: CP Pre-Use	0.000	0.000	0.000	0.250	0.000	0.000	0.000	0,.000	0.167	0.167	0.167	0.167	0.167	0.167	0.167
CP2: CP Post-Use	0.000	0.000	0.000	0.250	0.340	0.000	0.000	0.000	0.167	0.167	0.167	0.167	0.167	0.167	0.167
A1:B-konv_DE_StB	0.009	0.036	0.000	0.071	0.029	0.281	0.018	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A2:B_DE_BST_tE	0.226	0.056	0.068	0.071	0.066	0.080	0.179	0.056	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A3:B_DE_BSP_nE	0.034	0.063	0.067	0.071	0.062	0.094	0.068	0.043	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A4:B_DE_R_nE	0.017	0.044	0.065	0.071	0.043	0.101	0.065	0.046	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A5:B_DE_HK_nE	0.019	0.047	0.067	0.071	0.049	0.098	0.068	0.046	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A6:B_DE_HBV(HTB)	0.012	0.041	0.031	0.071	0.038	0.253	0.037	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A7: B_DE_HBV(BST)	0.016	0.047	0.036	0.071	0.052	0.093	0.065	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000

A.4. Weighted supermatrix - variant 2

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	A2	A3	A4	A5	A6	A7
Em1: GWP	0.000	0.475	0.400	0.000	0.298	0.000	0.000	0.000	0.614	0.614	0.614	0.614	0.614	0.614	0.614
Em2: ADPf	0.484	0.000	0.418	0.000	0.303	0.000	0.000	0.000	0.068	0.068	0.068	0.068	0.068	0.068	0.068
Em3:ADPe	0.334	0.343	0.000	0.000	0.208	0.000	0.000	0.000	0.068	0.068	0.068	0.068	0.068	0.068	0.068
Em4: Harmful Em.	0.000	0.000	0.000	0.000	0.000	0.000	0.900	0.818	0.068	0.068	0.068	0.068	0.068	0.068	0.068
En1: PERT/PET	0.091	0.091	0.091	0.000	0.000	0.000	0.000	0.091	0.045	0.045	0.045	0.045	0.045	0.045	0.045
En2:Thermal Mass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.045	0.045	0.045	0.045	0.045	0.045	0.045
CP1: CP Pre-Use	0.000	0.000	0.000	0.250	0,.000	0.000	0.000	0.000	0.045	0.045	0.045	0.045	0.045	0.045	0.045
CP2: CP Post-Use	0.000	0.000	0.000	0.250	0.095	0.000	0.000	0.000	0.045	0.045	0.045	0.045	0.045	0.045	0.045
A1:B-konv_DE_StB	0.003	0.010	0.000	0.071	0.008	0.281	0.004	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A2:B_DE_BST_tE	0.062	0.015	0.018	0.071	0.019	0.080	0.036	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A3:B_DE_BSP_nE	0.009	0.017	0.018	0.071	0.017	0.094	0.014	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A4:B_DE_R_nE	0.005	0.012	0.018	0.071	0.012	0.101	0.013	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A5:B_DE_HK_nE	0.005	0.013	0.018	0.071	0.098	0.116	0.014	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A6:B_DE_HBV(HTB)	0.003	0.011	0.008	0.071	0.011	0.253	0.007	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A7: B_DE_HBV(BST)	0.004	0.013	0.010	0.071	0.014	0.093	0.013	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.000

A.5. Limit matrix- variant 1

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	A2	A3	A4	A5	A6	A7
Em1:GWP	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
Em2:ADPf	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Em3:ADPe	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
Em4:Harmful Em.	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105
En1:PERT/PET	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155	0.155
En2:Thermal Mass	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
CP1:CP Pre-Use	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.0759	0.075	0.075	0.075	0.075	0.075
CP2:CP Post-Use	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128
A1:B-konv_DE_StB	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
A2:B_DE_BST_tE	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065
A3:B_DE_BSP_nE	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043
A4:B_DE_R_nE	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
A5:B_DE_HK_nE	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
A6:A6:B_DE_HBV(HTB)	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
A7: B_DE_HBV(BST)	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037

A.6. Limit matrix- variant 2

	Em1	Em2	Em3	Em4	En1	En2	CP1	CP2	A1	A2	A3	A4	A5	A6	A7
Em1:GWP	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289	0.289
Em2:ADPf	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256	0.256
Em3:ADPe	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207	0.207
Em4:Harmful Em.	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
En1:PERT/PET	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
En2:Thermal Mass	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
CP1:CP Pre-Use	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
CP2:CP Post-Use	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
A1:B-konv_DE_StB	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
A2:B_DE_BST_tE	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
A3:B_DE_BSP_nE	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
A4:B_DE_R_nE	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
A5:B_DE_HK_nE	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
A6:A6:B_DE_HBV(HTB)	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
A7: B_DE_HBV(BST)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011