RECOMMENDER SYSTEM FOR SUSTAINABLE ALTERNATIVES OF BUILDING MATERIALS

Sustainability-Focused Decision Making in the Construction Industry

Lappeenranta–Lahti University of Technology LUT

Double Degree Software Engineering and Digital Transformation

PROPHET – Sustainable ICT Solutions of Tomorrow

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Examiner(s): Professor Jari Porras

Associate Professor Lene Tolstrup (Engineer, Ph.D.)

ABSTRACT

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Recommender System for Sustainable Alternatives of Building Materials

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The construction industry contributes an estimated 39\% of global carbon emissions. This master thesis presents the design and development of a software platform aimed at promoting sustainability-focused decision making in the construction industry. The platform serves as a recommender system, assisting users in identifying sustainable alternatives to input building materials.

The research follows a design science methodology, involving requirements specification, system design, implementation, and evaluation. The recommender system combines user preferences, environmental criteria, and material properties to provide personalized recommendations. The system incorporates a comprehensive database of building materials and their properties, centred around their embodied emissions.

The findings of this study demonstrate the potential of the developed software platform to contribute to the reduction of environmental impact in the construction industry. By providing accessible and tailored recommendations for sustainable building materials, the platform empowers users to make informed choices and foster sustainable goals early into construction projects. Furthermore, enhancing transparency and enables users to compare different options based on their requirements.

ACKNOWLEDGEMENTS

Before delving deeper into the intricacies of the interesting problem this project attempts to resolve, I want to use this space to dedicate a few acknowledgements to some individuals who have been a great support for me in the fulfilment of my master thesis. To start, I want to thank my professors Lene and Jari, who have been guiding beacons for me throughout the making of this report, supporting all my ideation processes, providing me always with relevant knowledge and feedback to fill the gaps where I was lacking and helping to keep me accountable throughout the process. Moreover, I want to thank both Aalborg University and Lappeenranta Technical University as well as the rest of the staff of the Nordic Master in Sustainable ICT Solutions for the opportunities you have ensured for me throughout these last two years. Allowing me to delve into new and uncharted knowledge domains, with focus on innovation and real-world problem solving, as well as exploring living and collaborating with different cultures in a very international environment.

I want to thank the entire staff at JAW Sustainability for collaborating with me in the making of this project. Thank you for opening your arms to an engineer that was at the start not very knowledgeable in your field and providing me with so many insights and findings that help me to build a substantial understanding of the intricacies of implementing sustainability in such a complex industry. Moreover, thank you for opening your doors to me during my stay at the company and allow me to feel like another one of you, even if for a short time. Special thanks to Matthew Higgs, for being such a trooper, and so thoroughly helping, guiding, and supporting me with all my questions and doubts, even sometimes at late hours of the day, I deeply appreciate all your knowledge, passion, and disposition.

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Contents

Chapter 1

Introduction

In spite of international efforts to reduce anthropogenic greenhouse gas (GHG) emissions to pre industrial levels, rates of emission continue to rise. The construction industry has a significant impact on the environment, with buildings accounting for approximately 39% of global carbon emissions [1].

Embodied carbon emissions refer to any and all green house gas emissions related to a particular material and include those produced during raw material extraction, transportation and manufacturing of the building materials [11]. They are generated prior to a building being placed on the ground and comprise around 50% of total life cycle emissions of said building [46]. As such, these emissions are hard to remediate after the construction has finalized. As opposed to operational emissions which can be reduced through energy optimizations of the building throughout the buildings lifetime and additionally benefit from general grid decarbonisation efforts resultant form the increased availability of renewable energy.

Each material utilised throughout a buildings construction has it's own level of embodied GHG emissions, resultant primarily from it's raw material and manufacturing processes, with concrete being the biggest emitter. In 2012, the global consumption of concrete had been estimated to reach over 10 billion cubic meters, and this number has since then increased [80].

The London Energy Transformation Initiative (LETI), created a guide that shows trends in the design of buildings in London over recent years. It shows how the industry has so far focused towards optimizing operational carbon emissions by reducing energy use of the buildings [46]. However, reductions in embodied carbon have not received this level of focused attention and as such, make up a greater proportion of a buildings lifecycle emissions as time goes on [45]. This indicated that it is a critical moment to develop solutions that can aid in the reduction of embodied emissions[70].

The selection of low carbon materials within the building sector is one potential avenue for the reduction of the embodied carbon emission of new buildings. For years the decision making in the selection of building materials has focused upon financial factors and cost-effectiveness, particularly on large-scale projects [63]. In some cases, the cost of materials is the driving factor, with cheaper, less sustainable materials being chosen over more expensive, environmentally friendly options. However, a shift is taking place now were prioritization of sustainable building materials is taking precedent [32]. Ultimately, the goal is to ensure a reduction in environmental burden without compromising the materials performance.

The selection of sustainable building materials can be a complex process due to the large number of materials available, each with different properties and environmental impacts [60]. The decision-making process for selecting sustainable building materials can be time-consuming and requires a thorough understanding of the material properties, environmental impacts, and cost implications. The lack of knowledge and information about sustainable building materials can also be a significant barrier for construction professionals to select and use sustainable building materials in their projects [18]. Particularly at earlier stages of building development when design teams are made up of a small number of individuals. In these cases, currently, if professional input is not sought then several significant decisions regarding the building fabric can be made utilising well known metrics such as availability and cost. However, a lack of information can prevent environmental impact from being considered at these early stages resulting in a disadvantaged position for these materials.

Environmental consultancies are growing in the construction industry. Experts in these companies help different stakeholders understand the impact of their activities at every step of the construction process, but also what changes they can implement to reduce said impact. They do so by providing domain knowledge and resources as well as help defining requirements and evaluating the final construction after its been handed in to the client [66]. However, it is often the case that such professionals are included within design teams at the later stages of project development when a number of significant decisions affecting the environmental profile of the design have already been made. Potentially further constraining the specification of sustainable materials.

An automated recommender system can help simplify the decision-making process for selecting sustainable building materials by providing construction professionals with a recommendation based on a range of criteria. The system can also help improve the uptake of sustainable building materials in the construction industry by providing easy access to information and knowledge about sustainable building materials.

This project will focus on the development of such an automated recommender system. This will be performed in collaboration with JAW Sustainability, an environmental consultancy company, based in London, focusing on the construction industry in the UK [76]. This will allow the project to tackle this problem from multiple perspectives, engineering development, sustainability assessment and market analysis, to provide a versatile solution tackling different types of key stakeholders in the construction industry.

In conclusion, the use of sustainable building materials is crucial in reducing the carbon footprint of the construction industry. An automated recommender system for sustainable building materials can help ease the decision-making process for construction professionals, ultimately leading to increased adoption of sustainable building materials. The proposed system aims to address the knowledge and information gap that exists in the selection of sustainable building materials and improve the sustainability of the built environment. The goal for this project is to develop a service which can provide recommendations for sustainable building materials in construction projects based on a user input material. For this it will be important to understand the processes involved in a construction project, and how carbon emissions are distributed along the different construction phases[45].

1.1 Research Questions

This section will set the foundation for the project, and define the research questions that will be explored. This will include a main problem formulation and some research sub-questions:

How to develop a sustainability focused recommender system to promote alternatives for building materials with less embodied carbon emissions?

Sub-questions

- *How can additional material parameters be accounted for to perform the material recommendation?*
- *What type of emissions should be targeted to reduce the overall environmental impact of the industry?*

- *What environmental impact can this software tool have on the construction industry?*

These questions were formulated in a way that would allow to define a clear overall goal for the research project. Additionally, each of the sub-questions provides precise target areas to cover through activities of literature review and market context understanding, as well as development of the proposed solution. This will help to provide multiple perspectives or lenses through which the main problem can be looked at.

In chapter 3 of this report, descriptions will be presented of how it is intended to tackle the process of answering each of these questions. Furthermore, the final chapter 6 will utilize the research questions once again to round off the project in a clear way, reflecting on the original goals and hypothesis, whether they were answered and fulfilled and how.

1.2 Expected Outcome

It is important to set a clear goal for the project, to ensure it remains on scope throughout the months it will develop through. This will include understanding the internal stakeholders involved, the expectations for the project outcome and limitations that might delimit the extent of the project. The project involved multiple internal stakeholders:

- Student, Aalborg University - Jacobo Domingo. In charge of the full development of the service, report writing and project management.
- Supervisors, AAU and LUT - Lene Tolstrup and Jari Porras, respectively. Support the student in the development of the project plan and execution, with recurring meetings and a final evaluation.
- Company collaborators, JAW Sustainability - Providers of the use case for the project, as well as of relevant domain knowledge and access to relevant databases. Furthemore, supporting the solution design process.

Managing the expectations from the different stakeholders will be key to ensure a smooth collaboration, and reaching the desired outcome for the project. In order to achieve this, it will be key to establish an expected outcome to achieve at the end of this project.

To aid this process a timeline was designed to overview of the stages involved in a construction project. This figure 1.1 includes what stakeholders are involved at each stage and an understanding of the weight that decisions on building materials have at each stage. This was designed following multiple sources of information: On the one hand interviews with industry contacts with domain knowledge.

Conversely, relevant research into the construction stages designed by the Royal Institute of British Architects [5]. Later, section 2.6 on chapter 2 will present more information on the RIBA institution and its defined construction stages.

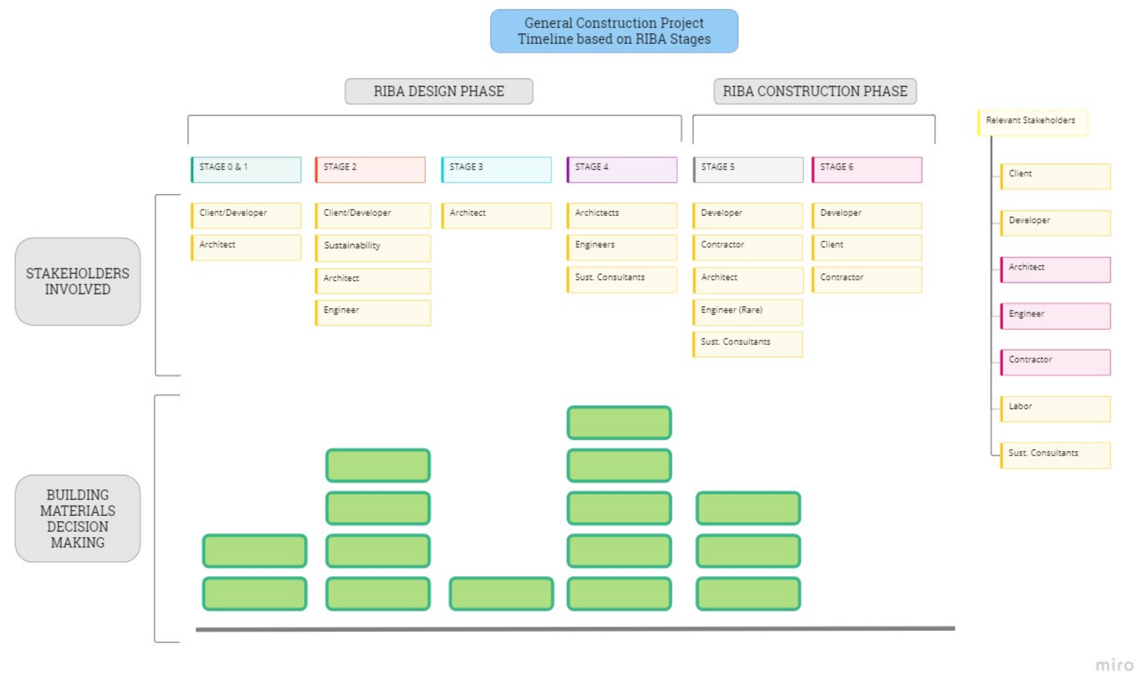

Figure 1.1: Graphical overview of the stages of a construction project, stakeholders involved and weight of building material decision at each stage, designed by the author

The section of the aforementioned graphic covering building materials decision making was designed to better understand the context in which the recommender tool would be most relevant. Following these insights the most relevant phase is Stage 4, which as the literature will later show refers to the technical design stage. The focus of this platform will be to recommend sustainable alternatives to building materials. During this stage the one of the higher concentration of stakeholders with grand decision making power will be found. As such, it will be a very important phase to propose sustainable alternatives, harbouring a collaboration on the environmental front from the different stakeholders and providing recommendations at the peak of building material decisions.

Moreover, decisions on building materials will be present in most other stages of the project, with different levels of relevance. Stage 2 and in some cases 5, namely concept design of the building and manufacturing, will follow as the consecutively relevant stages where recommendations of building materials can be effective. Given that different types of stakeholders will be involved in this decision making process, it will be important to make the service light-weight and flexible. The tool should be adaptable, so it can be operated by different users, with different knowledge levels.

Research, that will be further elaborated in section 2.1 of the following chapter, shows that these stakeholders will also convey different focuses: A contractor will be focused on money savings and time effectiveness, engineers will focus on functionality and optimization of the building, whereas architects will focus on aesthetics, and how that the building fits in its surrounding context. These factors will need to be taken into account when making material recommendations.

Given this needed flexibility, and diversity of users, will most likely lead the software platform to be developed in this project, to be focused on the back-end side of the development, and making it somewhat modular, so it could be later tailored through a comprehensive front-end to fit these multiple user needs.

Proposed Solution Given all of the provided information, certain initial expectations or light requirements are established for this master thesis project:

1. Design of a software platform that can retrieve input from a user for a building material to be replaced, and its material property information, to compare to more sustainable alternatives and provide a final material recommendation
2. The material recommendation calculations will focus on embodied carbon emissions, but will account with additional features such as location, standard materials, material strength, etc.
3. Focus development process on a back-end software model, as part of a wider software platform.
4. Additionally a front-end platform should be developed to ease the journey of user interaction.
5. The software platform will be flexible so it can be adapted to diverse stakeholder types.
6. The software platform should be light weight so it can easily be used without exherting time resources on training and operation, during ongoing construction projects.

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1.3 Project Motivation & Definition

The motivation behind this project, comes from the desire of the author to explore the nexus between sustainability and technology, and how can technology-based solution help reduce the environmental impact of human activities on our planet. In exploring this, it was thought that targetting an industry that currently sits within the largest emitters, such is the construction industry, could ensure the value creation of the final solution.

It is through this keen exploration that the author desired to gain a deeper understanding of the market context, and the role sustainability currently plays in the construction industry. Furthermore, establishing a collaboration with an industry partner could help provide insider knowledge to the project and through this collaboration validation for design and functionality decisions of the proposed solution.

Given the nature of the project in collaboration with a company and involving different types of stakeholders, certain project limitations have been put in place:

For instance the collaboration with the company defines some project scoping conditions that ought to be fulfilled. This includes the location that will be analyzed. Given that JAW sustainability operates at a UK level, and mostly within the London market, this will be the focus of the projects development too. Building material databases that will be used, will be UK based. Similarly any policy or standardization will aim to comply by those established for the London area, and its different districts, otherwise known as boroughs.

This will benefit the service development as it will simplify the algorithm's development scope, and provide a specific use case to analyse the final solution with. But also limit the researching resources available to those fitting within this context. All of the data gathered for database building, research material, specially for resources that help determine critical requirements for the solution development, they must focus on the context of the United Kingdom.

Chapter 2

Background

Providing background information is required to contextualize the problem at hand that will be covered throughout this report. This will provide the reader with construction industry-specific terms and knowledge sources that will be key to be understand further concepts discussed in the different chapters ahead. The content for this thesis report will come from different sources including research papers, industry reports, industry-recognized institutions, extracts from interviews with domain knowledge experts and relevant stakeholders, and lastly original content written by the author.

This chapter will help establish a series of pillars to support contextualizing the aim of the project better. Moreover, providing the necessary knowledge to proceed with a literature review and analysis of the problem being addressed. The five pillar of this project will be covered in individual sections and will include:

- Environmental impact of the construction industry
- Measuring said environmental impact
- Understanding the different phases of a construction project (RIBA Stages)
- Exploring how to make building materials sustainable
- Overview of building types and viable material applications

2.1 Environmental Impact of the Construction Industry - United Kingdom

The construction industry is a significant contributor to the economy in the UK. It employs over 3 million people, over a 6% of all jobs, and contributes around £117

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billion to the UK's gross domestic product [67]. Given London's size and global status as a mega city and one of the capitals of the world, the construction industry is particularly important, with numerous large-scale projects underway[61]. An example is the construction of the new HS2 high-speed railway line, which is set to improve connectivity across the city. Consisting of 170 miles of high speed railway to connect London with the North-West province in England[41].

Figure 2.1: Diagram showcasing different construction industry stakeholders, designed by the author

The construction industry involves various stakeholders, including architects, engineers, contractors, developers, and local authorities. The figure 2.1 shows an overview of said stakeholders. Each one plays a critical role in ensuring that construction projects are executed efficiently and effectively [78]:

- Architects and engineers are responsible for designing buildings that meet the needs of the client while also adhering to building codes and regulations.
- Contractors are responsible for the physical construction of the building, and developers are responsible for financing said construction and working directly with the clients.
- Local authorities, on the other hand, are responsible for approving planning applications, ensuring that construction projects are compliant with local planning policies and regulations
- Clients, normally refers to the owners of the plot, which can often be the

developers themselves. These are the stakeholders who provide the financial support for the project and will use it once it is finalized.

- Developers, are business entities that help procure land, finance projects and oversee a range of tasks related to transforming a plot of land into a property available for purchase.

The construction industry is one of the significant contributors to greenhouse gas emissions in the UK. According to a report by Osborne Clarke, the construction industry accounts for 40% of the UK's carbon emissions [21]. Additionally, construction projects are known to produce a significant amount of waste, with the Woodhart Group reporting that this industry produces over 120 million tons of waste per year in the UK, accounting for a considerable portion of the country's landfill waste[37]. These construction processes also contribute to air pollution, noise pollution, and loss of wildlife habitats. The use of fossil fuels in the construction process, such as diesel generators and machinery, also contribute to air pollution.

The UK government has developed various policies to promote sustainable construction practices and reduce the environmental impact of buildings. In 2019, the UK government set a target to achieve net-zero carbon emissions by 2050, which includes reducing carbon emissions from buildings [33]. The government has also introduced policies such as the Minimum Energy Efficiency Standards (MEES) to improve the energy efficiency of buildings and the Building Regulations to ensure that new buildings meet minimum energy efficiency standards [17]. The Royal Institue of British Architects (RIBA) introduced their Climate Change 2030 initiative to aid architects design within a climate conscious trajectory, and providing a stepped plan to help them achieve net zero. [68]

In London, the Greater London Authority (GLA) is responsible for planning and coordinating the city's development. The GLA's created in 2020 the London Plan, which sets out policies and proposals for sustainable development in the city, including policies to reduce carbon emissions, promote sustainable transport, and protect the city's green spaces. [54].

2.2 Measuring Environmental Impact in Construction

In order to assess better the environmental impact of the construction industry, its important to establish a global factor for said assessments, a unit that allows measuring said impact, and this unit are carbon emissions. This section will allow

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a deeper dive into this topic. Multiple measures exist to assess environmental impact, research highlights five measures in particular [75]:

- **Global Warming Potential - GWP.** Also referred to as "carbon footprint". Global warming occurs as the increase of accumulation of gases in the atmosphere, such as Carbon Dioxide or Methane, enable the agglomeration of the suns radiation within the atmosphere, raising temperatures dramatically. The GWP calculates how much heat a certain amount of gas can retain in the atmosphere, comparing it an equivalent mass of CO2. This is the reason why this potential is expressed in a unit known as carbon equivalent, or CO2e.
- **Ozone depletion potential - ODP.** This is a potential that is utilized to measure the impact of certain materials during their production, normally focusing on insulation materials. To perform the calculations for this potential, focus sets on one particular gas, CFC-11 otherwise known as R-11. This is a gas that is utilized for the production of certain molded foam panels as a foam blowing agent, and it is banned already in many countries.
- **Photochemical Ozone Creation Potential - POCP.** This potential focus on certain compounds that commonly appear as ground contaminants. These are known as volatile organic compounds (VOS) often being byproduct of fuels, hydraulic fuels or dry cleaning agents [2]. POCP quantifies the capacity for these compounds to produce ozone at soil level. This is because high concentrations of ozone can be harmful to human being and even affect breathing. This potential is measured in units of ethylene equivalents (C2H4EQ) as an indicator unit.
- **Acidification Potential - AP.** Acidification is one of the leading culprits in the case of damage to ecosystems and their flora. The AP calculates an estimate of two metrics: The amount of gases that produce acidification on a specific area of surface environments. Additionally, the effect these gases have on the fauna and flora that inhabit these environments. The indicator unit for this potential, within the context of the construction industry, is the sulfur dioxide equivalents, SO2 EQ.
- **Eutrophication Potential - EP.** Imbalances can occur in ecosystems when concentration of certain nutrients occur. This can have grave effects on the environment leading to desertification or super fertilization. An example of this is the production of steel, as it emits large amounts of nitrogen oxides. While this chemical element is vital to soils, too much concentration can affect soil biodiversity and aquatic environments.

However, one measure prevails amongst the others, the Global Warming Potential, since this potential uses CO2 equivalence as the indicator unit, and therefore

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in particular tackles carbon footprints, it will be selected as the reference potential for this project. Carbon emissions are normally divided into two types:

- **Embodied Carbon Emissions** - Which refer to the emissions originated from extracting the raw materials, transportation and manufacturing.
- **Operational Carbon Emissions** - On the other hand are emitted once the building has been constructed and originate from its use, in terms mainly of electrical, lighting, heating and water consumption.

2.2.1 Embodied Emissions

Embodied carbon emissions are normally associated with the building material life cycle, as they represent all the emissions produced during the different phases the material goes through, including extraction, manufacturing, transport, construction and disposal of the material. As these emissions account for 11% of global greenhouse gas emissions, it is becoming a priority in the list of policymakers and other stakeholders looking to meet the established climate goals [20].

The reduction of embodied carbon is becoming a predominantly critical goal in the process of decarbonizing buildings. This is causing it to receive special interest and recognition at a global scale, among leaders in architecture & design, manufacturing, and construction. Embodied emissions are often contrasted with operational carbon emissions, which are the emissions associated with the energy use of a building during its operational lifetime [70].

In order to effectively measure embodied carbon emissions, they first need to be converted into metrics, and these should reflect the effect these emissions have on the environment. As described earlier in this section, one of those metric is the global warming potential (GWP), expressed in terms of CO2 equivalents (CO2e). The embodied carbon of a building material is calculated by adding up the emissions associated with the entire life cycle of the material. These include the extraction and transportation of raw materials, the manufacturing process, and the transportation of the finished product to the construction site, covering lifecycle assessment stages A1 to A4, as seen in figure 2.5 [70]. The embodied carbon emissions of a building are then calculated by adding up the embodied carbon of all the building materials used in the construction process [53].

The calculation of embodied carbon emissions is a complex process, as it involves tracking the entire life cycle analysis of a building material, from cradle to grave [70]. Figure 2.2 shows a graphical overview of the different components involved in the calculation of carbon emissions, taken from the Carbon Life cycle

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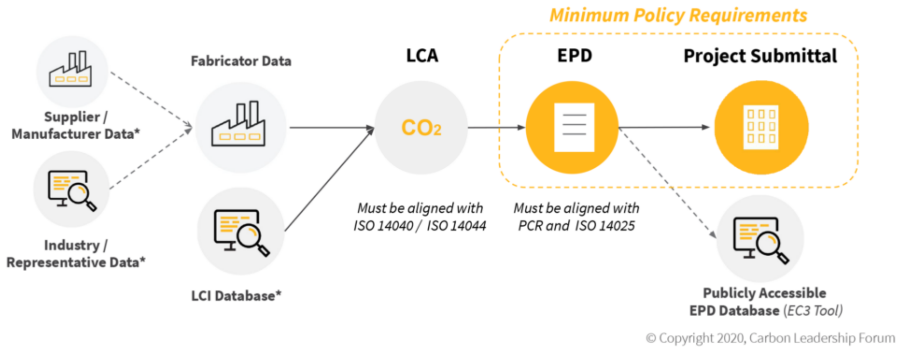

Figure 2.2: Diagram showcasing carbon emission calculations in the industry, created by the Carbon Lifecycle Forum [31]

Forum reports [31]. The embodied carbon emissions of a building material can vary significantly depending on factors such as the location of the material source, the manufacturing process used, and the transportation methods used to move the material to the construction site. The results of the life cycle analysis get disclosed through EPDs, Environmental Product Declarations [77]. These are independently-verified documents based on international standards that report the environmental impacts of a product [31].

Reducing embodied carbon emissions in the construction industry is essential for mitigating the environmental impact of buildings. This can be achieved through various measures including the use of low-carbon building materials, reusing buildings and materials, the optimization of the design and construction process to reduce waste and emissions, and the promotion of circular economy principles to reduce the amount of waste generated during the manufacturing process [36].

2.2.2 Operational Emissions

Conversely to embodied carbon emissions, operational carbon emissions are the emissions associated with the energy use of a building during its operational lifetime. These emissions are typically associated with the use of heating, cooling, lighting, and other energy-consuming systems within a building [36]. Operational carbon emissions are typically calculated using the energy consumption data of a building, and they are often expressed in terms of CO2e. Optimization in the different consumption flows of a building can occur to reduce operational emissions. Embodied emissions on the hand, are much more difficult to decrease after the building is constructed, unless through process of replacing certain materials, which can prove costly and time consuming [31].

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The reduction of operational carbon emissions has become a major focus in the construction industry due to the significant environmental impact of buildings during their operational phase.[46] As the report has been showing, buildings are responsible for a large portion of global carbon emissions, and addressing operational carbon emissions is essential for achieving climate change mitigation goals. Energy-efficient design, renewable energy systems, and improved building management practices are some of the key strategies employed to reduce operational carbon emissions [42]

Building regulations and certification schemes, such as BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design), have been established to encourage the construction industry to prioritize energy efficiency and reduce operational carbon emissions[12]. These standards provide guidelines and criteria for sustainable building design, construction, and operation. They promote the adoption of energy-efficient technologies, renewable energy sources, and sustainable building management practices to minimize the carbon footprint of buildings.

2.2.3 Embodied vs Operational

The relative contribution of embodied carbon and operational carbon emissions to the overall carbon footprint of a building can vary depending on factors such as the energy efficiency of the building, the lifespan of the building, and the type of building materials used in its construction. However, research has shown that embodied carbon emissions typically account for a significant portion of the total carbon emissions associated with a building, particularly for buildings with longer lifespans and lower operational energy consumption [50]. This can be seen in the graphs shown in figure 2.4, where two columns of pie charts are contrasted, showcasing the difference in distribution of emissions for buildings with an without highly optimized energy consumption measures. This figure was extracted from the LETI carbon primer report [46].

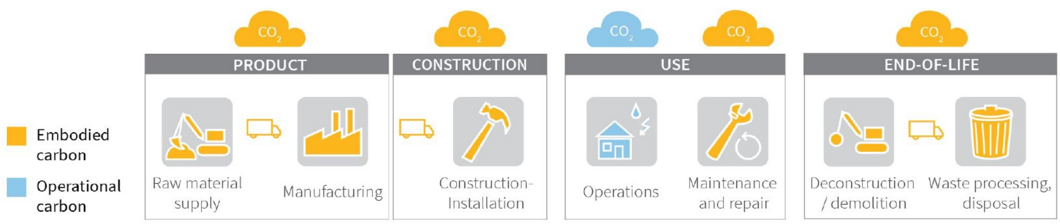

Figure 2.3: Embodied vs Operational Carbon Emissions, from Carbon Leadership Forum [31]

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The figure 2.3, extracted from the Carbon Leadership Forum's report [31], showcases the distribution of embodied carbon emissions compared to those of operational sources. This helps to represent the substantial difference between both sources and further highlight the importance to focus on reduction of embodied emissions which are much more present in the graphic [31].

In recent years, the UK construction industry has shifted its focus from reducing operational carbon emissions to embodied carbon emissions. As shown in figure 2.4, extracted from the LETI carbon primer report, the years of policy focused on reducing operational emissions, caused embodied emissions to now have greatly increased and are slowly becoming the most critical problem. As such, and as explained by Matthew Higgs, Associate Director of JAW Sustainability, during his interview which can be found in the annex B.2 of this report, this is causing the industry to shift their focus and find effective solutions to reduce embodied carbon emissions. In addition, the UK Green Building Council has developed a framework for embodied carbon assessment and reduction, which provides guidance on how to measure and reduce embodied carbon emissions in buildings [88].

As part of the policy changes taking place in the UK, the UKGBC created the Net Zero Carbon Buildings Framework Definition in 2019 to provide the industry with clarity on the definition of net zero carbon buildings [23]. The shift in focus towards embodied carbon emissions is also reflected in the way that building materials are selected and specified. Building designers are increasingly looking for materials that have a low carbon footprint and are environmentally sustainable. This includes materials that are locally sourced, have a high recycled content, or are made from renewable resources. Materials that have a high embodied carbon footprint, such as concrete and steel, are being improved by means of for example carbon storage [38], which allows the concrete to extract CO2 from the air. Otherwise they are being replaced with alternatives that have a lower carbon footprint, such as timber, straw bale, and rammed earth. The process of elaboration of the latter can be seen in figure 2.7. This will further investigated later in section 2.4.

2.3 Project Building Phases (RIBA Stages)

Each construction project is different, as with each building type the steps and requirements to undergo its completion vary. However, there are frameworks that have helped standardizing these steps, to some extent, so that it can be easier to analyze and compare different constructions projects against each other. These frameworks also vary in different countries, some following more standardized procedures than others. An example is shown in figure 2.5, extracted from the

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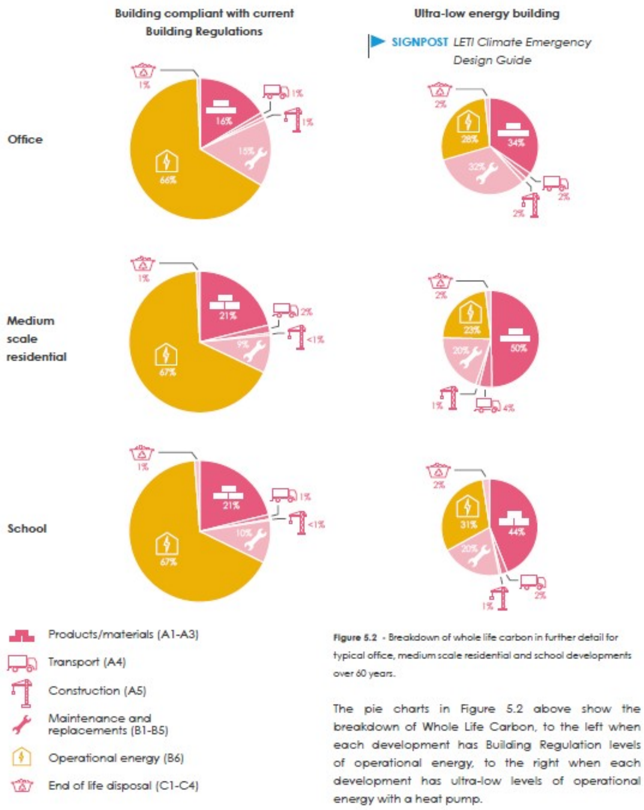

Figure 2.4: Graphs extracted from the LETI Carbon Primer report showcasing the shift from operational to embodied emissions [46]

LETI report of Embodied Carbon Primer [46], that shows the different standardized phases a construction project is divided into when performing a lifecycle assessment.

The Royal Institute for British Architects, also known as RIBA, developed in 2020 the "Plan of Work", the definitive model for the design and construction process of buildings [13]. As part of this plan the 8 RIBA stages are included, to help define steps for a construction project [35]. Figure 2.6, shows how these steps are interconnected to each other. These RIBA Stages will be utilized as reference throughout this project, to help provide a clear understanding of where in the process we are at each step. Throughout the following section the 8 stages will be briefly explained [5]:

- **Stage 0 - Strategic Definition:** This stage involves the client and the architect working together to establish the project's goals, objectives, and feasibility, as well as available budget. It also includes defining the project brief and

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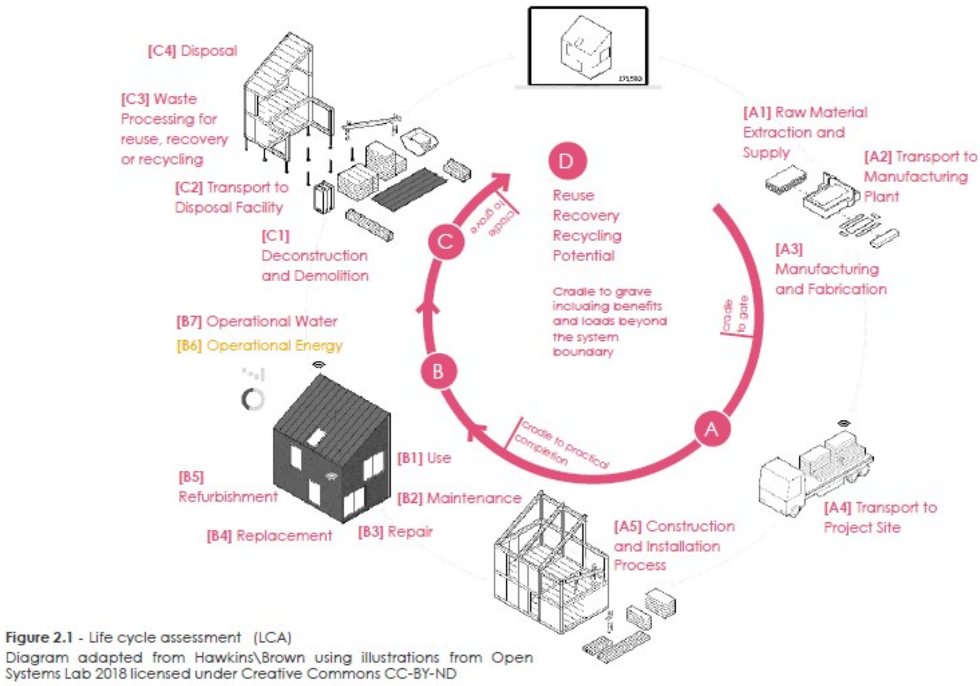

Figure 2.5: Embodied Carbon Emissions in Project Phases, extracted from the LETI Climate Emergency Plan [45]

developing an initial project strategy.

- **Stage 1 - Preparation and Brief:** During this stage, the architect works with the client to develop a comprehensive brief that outlines the project's requirements, including the budget, timeline, and design objectives. This stage also involves identifying potential risks and constraints that may impact the project's development.

- **Stage 2 - Concept Design:** The architect develops initial design concepts that correspond to the project brief and presents these to the client. The concepts include drawings, sketches, and 3D models that illustrate the design intent and key spatial relationships.

- **Stage 3 - Spatial Coordination:** At this stage, the architect develops the concept design into a more detailed proposal that includes information on materials, finishes, and construction systems. The design is further refined to address technical and functional considerations, and the architect works with other consultants to ensure that the design meets all regulatory requirements.

- **Stage 4 - Technical Design:** In this stage, the design is developed further with detailed technical specifications and construction details. The architect works

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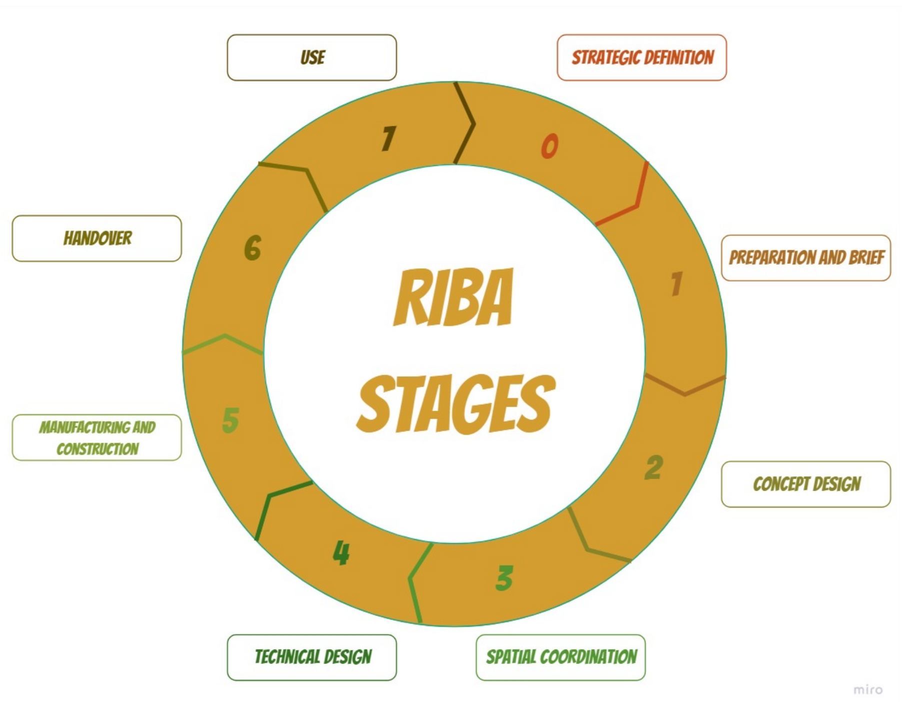

Figure 2.6: RIBA Plan of Work 2020 Stages graphical overview, designed by the author

closely with other consultants to ensure that the design is fully coordinated and meets all regulatory requirements.

- **Stage 5 - Manufacturing and Construction:** This stage involves managing the construction process, including tendering, contracting, and site supervision. The architect ensures that the project is delivered on time, on budget, and to the required quality standards.

- **Stage 6 - Handover:** During this stage, the architect oversees the final completion and handover of the project to the client. The architect ensures that all necessary documentation, including as-built drawings and operation and maintenance manuals, are provided to the client.

- **Stage 7 - Use:** This stage involves monitoring the building's performance during its operational life, including its energy efficiency, environmental impact, and maintenance requirements. The architect may also provide ongoing support to the client, including advice on building maintenance and improvements.

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2.4 Building Materials

The choice of building materials for construction projects depends on several factors, such as the purpose of the structure, the local climate, the available resources, and the budget. They can be broadly classified into three categories: natural, synthetic, and composite materials: [60]

- **Natural Materials** - are materials that are sourced directly from nature. These materials are typically renewable and have a low carbon footprint. However, they may not be as durable as synthetic materials and may require more maintenance [60]. Examples of natural materials include:
  - Wood, a popular natural material that is renewable, biodegradable, and has a low carbon footprint. However, wood is susceptible to rot, insect damage, and fire. To address these issues, wood is often treated with preservatives or fire retardants.
  - Stone, durable, fire-resistant, and has a high thermal mass, making it an excellent choice for buildings in hot climates. However, stone is heavy and energy-intensive for transport and installation.
  - Clay, a traditional building material that has been used for centuries. It is abundant, inexpensive, and has excellent thermal properties. Clay can be used to make bricks, tiles, and earthenware. However, clay is not as strong as concrete and may require reinforcement.
- **Synthetic Materials** - are materials that are produced artificially, such as plastics, metals, and cement. These materials are typically durable, fire-resistant, and require less maintenance than natural materials. However, they may have a higher carbon footprint than natural materials and therefore may not be as environmentally friendly [60]. Examples of synthetic materials include:
  - Plastics, are lightweight, durable, and can be molded into various shapes. However, plastics are not biodegradable and can release harmful chemicals when burned.
  - Metals, such as steel and aluminum. They are strong, durable, and have excellent thermal properties. However, metals have a high carbon footprint due to the energy required to extract and process them.
  - Cement is a synthetic material used to make concrete. It is a binder that holds the aggregate (such as sand and gravel) together. Cement is a high-emitting material, with the production of cement accounting for approximately 8% of global carbon emissions [80].
- **Composite Materials** - are materials that are made by combining two or more materials, such as fiber-reinforced polymers (FRP) and engineered wood [60].

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Composite materials have the advantages of both natural and synthetic materials and can be designed to have specific properties:

- FRP is a composite material that consists of a fiber reinforcement (such as carbon or glass fibers) and a polymer matrix (such as epoxy). FRP has excellent strength-to-weight ratios and can be used to strengthen existing structures or create lightweight structures.
- Engineered wood is a composite material made from wood fibers and resins. It is strong, durable, and has excellent thermal properties. Engineered wood can be used as a substitute for traditional wood in construction.

Further classifications of materials can be roughly defined into further categories based on their composition and properties [16]. The table 2.1 shows these categorizations:

Sustainable Building Materials Sustainability is becoming a critical concern for the construction industry, and various measures have been adopted to address the issue. Sustainable building materials refer to materials that have a lower environmental impact throughout their life cycle, from manufacturing to disposal. However, it can sometimes be complicated to define a material as sustainable. Concrete is a good example of this as some types of concrete have the highest environmental impact among building materials, whereas some newer types of concrete are able to absorb concrete, and therefore present a much lower overall environmental impact. There are several methods and processes being utilized to make building materials sustainable, and some of them are discussed below[38].

Sustainability is an increasingly important consideration in the UK construction industry, and several methods and processes are being utilized to make building materials more sustainable. One approach is the use of recycled and reused materials, such as recycled steel, reclaimed wood, and recycled glass. Another strategy is the use of low-carbon or zero-carbon materials, such as engineered wood, hempcrete, and straw bale. Additionally, the promotion of circular economy principles, which aim to reduce waste and maximize the use of resources, is becoming more common in the construction industry [24].

It should be discussed what, according to research from the USGBC, are the three main areas of focus are when making choices for both building materials as well as techniques to improve the construction processes [83]:

- **Conservation of material**. As established earlier in this chapter, a large share of the environmental impact of building materials is the waste that is gener-

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Table 2.1: This table presents a list with some examples of building materials common in the construction industry [16]

Building Material Examples	
Material Name	**Description**
Wood	Natural, renewable resource that is widely used in construction. It is commonly used in residential buildings for framing, flooring, and finishes. It is also used in commercial buildings for structural supports, such as roof trusses and beams. The use of wood in construction can help reduce the environmental impact of building, as it is a renewable resource that can be sustainably harvested.
Concrete	Composite material made of cement, water, and aggregate (such as sand, gravel, or crushed stone). It is a strong, durable material that is widely used in construction for foundations, walls, and floors. Concrete has a relatively low environmental impact compared to other building materials, as it is made from abundant resources and is highly recyclable.
Steel	Durable and strong material that is commonly used in construction for framing and structural supports. It is also used for roofing, siding, and other building components. Steel is highly recyclable, which makes it an attractive material for environmentally conscious building projects.
Brick	Made of clay or other materials, bricks are used in construction for walls, flooring, and landscaping. They are a durable and long-lasting material that can provide excellent insulation and soundproofing. Brick is also a recyclable material that can help reduce the environmental impact of building projects.
Stone	Natural, durable material that is commonly used in construction for building exteriors, walls, and flooring. It is a highly durable and long-lasting material that can provide excellent insulation and soundproofing. Stone is also a recyclable material that can help reduce the environmental impact of building projects.
Glass	Versatile material that is commonly used in construction for windows, doors, and skylights. It is a highly durable and long-lasting material that can provide excellent insulation and soundproofing. Glass is also a recyclable material that can help reduce the environmental impact of building projects.
Plastics	Versatile group of materials that are commonly used in construction for insulation, roofing, and flooring. They are a lightweight and cost-effective materials that can provide excellent insulation and soundproofing. However, plastics can have a negative environmental impact due to their production process and their potential to release toxic chemicals.
Composites	Group of materials made from a combination of different materials. They are commonly used in construction for roofing, flooring, and siding. Composites can be highly durable and long-lasting, but their environmental impact can vary widely depending on the materials used to make them.

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ated during the different construction processes. A good way to start promoting a meaningful reduction in the amount of waste that is being generated, is by eliminating the need for materials during planning and design phases.

- **Environmentally preferable materials**. These materials share some common properties such as being sourced from local suppliers, grown with sustainable methods, made from materials that are not only biodegradable and free of toxins but that can also be rapidly renewable. All these designations demonstrate awareness for sustainability.
- **Waste management and reduction**. Establishing the goal to reduce the amount of waste that is hauled to and disposed of in landfills or incineration facilities. During construction or renovation, materials should be recycled or reused whenever possible. During the building's daily operations, recycling, reuse, and reduction programs can drastically reduce the amount of material destined for local landfills.

When creating sustainable value in a project, an approach is to use natural materials or materials that are renewable and have a lower environmental impact. For instance, wood is a sustainable building material since it is renewable and has a lower carbon footprint compared to other construction materials such as concrete and steel. Similarly, bamboo is a renewable material that has a lower environmental impact and can be used for flooring, paneling, and structural elements in construction [8].

Another approach is to use recycled or reclaimed materials. This helps reduce waste and energy consumption since these materials have already been manufactured and processed. For instance, recycled plastic can be used as insulation material, while recycled glass can be used in the production of concrete [72]. Reclaimed wood can also be used as a flooring material or for decorative purposes in interior design .

Moreover, the production of building materials can be optimized to reduce waste and emissions. For instance, using precast concrete can significantly reduce the amount of waste generated during construction [24]. This is because precast concrete is often manufactured in a controlled environment, resulting in less waste and higher quality products, although this is not always the case. Other measures include the use of energy-efficient manufacturing processes, such as the use of renewable energy sources like wind and solar power .

There are also processes being used to make construction more sustainable. One example is offsite construction, which involves manufacturing building components in a factory and then assembling them on site. This method can reduce waste, improve energy efficiency, and decrease construction time [86]. Another approach is the use of Building Information Modeling (BIM) technology, which allows for more efficient planning, design, and construction, resulting in reduced waste and improved energy efficiency [7].

Circular economy principles can be applied to reduce waste generation during the manufacturing process. This involves reducing the amount of raw materials required to manufacture building materials, reusing materials, and recycling waste products [82]. For instance, waste materials generated during the production of ceramic tiles can be recycled and used to produce new tiles. This reduces the amount of waste sent to landfills and conserves natural resources.

Lastly, table 2.2 features a comprehensive list with examples of sustainable building materials [24] [8] [72]:

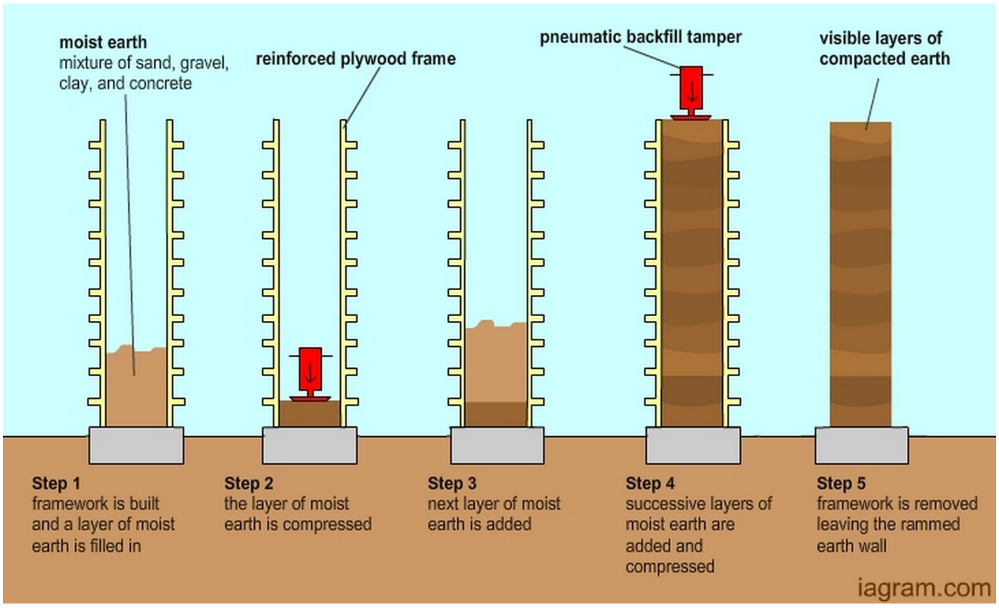

Figure 2.7: Graphic depicting the process of making rammed earth blocks, sourced from the Rethinking the Future article [72]

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Table 2.2: This table presents a list with some examples of sustainable building materials common in the construction industry [24] [8] [72]

Sustainable Building Material Examples	
Material Name	**Description**
Reclaimed Wood	In simple terms this refers to using wood from other project and re-purposing it for new constructions. It could be: Sourced from old fences and furniture, which then can be recycled and compressed; Wooden planks could be reused as flooring, or even old wooden beams which can be taken from demolished homes and barns. However, certain types of wood cannot be reclaimed for construction if it's been treated with or exposed to chemicals
Bamboo	This plant grows at incredible rates and is famous for its strength and hardness. It is quickly becoming one of the most sought out sustainable materials. Given its higher compressive strength as compared to materials like wood or brick, and a tensile strength that can stand up to that of steel almost. It can be harvested from the plant without damaging it or its surrounding environment, which makes it a highly renewable resource. It has multiple applications including structural framing or scaffolding, flooring and decorative finishes.
Cross Laminated Timber (CLT)	Has become one of the prime example of a sustainable building material in the UK. It is obtained by laminating and compressing soft woods. This creates a timber material that has enough strength to support heavy structural constructions. It is a lightweight material with high strength and a lower carbon footprint compared to other traditional building materials. It is normally produced as panels with varying thickness and can have applications such as flooring, roofing, walls and furniture.
Cork	Cork is a natural material that is harvested from the bark of cork oak trees. Similarly to bamboo, the tree does not need to be cut down to extract the cork material, making it a greatly renewable resource. This highly sustainable material found its unique purpose in building cork ceiling panels, acoustic wall and flooring. Moreover, it is a resilient material, resistant to moisture and any liquid and due to its structure, it can absorb vibration.

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Continuation of Sustainable Materials Table 2.2	
Material Name	**Description**
Wool	Wool of sheep or other animals can be used as an insulating material in walls and roofs. Wool insulation is a renewable resource and has a very low embodied energy. It can be an expensive material considering the amount of wool needed to insulate a whole building. Given the overall carbon emissions produced by agriculture, plant fiber materials, such as straw bales, might serve as an even better alternative.
Straw Bale	This consists on the utilization of bales of straw combined together as the main building material to create walls. They can serve, bound together, as good material for insulation or even load-bearing structural elements. The form of the straw bales can be taken advantage of for thermally insulated wall systems reducing the need for mechanical heating or cooling. However, straw bale construction is prone to moisture and mold; hence, it is not suitable in wet conditions.
Natural Clay/Clay Bricks	A famous construction material due to its high plasticity, large availability and low cost. It fits the bill of a sustainable material greatly due to it being entirely recyclable while releasing no toxic chemicals in the landfill. Clay is mostly used in the tiling of roofs and as a plaster, render paint, and flooring. Moreover, it is known for its thermal insulation, robustness, durability, and fire resistance.
Rammed Earth	It involves using a mixture of soil, sand, and clay that is compressed into a form to create walls. The figure 2.7, shows a graphical representation of how rammed earth is made and processed. It can be used to form walls, floors, and foundations It can be utilized for structures that require load-bearing capacity. Additionally it has high thermal mass, low embodied energy, and almost complete reusability post demolition. It is typically used for residential and commercial buildings.
Recycled Steel	It is a sustainable building material as it can be recycled indefinitely without losing its strength. Steel is highly durable and has a low embodied energy. Using recycled steel reduces the amount of waste in landfills and conserves natural resources.

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Continuation of Sustainable Materials Table 2.2	
Material Name	**Description**
Recycled Plastic	It can be found in polymeric timbers, polycarbonate panels, polymeric tiling, and machine-compressed single-use plastic blocks. Currently, recycled plastic products are only used in small-scale construction but new architectural solutions are being developed. Recycled plastic can be used for a variety of building applications, including decking, fencing, and insulation. Using recycled plastic reduces the amount of waste in landfills and conserves natural resources.
Hempcrete	A bio-composite material of hemp, the balsa wood-like core of a cannabis plant combined with lime, and water. This material is lightweight and durable, however it is not suitable for load-bearing elements and needs a framework and finishing for installation. It can be a great alternative to concrete and traditional insulation. Being a plant product and with lime turning to limestone, hempcrete has a negative carbon footprint. It is typically used for residential and commercial buildings.
Mycelium	Another example is mycelium-based materials, which are grown from fungi and can be used as an alternative to plastic insulation or traditional building materials. Mycelium-based materials are biodegradable, lightweight, and have good thermal and acoustic properties.
Adobe	Is a composite of earth, clay, straw, and/or other organic materials. Adobe bricks have similar properties to that of rammed earth construction with high thermal insulation and energy efficiency. These type of bricks are created in open-cast molds and dried in the open air before being laid using earth mortar. Excess exposure to wet conditions can lead to damage, thus deep waves are used in adobe construction.
Plants (Green Roof)	A novel model for natural insulation in roofing, with an additional biodiversity value. Installing plants across the roofing of a building, to help regulate the temperatures inside and around the building. Moreover enabling biodiversity, such as insect and birds, to nest and thrive in these environments.

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2.5 Building Types & Viable Applications

Buildings can be classified into different types based on a multitude of factors. These can include the form, function, cost, size, style or period, to name a few [87]. Understanding the different types of buildings is crucial for architects, engineers, and contractors when undertaking building design projects. The selection of building materials varies depending on the building type, the intended use of the building, and the local regulations and codes.

In this section, we will discuss the different building types, the viable applications of materials going into the structure of a building, and how these factors impact the recommendation of building materials for different types of buildings. Even though multiple ways of categorizing building exist, a common way to accomplish this is to divide them into the following categories [84][52]:

- **Residential** buildings are designed for inhabitants to populate them in and are employed for what are referred to as dwelling purposes. Residential buildings can have many sizes and shapes depending on the nature of the inhabitants within.
- **Educational** buildings, which are designed for the purpose of instruction, recreation or education. These include schools, universities or day cares.
- **Institutional** buildings are designed for any purpose regarding the health of the citizens. These can range from hospitals, clinics, prison or mental care facilities.
- **Industrial** buildings are used for manufacturing, processing, or storage of goods. This can include manufacturing plants, gas plants or refineries.
- **Business** buildings, include any building that is used for the purposes of undergoing business transactions or keeping accounts on public records. This can include offices, courthouses or city halls.
- **Mercantile** buildings, designed to house retail operations such as shops, markets or stores.
- **Assembly** buildings which refer to facilities where people gather for purposes of entertainment, social or religious purposes. This includes for example restaurants, museums or theatres.
- **Storage** buildings, are utilized for the purposes of safeguarding or sheltering goods. This includes warehouses, garages or stables.

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- **Hazardous** buildings, are designed for storage, handling, manufacturing, or processing of highly combustible explosive materials [52]. These buildings have to be designed with special safety precautions to ensure the safety for surrounding citizens against the hazards that may lay within. This can include factories destined to the production of ammunition or explosives.

The recommendation of building materials for different types of buildings depends on various factors, including building codes, regulations, and local climate conditions. For instance, in areas prone to earthquakes, buildings require seismic-resistant materials such as reinforced concrete and steel [19]. In coastal areas, buildings require materials that are resistant to moisture and salt corrosion, such as treated timber and stainless steel. Moreover, the choice of building materials can impact the energy efficiency of a building. Energy-efficient materials such as insulation, double-glazed windows, and green roofs can reduce energy consumption and minimize the carbon footprint of a building [59].

Beyond just considering the building type itself, its also important to consider the applications of said building. For instance, the same level of hygiene considerations are not required for a residential building, as they are for a hospital. The same happens with building materials, different materials are effective at performing different tasks and fulfilling different purposes. This is why it is important to consider what those viable applications will be when constructing a building. Below, the report will explore what methods have been established to help standardize this materials applications in the construction industry.

Viable Applications Building materials have a variety of applications in the construction industry, depending on their properties and characteristics. Understanding the different applications of building materials is important for selecting the right material for a specific project.

Building Cost Information Service, or BCIS, is part of the Royal Institution of Chartered Surveyors (RICS) institution in the UK. They created a list with viable applications for buildings, known as the BCIS Elements, to establish a standard for the industry to base their work on.

This list comprises every possible application for a material in the construction industry and can guide stakeholders when exploring material use and making decisions. As such this complete list could be a good reference to include into the database of the proposed solution of this project, which can be explored later in Chapter 5. This list of viable applications will be presented on table A.1 in the annex of this report, as to not overcrowd the document with information.

Chapter 3

Methodology

Throughout the following chapter the report will create an understanding of the methodology utilized to execute this project and the different goals that were set out in Chapter 1. It will begin by reiterating the research questions that have been defined for the project in Chapter 1, which includes the main problem formulation and consequent sub questions:

How to develop a sustainability focused recommender system to promote alternatives for building materials with less embodied carbon emissions?

Sub-questions

- *How can additional material parameters be accounted for to perform the material recommendation?*
- *What type of emissions should be targeted to reduce the overall environmental impact of the industry?*
- *What environmental impact can this software tool have on the construction industry?*

Different steps will be taken to answer the aforementioned research questions, and in order to execute the goals set up for this project in Chapter 1. To begin with, describing the overall strategy to answer each research question, as well as the steps involved to develop a solution for the problem at hand. Answering the main research question will consist of different steps, beginning with creating a breakdown of the industry and market context, as presented in Chapter 2. Then, it will be important to interview relevant stakeholders in the industry, to get hands-on domain knowledge, and which will potentially enable the beginning of the requirements specification process. Once an understanding of the problem has been established and some requirements created, a development process will allow the creation of a prototype of the proposed solution to showcase its viability. All of the

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collected knowledge will be analyzed to discover how it can be translated into the proposed solution, and how said solution will be developed. Finally conclusions on the project will be compiled into the rest of this report and shared with the scientific community.

Moreover, each sub-question has been formulated to tackle different parts of this process. The first sub-question, for example will require to gain an understanding of what parameters are important to address when looking at functional material properties. This will also translate into a system requirement for the solution to feature this functionality.

For the second sub-question, the answer starts in Chapter 2, where the report delves deep into how environmental impact is measured and what kind of emissions are being targeted by the industry, to argue the focus in embodied emissions, which will also be discussed further in this report.

Then, for the third sub-question, it will be required to first understand the full functionality the platform can offer, what that functionality can do in terms of enabling a reduction in environmental impact of construction activities and finally assess what impact can have in the market context. This will be addressed throughout the development of the software platform and finally discussed along with the rest of the questions in Chapter 6.

That overall project methodology resembled that of the Design Science Research Methodology, and as such this framework will be used as reference. The Design Science Research Methodology (DSRM) was developed as a framework tailored for research conducted within the area of Information Systems (IS). It aims to address real-world problems by designing and creating innovative artifacts as solutions [65].

Researchers using the DSRM methods start with defining clear objectives and design requirements based on the identified problem, serving as a foundation for the subsequent artifact design and development [65]. The design process for this artifact rigorously adheres to design principles and integrates existing knowledge and theories from available literature. Once the artifact is created, it undergoes evaluation using predetermined criteria to assess its effectiveness, efficiency, and utility in addressing the identified problem.

The research outcomes, including the developed artifact and associated knowledge, are communicated to the research community and relevant stakeholders through comprehensive reporting. This involves sharing the design rationale, im-

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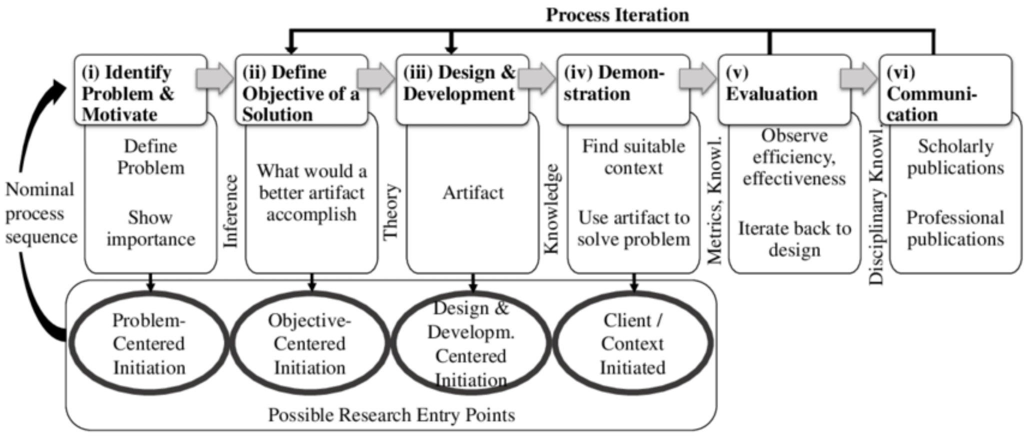

Figure 3.1: Design Science Research Methodology approach as presented in the paper by Peffers et al [65]

plementation details, evaluation results, and lessons learned from the research process [65]. Reflection and learning play a crucial role in the DSRM, as researchers critically analyze their artifacts, identify any limitations or areas for improvement, and contribute to the overall body of knowledge in the field of Information Systems [65]. Here's a summary of the key steps involved when implementing the DSRM from the perspective of this project:

1. **Problem Identification**: To start off the researcher must identify and understand the real-world problem to be addressed in the context of information systems. In this project that came through the process of elaborating the initial research questions, as well as defining the topic for this report in collaboration with the company

2. **Objectives and Design Requirements**: Clear objectives and design requirements are defined based on the identified problem, specifying what the artifact or solution should achieve. This is where the company collaboration had even more relevance in the case of this project, as it was the combination of their industry and sustainability knowledge and the author's sustainability and technology knowledge that combined allowed them to set up objectives and some requirements for the project as stated in sections 1.2 and 5.1. It was throughout this phase and part of the next one that interviews with relevant stakeholders took place. The goal for this interviews was to talk directly with domain experts to gain and understanding of the industry at large, the current methods employed for selection of building materials and gather clues on what the future might have in store. Additionally, these conversations helped influenced some of the design decisions for the developed solution,

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in order to fit better with industry requirements and expectations.

3. **Design and Development**: This phase emphasizes the creation of artifacts, such as software systems or prototypes, as a means of providing solutions to the identified problem. During this phase, pre-existing knowledge is applied. This phase occupied most of the allocated project time in this case, and was thoroughly explained in Chapter 5 of this report. It ultimately allow the development of the multiple iteration including the final version of this project's proposed solution system.

4. **Evaluation**: The designed artifact is evaluated using well-defined criteria to assess its effectiveness, efficiency, and utility in addressing the identified problem. In the case of this report the evaluation was done around fulfillment of the specified requirements, exploring which ones were implemented, as explained in section 5.5. Further usability testing is required, which is further discussed in the final Chapter 6 of this report.

5. **Communication of Research Outcomes**: All of the outcomes of the research are communicated to the research community and relevant stakeholders. This includes sharing the design rationale, implementation details, evaluation results, and lessons learned. For the case of this project that meant outputting this master thesis report, as the final assignment for the Master education undertaken by the author, which will later be evaluated.

6. **Reflection and Learning**: The DSRM encourages reflection on the research process and outcomes. Researchers assess the effectiveness of their artifacts, identify limitations, and reflect on how the research contributes to the overall body of knowledge in IS. All of the reflections on the process, methodology, effectiveness of the developed solution and more can be found in the discussion section of Chapter 6 of this report.

Throughout the following sections the report will delve deeper, first into the company collaboration for this project and how they influenced it with the proposal of value engineering as a guiding framework for the proposed solution. Later it will proceed into some of the frameworks that were established in order to perform some of the aforementioned tasks related to research, interviewing and development.

A disclaimer should be added that throughout the last three sections of these chapter, a common practice will be found. Since the project was written and developed by one single author, it was difficult to establish formal frameworks for the tasks there mentioned. For this reason those three sections will cover frameworks that were used for inspiration to follow, and how ultimately they were shaped into

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"custom" methodologies followed by the author.

3.1 Use Case: JAW Sustainability

In order to enhance the potential of the project, it was thought it would be advantageous to create a collaboration with the industry. By partnering up with a relevant company, it would allow the project to grow to a higher dimension, gaining the practical perspective of a potential use case for the solution. For these reasons a collaboration with JAW Sustainability was established.

As explained in Chapter 1 of this report, JAW functions as an environmental consultancy that is focused on providing services for the construction industry in the UK. These service range through a variety of activities including [76]:

- Energy planning and assessment of new and existing constructions.
- Whole Life Carbon Assessments (LCA)
- Energy Reporting for ESG
- Circular Economy Assessments
- BREEAM Audits

It is through these services that JAW can utilize their expert knowledge in sustainability and environmental assessments to improve the impact of construction projects in the UK. Since 2017 they have grown into a SME that has executed hundreds of projects across multiple building types from residential, commercial, educational and retail. Their ambition is to keep growing their roster of projects and clients to create an even larger green impact on this very complex industry.

As part of this ambition they have begun to take an interest in how technology can help them accomplish these tasks. It is with this spirit that when the author of this project reached out to them they were happy to explore a collaboration. It was quickly established, as can also be read in the transcript of the interview with Matthew Higgs, in annex B.2, that it would be important to focus on improving the process of choosing building materials.

Three main reasons led to this conclusion, the first one which has been introduced in the previous chapter, about the importance of reducing embodied carbon emissions and not operational emissions, as a next step for the industry in the UK. Moreover, a discussion regarding implementing machine learning into this solution, which will be discussed in later chapters, as a method to enable automated

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decision making. Lastly, the use of Value Engineering as a framework to guide the solution development, which will be covered in the following section 3.2, would enable to tackle environmental impact without discarding other important decisive factors, which will be delve into in the following section.

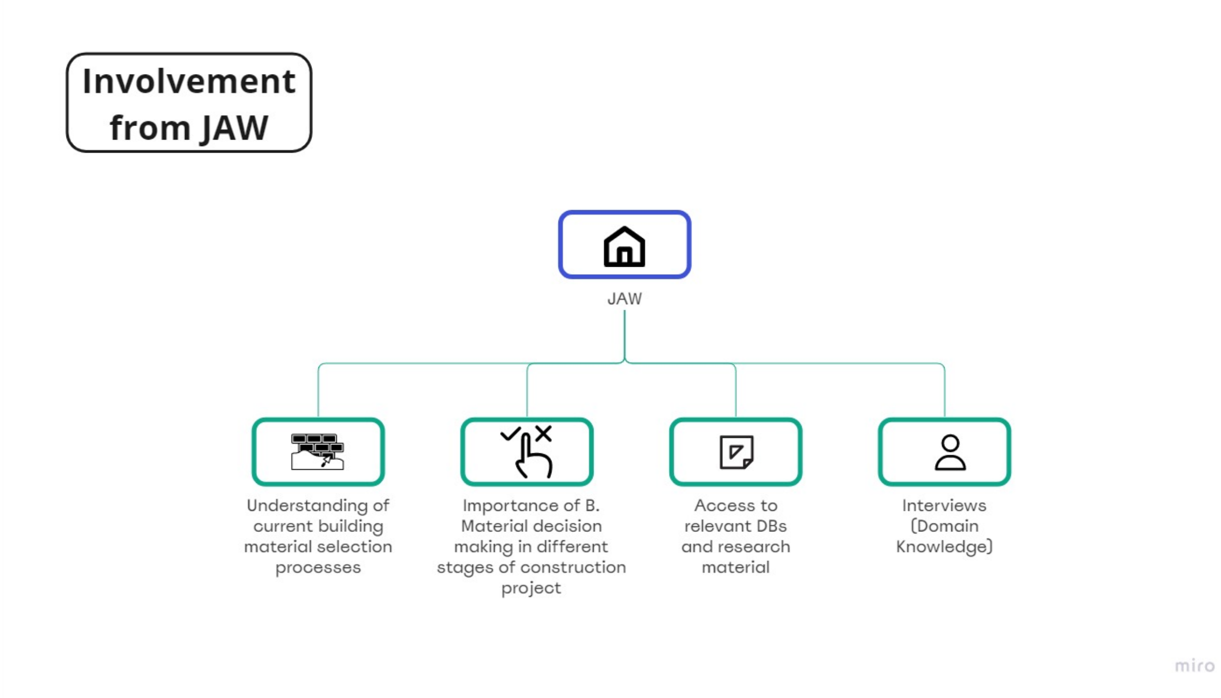

Figure 3.2: Graphic describing the contribution from JAW to the project, created by the author

The figure 3.2 describes the company's expected contributions. This is how the collaboration was established, and goals were set up for what was expected from the participation of JAW in this project, which came mainly in the way of the following contributions:

- Host the author for a company visit.
- Interviews to provide domain knowledge.
- Support in creating an understanding of current material selection methods.
- Access to relevant databases and research material.
- Support brainstorming and validation of solution conceptualization.

To sum up it is through this collaboration that the author intended to elevate the project to a practical level, backing its topic and elaboration up with practical and

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domain knowledge from industry experts. By working alongside sustainability experts of the field, that understand the industry until now and what changes are coming for it, the project will attempt to discern the potential business and commercial value of its proposed solution.

Company Visit During the second half of March 2023, the author was able to take part in a company visit to the offices of JAW in London for a period of two weeks. This visit was instrumental to the development of the project as it enabled the author to get a hands-on experience of the activities carried out by JAW on a day to day basis. Throughout this period the author was able to meet the employees working at JAW, who each focused on different activities and learn about them and how they are carried out in the industry. This included life cycle assessments, auditing, and other consulting services.

It was also throughout this period that a final conceptualization for the solution was designed, alongside the collaborators at JAW, ideating how to best approach the task at hand, elaborating requirements, which will be disclosed later in Chapter 5, as well as validating some early iterations of the prototype. An interview with the Associate Director of the company was also carried out, which enabled a higher understanding of the industry and context, a lot of which was presented in the previous chapter and will be elaborated on throughout the rest of this report.

It was also beneficial for the company, as they were able to witness first hand how technology could be developed and implemented to support their activities and validate this vertical as a potential to explore moving forward in their operations.

3.2 Value Engineering as a Framework

As mentioned above, one of the early contributions to the project from the company collaborators was to bring to the author's attention Value Engineering as a potential framework to follow throughout the project. This would specially help to target the first of the research sub-questions presented above, namely how could the algorithm take into account other factors for decision making besides its main one of carbon emissions. Throughout this section a deeper insight into Value Engineering will be provided and how this methodology can be utilized as a guiding principle for development of this project's solution.

Value engineering (VE), also referred to as Value Management, can be defined as an organized method employed by teams to analyze designed features of a

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building, its systems, equipment and the materials that were selected for it [47]. This is done in order to understand how to fulfill said system's basic functionalities while aiming to reduce its lifecycle cost, in-keeping with the systems performance, quality, safety and reliability [47].

VE is based on the idea that every building system or component has a specific function that can be performed in different ways, using different materials or techniques. By analyzing the function of each system or component, VE experts can identify the best way to perform the function at the lowest cost. This process involves a series of steps, including data gathering, analysis, and recommendations [69].

Value can be a difficult concept to define, as it can be somewhat inherently subjective. This is why a criterion had to be defined that could function as the sole measure of what value actually means, and this criterion is cost [47]. According to a study presented by the Royal Institute of Chartered Surveyors (RICS) [69], this unit served the purpose of making value measurable and therefore tracking of an increased or decrease in value measurable as well.

This engineering and analysis discipline has been applied across many industries, since it was developed in the United States in 1940 [47]. Moreover, when looking at the construction industry, value engineering can be a helpful tool for assessment of building materials, to enable increase in value with decrease in costs. In other words, VE can be seen as a framework for recommending building materials that provide the best value for money.

Value Engineering generally involves five steps [28]:

1. First step in VE is to gather data about the building system or component through either documentation or interviews with relevant stakeholders.
2. Next is the speculation phase, which is the creative brainstorming phase to generate as many ideas of how to provide the necessary function while reducing economic impact.
3. Then comes the evaluation phase, working together with the clients to set up the evaluation criteria and judge the ideas from the first phase.
4. The following phase is the development phase, where the team turns the ideas from previous phases into workable solutions
5. Finally, the presentation phase allows the team to output in a report the recommendations for the client, whether written or orally.

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One of the key benefits of VE is that it can help identify alternatives to expensive or inefficient building materials that fulfill the same functionalities [39]. For example, in a building's envelope system (the exterior walls, foundations, roof, windows and doors), a VE team may identify that a particular type of insulation is unnecessarily expensive and suggest an alternative material that provides the same level of insulation at a lower cost [39].

Implementing VE in the decision-making process of building materials requires a collaborative effort between stakeholders, including architects, engineers, contractors, and building owners. VE requires a willingness to challenge conventional thinking and to explore new ways of achieving the same or better results at a lower cost. This requires a culture of continuous improvement and a commitment to finding the best value for money [39].

It is for all these reasons that Value Engineering can be a powerful tool in the implementation of sustainability practices in the construction industry. Just as cost is used as a functional unit for analysis, this could be replaced by for example embodied carbon emissions, and still be utilized to increase value for the project. By analyzing the function of a building system or component, the VE team can identify materials that have a lower environmental impact or are more sustainable. This was the main conclusion extracted from the early meetings between JAW and the author, as to why this framework could be a useful methodology to employ in the development of the proposed solution.

3.3 Research Process

An important part of the work required to undergo this thesis project is to gain a deep understanding of the industry, the role sustainability plays in this industry, the problem being addressed, as well as what relevant solutions exist to address said problem. This section will explain the methodology behind research was done on this topic, and the approach to answer the second research sub-question presented above.

In performing research for this report the main goal was to obtain a foundation for the work that was to be done. This meant finding knowledge and reliable sources that could contextualize the problem in more detail. Gaining this understanding would enable the author to ideate better what a solution for the formulated research problem could be.

Moreover, it was important to understand what the state of the art level in terms

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of solution in the market currently was. This meant deep diving into competitor tools, research models and databases attempting to solve similar problems, and overall a deeper understanding of the role IT and technology currently play in the construction industry.

An important part of this process was to have an effective formulation of research questions that could look at the given problem from different perspectives. Furthermore, finding relevant search engines for research papers and publications which included both the AAU and LUT Online Libraries, other portals including IEEE, Research Gate and Google Scholar, as well other lesser known publishers belonging to the construction industry specifically such as the UK Portal Design Buildings.

3.4 Development Process

The proposed solution for this project will involve a software platform for recommending sustainable alternatives for building materials. As such it is important to define a methodology for how to undergo said development. Now that the research has enabled a deeper understanding of the problem to tackle, it is possible to proceed to designing and developing a solution. Both of these processes will be described more in depth throughout Chapter 5.

The design process was done in close collaboration with the project partner JAW, as they helped in the definition of some of the requirements used to guide the software development process. These design process was supported visually through the elaboration of UML and design diagrams of the software solution, its data flow, and the use cases that would appear throughout the user's journey in the platform. These diagrams will also be presented in the first half of the Design & Development chapter 5.

Originally, it was intended to implement a machine learning algorithm to form the core back-end of the project. However, one of the findings that the design along with the research phases provided was that in this case such an approach would create an unnecessary level at this stage of this particular platform, the way it had been defined, so other algorithms were explored, more on this in the development chapter.

Next, for this overall development process the Agile framework, with its Scrum subset, were utilized as inspiration. Agile and Scrum are widely adopted methodologies in the field of software development, particularly for projects with dynamic requirements and the need for flexibility [4] [81]. These frameworks offer a structured approach that enables developers to work efficiently and effectively, mostly destined towards teams of developed but that can be effective even when working on projects individually.

In general terms, the Agile approach is focused on iterative and incremental project management [4], that through its Scrum subset focuses on short, dynamic development "sprints", which constitute periods of 1-4 weeks were very focused development takes place [81]. The main drivers for this approach are customer satisfaction and value creation, meaning that the focus is to fulfill requirements established by the customer. Moreover, the goal is not to develop software or technology that will satisfy the engineers or developers behind it, but rather to set the focus on how to create value for its intended end-users.

By establishing this short periods of "sprint" developing, you are able to react quickly and dynamically to changes that might occur, or move on from features that might not be working as well as originally designed, adapting to circumstances. It is this guiding principles that led this project to the identification of the main two stakeholders this solution was targetting, namely architects and structural engineers, and use them as reference for value creation.

Ultimately, this meant that a mind map was created early on for the user journey in the platform and what the goal for each stakeholder throughout said journey was, which was then translated into the software functionalities. By utilizing a not-formal sprint approach, the author was able to iterate often and effectively throughout different sections of the software, which was very handy when getting stuck on a particular function for example, as they could move on from it and return at a later time with a different approach. The flexibility also allowed to add changes to this model as new feedback was received, for example from the interviews that were conducted.

Finally, different prototypes with increasing levels of complexity were developed, which allow to test assumptions along the way and better visualize the concepts that were being treated. Once a simple version of a certain functionality was successfully programmed, it was possible to increase the complexity of said functionality, and through combination of different functionalities create the overall software platform. The back-end side of the software was targeted first, making a terminal based prototype of the solution, before proceeding to developing a front-end interface that users could interact with.

To sum up, using established development frameworks, that the author had

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worked with in the past and was familiar with, so they could be adapted to this single-developer approach, allowed the creation of a platform that serviced the users and prioritized creating value for the identified stakeholders.

3.5 Interview Process

The last section of this chapter will cover the methodology to follow for interviews. These interviews were be conducted with industry and domain experts and will focus on understanding better the context of a construction project: What stakeholders are involved, the steps that take place and their estimated timing.

They will also aim to better understand building material selection processes, what priorities each of the stakeholder seeks for, and what features weigh more in the decision making process. These interviews were conducted in English and the transcripts will be provided in the first annex of this report, Annex B.

Interviews with industry experts play a crucial role in gathering valuable insights and expertise for a report such as this one. Designing a well-structured interview framework is essential to ensure that the interviews are conducted effectively and yield meaningful data. With the most important part being the post interview understanding and extraction of relevant information to implement into the project later.

A set of questions was defined for the interviews that were conducted, to ensure similar and relevant topics were covered in both cases, those questions were as follows:

- What is your role in the organization, and how many years have you been working in the industry?
- From your perspective what is the role that sustainability is playing in the construction industry currently?
- What are the obstacles being faced that might be preventing sustainability to be implemented further?
- What are the trends in terms of building materials and making them more sustainable?
- What are the current methods being utilized in the industry to select building materials?

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- According to your knowledge, what are the different steps that are normally followed in a construction project, since the need for the building is identified until the building has been constructed?
- Throughout those processes where would you say decisions on building materials have more weight?
- Finally, what kind of tools would you say are missing to ease this process?
- If there was a tool that could support stakeholders in making decisions on sustainable building materials, at which stage of a construction project would you say it would have the most impact?

Given the different nature in roles and levels of experience between both participants, the questions saw some slight variations between interviews, but the goal was fulfilled to ultimately gain knowledge on targeted topics. As stated above those included learning about the level of implementation of sustainability in the construction industry, trends on sustainable building materials, understanding the process of selecting building materials better and getting a sense of what tools or methods were being utilized for this decision making currently. Finally it was good to establish a relative understanding of where would a solution like the one being proposed in this report result most effective, and at which stage of the construction process would this be more effective.

Chapter 4

Examining the Knowledge Base

So far a context has been established for the aim of this project, the construction industry the role sustainability plays within it, and the methodology behind this project. In order to better understand what work has been done in the area of building materials selection, a review of state of the art research will be presented. This will provide insights into two main solution aspects, exploring current methods of building material selection and of competitor tools. Afterwards, said knowledge will be used to draw insights that can help inspire the design of the proposed solution for this project.

4.1 Exploring Current Solutions and Competitor Evaluation

The first section will focus on how building materials are currently being selected. Moreover, the report will attempt to provide a general overview of some of the tools currently being offered in the market to solve the challenge of finding sustainable building materials and reducing environmental impact of the construction industry.

4.1.1 Current Material Selection Methods

This report has attempted to shed light so far on the importance of understanding the impact building materials can mean for a construction project, in terms of financial, time as well as environmental impact. Various factors such as durability, cost, sustainability, and aesthetic appeal must be considered when deciding which materials to use. This helps to highlight the importance of selecting the correct building materials for a construction project. Throughout this section the report will present methodologies being currently implemented in order to help clients,

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developers, architects and engineers in the selection of building materials for a construction project.

Figure 4.1: Building Material Pyramid retrieved from [79]

To start, we will address one of the traditional methods employed in the construction industry for selecting building materials, and that is through experience and knowledge. Architects, engineers, and contractors rely on their experience and knowledge to select the appropriate materials for a particular project. They take into account the type of building, location, climate, and the intended use of the building. This method has been used for many years and is still used today, especially in smaller projects. Relying on the education and expertise of trained professionals is an effective method to ensure the quality of the outcome, but this also can mean a lot of costs and resources are directed towards employing said professionals.

This why new tools and methodologies are being developed to support this professionals in making said decisions, and to speed up the selection processes. One well extended method of addressing selection of materials through the lens

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of the project's environmental impact is the use of Life cycle Assessments (LCAs) [85]. They are comprehensive evaluations that assess the environmental impact of a product or system throughout its entire life cycle, including its production, use, and disposal phases. They provide valuable insights into the environmental implications of different building materials, helping stakeholders make informed decisions to minimize the ecological footprint of construction projects. By considering factors such as energy consumption, emissions, resource depletion, and waste generation, LCAs enable a holistic understanding of the sustainability performance of building materials. They contribute to the identification of more environmentally friendly options and support the adoption of sustainable practices in the construction industry [85].

Let us deep dive into a methodology that was introduced within the context of Danish construction, the construction materials pyramid [79]. This model was developed in 2019 by CINARK, the Centre for Industrialised Architecture, in collaboration with the Royal Danish Academy. It was developed based off the food pyramid graphical methodology in order to present in an easy to digest manner, the environmental impacts of different building materials, expressed in units of Global Warming Potential, kg CO2 equivalent / m3. By decree of the developers, they decided to focus the platform on the initial phases of construction, namely lifecycle assessment phases A1-A3, as initially described in figure 2.5, [79]. In the digital platform featured in their website, the users can select materials, defining the volume, are and thickness in order to calculate the GWP of their project. This can ultimately help in the process of deciding certain building materials, for stakeholders that prioritize sustainability as a metric of focus. Unfortunately this tool is currently only available with data primarily concerning the Danish market. In figure 4.1 the graphical representation of the material pyramid can be found.

Following the interview with Matthew Higgs, he provided insights into how some of these selection processes take place, specially within the context of the UK. According to his statements, found on Annex B.2, several factors going into these decisions, such as the functions or viable applications of the material, the type of building and its aesthetic or the location the building will be placed upon. However, he recognizes the effect of the status quo, meaning what is being used by similar projects, what's readily available, or simply the materials that the architects and engineers in charge are aware of. He mentioned how often the design phase will not output a material list as such, but rather of requirements to be fulfilled and let the subcontractors source the right materials themselves.

Afterwards he discussed how the implementation of EPDs and relevant databases emerge that provide information for thousands of materials, but that in turn make

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it difficult to navigate the overwhelming amount of information. Ultimately, he explained that at the end it all comes down often to knowledge based decisions, and calculations done by the appropriate professionals in order to provide the right recommendations for materials to use. However, as policies and awareness around optimizing these processes are being spread, its allowing developing these frameworks, which in turn will prompt the appearance of more tools in the near future.

Finally, as technology develops further, so does it influence across most industries, and the construction industry is no exception. Multiple software tools have been or are being developed to further help in this process, we will have a broader look into what some of these tools are, how they operate and how they help support the building materials selection process.

4.1.2 Competitor Tools

Several software tools exist that have been developed to recommend building materials based on functional requirements. Below a list, in table 4.1 will be included that features these different software tools, the goal why they were created and how they work.

Table 4.1: This table presents a list of competitor software tools to the proposed solution in the construction industry

Competitor Software Tools	
Software Name & Purpose	**Description**
Tally [48] was developed by the Sustainable Design and Energy Lab at the University of Washington in collaboration with the KieranTimberlake research team. The software focuses on life cycle assessment (LCA) and supports sustainable design decisions by quantifying the embodied carbon, energy use, and other environmental indicators associated with different building materials [40]. Tally was specifically created to integrate with the Building Information Modeling (BIM) process, enabling users to make informed decisions from the early stages of a project.	Tally operates by leveraging extensive databases and streamlined workflows to simplify the complex process of conducting life cycle assessments. Users can select specific materials or assemblies and analyze their life cycle performance in terms of carbon emissions, energy use, and other environmental indicators [48]. Tally employs recognized industry standards and LCA methodologies to ensure accurate and reliable results.

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Continuation of Competitor Software Tools 4.1	
Software Name & Purpose	**Description**
Building Product Ecosystems (BPE) [22] was developed by the Open Eco Homes project in the UK. It is a database of building materials and assemblies that enables users to compare the environmental impact and cost of different materials [22]. This software aims to support sustainable design and decision-making by providing users with data-driven insights into the life cycle assessment (LCA) of various building components. BPE is targeted towards professionals in the construction industry who are seeking to incorporate sustainability principles into their projects and make informed choices regarding the selection and use of building materials.	The software allows users to define project parameters, input specific material choices, and generate comprehensive life cycle assessments for the selected products [22]. BPE employs recognized LCA methodologies and standards to ensure accurate and reliable results. Additionally, the software offers features for comparing different design alternatives, conducting sensitivity analyses, and exploring the potential environmental impacts of various scenarios.
One Click LCA [15] was developed by Bionova Ltd, it is a cloud-based LCA tool that allows users to evaluate the environmental impact of building materials based on the BREEAM and LEED certification schemes. The software aims to support sustainable design and decision-making by enabling professionals to evaluate the environmental performance of buildings and identify opportunities for improvement. By offering a user-friendly interface and powerful analysis capabilities, One-Click LCA empowers users to assess and optimize the sustainability of their projects, from material selection to operational efficiency.	Users can input project data, such as building specifications, materials, and energy consumption, and the software generates detailed reports on carbon emissions, energy consumption, water usage, and other environmental indicators. It incorporates a vast database of life cycle inventory data for building materials, enabling users to select and compare different materials based on their environmental characteristics. Additionally, the software allows for scenario analysis, enabling users to evaluate the environmental performance of different design alternatives and assess the impact of potential changes on the overall sustainability of the project.

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Continuation of Competitor Software Tools 4.1	
Software Name & Purpose	**Description**
Athena Impact Estimator [44] was developed by the Athena Sustainable Materials Institute in Canada, it is a database of building materials and assemblies that enables users to evaluate the environmental impact of different materials based on a range of factors, including embodied carbon emissions, resource depletion, and toxicity [44]. The tool provides recommendations on material selection based on environmental impact and cost by quantifying the embodied environmental impacts, such as energy consumption, greenhouse gas emissions, and resource depletion, associated with different material choices and construction practices.	Users can input detailed information about the project, including building specifications, material quantities, energy systems, transportation distances, and end-of-life scenarios. The software then calculates the environmental impacts associated with each component and stage of the building's life cycle, including raw material extraction, manufacturing, transportation, construction, use, and end-of-life disposal or recycling [44]. The software provides users with comprehensive reports and visualizations, allowing them to compare the environmental performance of different design options and identify hotspots where improvements can be made.
Green Building Estimator [14] was developed by Autodesk, it is a cloud-based energy analysis tool that allows users to evaluate the energy performance of different building materials and assemblies [14]. The tool provides feedback on the environmental impact and cost of different materials based on the energy performance of a building.	The Green Building Estimator software operates by integrating environmental performance metrics, building data, and construction cost data to provide a comprehensive assessment of the sustainability and cost implications of different design options. Users can input project-specific information, such as building specifications, material choices, energy systems, and site characteristics, and the software generates detailed reports on various environmental indicators, such as energy consumption, water usage, greenhouse gas emissions, and waste generation [14].

Continuation of Competitor Software Tools 4.1	
Software Name & Purpose	**Description**
BCIS Life Cycle Evaluator [10] was developed by the Building Cost Information Service, it consists on SaaS (Service as a Subscription) platform, operating online to help users compare different construction components. The tool focuses on comparisons of life cycle costs as well as the whole life carbon impact of some of the common construction components. In doing this it can support the most optimal selection of solutions for the design of the project [10].	The platform operates through the quantifying of these metrics, including costs and carbon impacts of the components over the full life cycle of the building. By combining both costs and carbon impacts and pitting them under the same scope, it can provide a thorough overview of the building. Moreover, it can help predict future maintenance and replacement activities allowing users to plan these type of activities and obtain materials and specialist labour in advance [10].

In the field of construction, these life cycle evaluation software tools are invaluable resources for assessing the environmental impact of building projects. These tools provide a systematic framework for evaluating the sustainability performance of materials, components, and entire buildings throughout their life cycles. While specific tools may differ in their features and methodologies, their common goal is to assist in decision-making processes that prioritize environmentally responsible choices. They enable users to analyze the life cycle stages of a building, including raw material extraction, production, construction, operation, maintenance, and end-of-life considerations. By quantifying factors such as energy consumption, carbon emissions, waste generation, and resource depletion, these tools help identify opportunities for improvement and support the selection of more sustainable alternatives.

4.2 Incorporating Lessons from Existing Knowledge Base

This section will utilize the existing knowledge provided in the first section of this chapter regarding current material selection methods, what tools are being utilized to provide life cycle assessments of building and how they are used to provide recommendations for building materials. Armed with these insights, the aim will be to incorporate lessons to analyse what features should be implemented into this project's proposed solution. To do this, the report will explore the common factors between some of the already established solutions, combined with the industry background previous chapters have provided. Furthermore, this inspiration will also serve in the ideation of a potential business model for the solution, as well as a value proposition for the stakeholders that would be potential users. Finally, this work, along with the insights gathered in conversations with the partner company JAW Sustainability, will aid in compiling a series of requirements, use case and data flow and other UML diagrams, that will aid in guiding the development process described in the next Chapter 5.

The research presented so far has made it clear that sustainability has become in recent years a relevant topic in the construction industry, however many challenges still lie ahead. As discussed in Chapter 2, the focus on reducing operational carbon emissions has allowed the development of policies and regulations to reduce energy use in buildings, leaving a big gap to be fulfilled in the challenge of reducing embodied emissions. The development of an automated recommender system for alternative sustainable building materials can help address these challenges by providing architects, engineers and contractors with information on building material properties and their environmental impact via metrics such as embodied emissions. This allows them to make informed decisions that reduce the environmental impact of buildings.

As such, and seen by the competitor tools showed, the automated recommender system should take into account various factors, such as the location of the building, the climate, the building's intended use, and the project budget. It can also consider the availability and cost of materials and the impact on the environment in terms of carbon emissions, energy or water usage, allowing users to make informed decisions.

Another important decision to present in this section is to define at which stage of the construction project would the proposed software solution be most relevant. Given the nature and scope of the solution that will be developed throughout this project, it is expected that the tool will be predominantly relevant for RIBA stages 0-4, as described in section 2.3 of Chapter 2. These stages focus on the design of the building material and following the model presented below in figure 4.2, will be the phases carrying a predominant weight when it comes to decision making towards selection of building materials. The model presented in that figure, reiterated from the beginning of this report, was based on the RIBA stages and has been validated with experts from JAW, the collaborator company of this project, to help create an initial estimate of the most effective phases of the construction process where the tool could be effective in.

In the aforementioned model, each of the RIBA stages is showcased along with a list of what stakeholders are normally involved in each stage. Given the nature of a construction project and how many variables can make each project unique, this is presented as a rough estimate for the general procedure. This model helps

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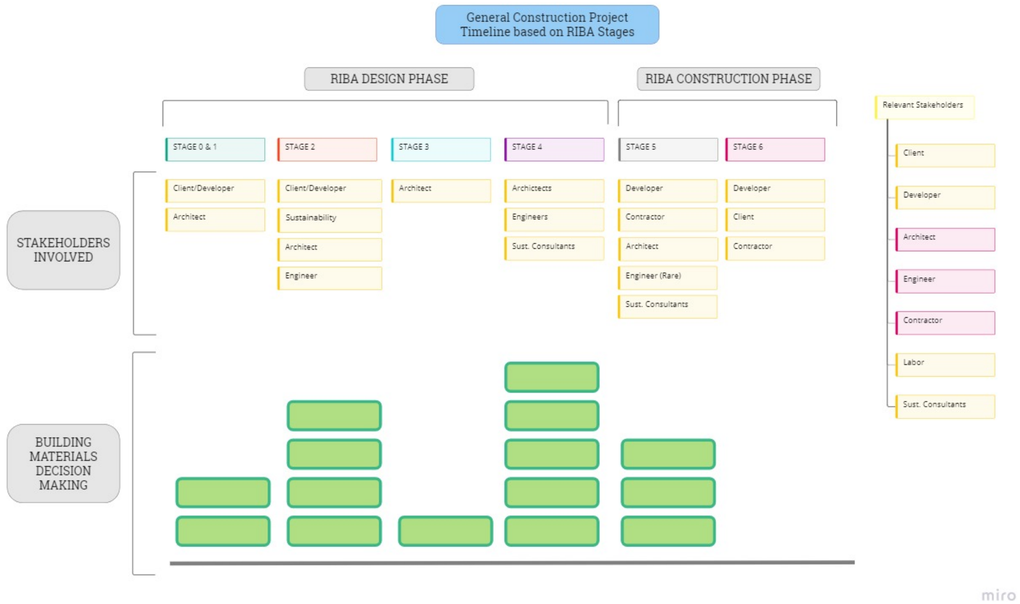

Figure 4.2: General construction project timeline based on RIBA stages, with estimated weighted distribution of materials decision making, designed by the author

to establish the understanding that most decisions in regards to what building materials are to be utilized take place during the early design stages of the project.

However, this might change for certain type of project such as Design-Build projects. In this types of project the contractor is involved in some of the design work prior to construction and has higher responsibility and decision power in regards to the selection of which materials are to be included in the construction [34]. This model can be found with some recurrence in the UK market, which is why the model showcases a mid-range decision making weight in phase 5. Now that a deeper understanding of when the highest effectiveness for using this tool can be attained, the next subsection will explore what insights can be drawn from existing solution for the design of the proposed application.

4.2.1 Empowering the Solution: Features Driven by Insights from Existing Methods

To begin with, it will be efficient to compile a short item list of common features provided by the solutions presented in the previous table 4.1. Below are said features:

- LCA-enabled (Cradle to Grave)

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- Quantifying environmental metrics (embodied carbon, energy use, water usage, toxicity)
- Implementation to existing tools and frameworks (BIM, BREEAM, LEED)
- Extensive databases
- Quantifying other metrics, such as cost and comparing with it
- Material selection and material comparison
- Inputting project and building data
- Clearly defined user base

Let us deep dive into the list provided above, and how this features could inspire functionality in the proposed solution for this master thesis project. The most important feature to include into the solution from existing solutions is the capacity to recommend materials. This will most likely include taking an input material, comparing it with existing databases and finding other material options with improved environmental impact.

Most solutions based their framework on that of a Lifecycle Assessment, this allows the tools to investigate the impact of the solution throughout all its lifetime. This means that the environmental impact analysis of the building material, can be seen from the perspective of its raw material extraction, transportation, manufacturing, use and later disposal, gaining an accurate assessment of its entire impact, measured through relevant metrics. In the case of this project's proposed solution, LCA could be a good method to establish along with the value engineering framework. The entire lifecycle would not be required, as per the initial problem formulation in section 1.1, embodied carbon emissions are the focus, and so phases A1-A4 of the LCA model, refer to figure 2.5, would be relevant here.

Moreover, in order to fulfill its purpose of sustainable recommendations of building materials, the solution should include an extensive database with different metrics. This will include those relevant to the materials environmental impact, namely embodied carbon emissions, but also those regarding other material properties that can be comparable amongst different types of materials, such as material costs, lifespan or viable applications.

In order to provide an experience that is customised to each user, the implementation of project related data would allow such an experience. The user could then create their own profile on the platform, helping them store building and project information, create preferences, and create case-specific recommendations.

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Additionally, this could include integrating the solution to other platforms relevant to the users workflow, such as BIM. Down the road this could even lead to the implementation of machine learning algorithms to enable an even more custom recommendation experience. Such algorithms could build upon those user preferences and previous project data to build comprehensive models of the user methodology, to make better recommendations.

Lastly, it will be important to clearly define who the users that will be targeted through this platform should be. This means gaining an understanding of the market context, the different phases of a construction project, and understanding of who is relevant in this decision-making process at each step. Luckily, this research has been presented in earlier chapters of this report, which combined with the interviews as well as discussions with the partner company JAW, has made it possible to determine just who these users are.

In the case of this proposed software platform, the main target users should be architects and structural engineers. They are the two stakeholders most involve in decision-making in regards to materials in the earlier phases of the construction project, RIBA stages 1 through 4, and therefore will be able to get the most value out of the platform. Following them, contractors could also be included in this list, although their decisions take place more often during the manufacturing and construction phase of the project, under much higher time constraints, unless for the case of Design-Build project. This means that for the contractors to gain real value from the platform it should be very fast and lightweight and potentially portable, via phone or tablet, so it can be easily utilized in the construction site.

Chapter 5

Design & Development

Having established a clear understanding of the identified problem, the industry context and methodologies, as well as extracting inspiration from this knowledge base, the report is ready to delve deeper into the proposed solution, how it was designed, developed and implemented. The proposed solution will be hereinafter referred to as the Sustainable Building Material Selection System, or SBuMSS for short. The last section in the previous chapter established some initial insights of what SBuMSS should feature, but these insights need to be formalized into requirements for the solution, which will be covered during the Requirements Specification.

Afterwards, the next section will help to provide some visual context to the design process of this solution, through the use of different UML resources. UML, or Unified Modeling Language, is one of the standard languages used in the field of engineering and software development for specifying, visualizing, constructing, and documenting the artifacts of software system [64]. In combination with these UML resources the report will include other resources such as flow, context and data flow diagrams.

After the first half, namely the design section of the chapter is covered, the report will proceed to cover the development and implementation of this solution. This will include describing the timeline of this development and the different iterations and prototypes that were developed. Additionally, explaining the decisions that were made at different stages, their reasoning and how they affected the overall solution functionality.

The goal for this chapter is to present in detail the answer to the main research question formulated at the beginning of this report and attempt to paint the picture of how the development of this solution for a system that enables the recommenda-

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tion of sustainable alternatives for building materials in construction projects was done.

5.1 Requirements Specification

The list of requirements will use knowledge from all the previous chapters, drawing specially from the section 4.2.1 above, as well as the interviews and discussions undergone with JAW Sustainability during the company visit. All this knowledge will be utilized to compile a series of requirements divided into User and System requirements, the latter being also divided into functional and non-functional requirements. This will be followed by a series of diagrams that will be implemented to describe the different interactions throughout the user journey, as well as within the system itself, visualizing the sequences and data flows within said system. Finally, these requirements will be analyzed under the scope of sustainability through the Sustainability Analysis Radar Chart.

To start this process off, it is important to describe the users that are targeted with this platform. This includes two main user targets and one with less priority. The table 5.1 below defines such users:

Table 5.1: Target users of the Sustainable Building Material Selection System

User	Description	Priority	Involvement Stage
Architects	Generally interested in the aesthetics of the building, the material essence or nature and giving considerations to certain functional requirements for the building, as well as material cost	High	Stages 0-5
Structural Engineers	Mostly interested in the functional requirements of the building, and their material decisions would focus on strength, mass and durability. They will also have consideration for material costs	High	Stages 2 & 4
Contractors	Material cost and availability are a very big concern for these users, but also buildability stemming from those materials	Medium	Stages 5 & 6

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Now that the users have been defined, and before the process begins for requirements specification, it is important determine a method that will allow the prioritization of said requirements. The method chosen for this will be the MOSCOW method, as this has been commonly established as a recurring method for categorization of requirements in the field of software development. It allows for clear communication and alignment of critical requirements by classifying into the following categories [49]:

- M - Must Have: Requirements categorized as "Must Have" are critical and indispensable for the success of the project. Without these requirements, the system or product cannot fulfill its primary objectives.
- O - Should Have: "Should Have" requirements are important but not as critical as the Must Have ones. They add significant value to the system or product but can be deferred to a later release or iteration if necessary.
- C - Could Have: "Could Have" requirements are desirable but not essential for the current release or iteration. They represent additional functionalities or features that would enhance the system or product but are not critical for its basic functionality or immediate success. These requirements can be considered if time and resources permit.
- W - Won't Have: "Won't Have" requirements are intentionally excluded from the current scope or release. They are deemed non-essential or not viable to include at the present moment. These requirements may be revisited and considered in future releases or iterations if circumstances change.

Now, the list of specified requirements will be presented. These requirements have been divided into two subcategories: Functional and non-functional requirements. Each subcategory will list the requirements, and their priority, and reasoning will be included in each subsection for the decisions behind prioritizing certain requirements over others.

5.1.1 Functional Requirements

In simple terms, these requirements help answer the questions of "what the system should do". They are otherwise understood as descriptions of what services should the software platform offer [58]. They can vary in level of complexity, and they generally describe input or outputs of data, certain behaviours or calculations. Below, in table 5.2, you can find the list of functional requirements elaborated for the proposed solution:

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Table 5.2: Functional requirements for the Sustainable Building Material Selection System

Functional System Requirements		
ID	**Description**	**Priority**
REQ-F-01	The system must be able to take in an input material name from the user	M
REQ-F-02	The system must be able to retrieve the material properties based on the input name from the user	M
REQ-F-03	The system must be able to provide a recommendation for a sustainable alternative material, for the given input	M
REQ-F-04	The system must contain an extensive database with information about different material properties	M
REQ-F-05	The database must contain information about embodied carbon emission values for each material	M
REQ-F-06	The database should contain information about other building material properties pertaining each material	S
REQ-F-07	The user must be able to manually enter new material information if input reference material is not already available	M
REQ-F-08	The system should be able to add manually entered information about a material into the existing database	S
REQ-F-09	The user could be allowed to select building materials from a list if they do not have a material to input themselves	C
REQ-F-10	The system should be able to establish an internal value to track the input material from the user as the reference material	S
REQ-F-11	The system should allow the user to define ranges of percentage deviations for functional material properties	S
REQ-F-12	The system should be able to filter out materials based on the user-defined deviation ranges	S
REQ-F-13	The system should be able to find most sustainable materials among functionally a filtered list of materials	S
REQ-F-14	The system will not feature an in-platform webshop to enable the direct purchase of recommended materials	W
REQ-F-15	The system's user interface could feature a dark and light mode design for ease of reading for the user	W

It will be important to explain the reasoning behind assigning the priority levels to the requirements the way it has been done. To begin with, the requirements of highest priority, rated "M" have been deemed so on the basis of answering the question "how can we ensure the most basic functionality of the system?", or otherwise what features does the system need to provide in order to fulfill its defined goal. This includes requirements such as being able to take a material input or out-

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put a material recommendation, tasks that will be necessary to fulfill the ultimate goal posed in the main research question of this report.

On second level of priority, this requirements have been established as secondary goals to be fulfilled during the development of the SBuMSS platform should time and resources allow it so. These functionalities would support greatly the main core functionalities of the system. However, if they are not able to be developed, the system would be able to fulfill its core functionalities nonetheless. These includes requirements such as having more building properties in the database, which would be a function implemented to answer only a research subquestion, not the main hypothesis.

Lastly, the latter two levels of priorities represents requirements that during the ideation phase with JAW were deemed as "nice to have" but not "need to have", similarly to the "S" requirements but with even less weight on the overall result. As for the "W" requirements, these are based on discussions of features that could be interesting to include should this platform become a more developed market product. However, at the proof of concept stage that its currently being presented in, these are not relevant.

5.1.2 Non-functional Requirements

Non-functional requirements on the other side attempt to answer the question "how does it do it?" in regards to the target software platform [71]. They describe system qualities to help guide how it should be designed, helping to guide how the system should respond to specific inputs. The list of non functional requirements will be found below:

Table 5.3: Non-functional requirements for the Sustainable Building Material Selection System

Non-Functional System Requirements		
ID	**Description**	**Priority**
REQ-NF-01	The application design must be overall lightweight and minimalist	M
REQ-NF-02	The system must be able to compare sustainable metrics of building materials in order to make recommendations	M
REQ-NF-03	The system should consider other functional material properties when making decisions on material recommendations.	S
REQ-NF-04	The system should be designed in a modular way so that new functionalities or changes can be easily implemented	S
REQ-NF-05	The system must contain a clear and concise user interface that enables intuitive interactions with the user	M

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Continuation of Non-Functional Requirements List 5.3		
ID	**Description**	**Priority**
REQ-NF-06	The system should contain an introductory text in the first page describing the purpose and functionality of the platform	S
REQ-NF-07	The system could contain in-page instructions to help guide the user on how to navigate each page	C
REQ-NF-08	The server must present the final results of its recommendations to the user in a clear manner	M
REQ-NF-09	The results could include metrics on the screen to compare the output recommendations properties with those of the input material	C
REQ-NF-10	The system could be designed using a defined colour pattern to showcase an aesthetic visual appeal	C
REQ-NF-11	The application must be divided into multiple pages to prevent overcrowding the user with information	M
REQ-NF-12	The application should contain a navigation menu to help the user understand in which step of the process they are at all times	S
REQ-NF-13	The system should contain simple widget for user interactions, such as sliders to enable setting up percentages for functional property deviations.	S
REQ-NF-14	The system could display the amount of materials that fit the functional deviation ranges set by the user	C
REQ-NF-15	The system could display the final material selected by the user in a separate page for clear presentation of results	C

Similarly to the example followed in the previous subsection, reasoning for prioritization of non-functional requirements will be hereafter presented. Moving away from functionality and focusing on methodology for the system, the non-functional requirements list focuses greatly on visual and otherwise arrangement design decisions for the platform itself. As such a lot of the requirements have attempted to explain what the look and feel of the platform will be. Nevertheless not all of these decisions carry the same weight. On the highest level of priority we find requirements such as the need for the platform to be lightweight and minimalist. This was deemed of highest priority as it will enable the highest value for the users of this platform. A lightweight platform would enable them to implement this tool into their existing operations and by making it minimalist you can reduce the training needs. This is why this along with other requirements to enable the core functionality of the overall platform have been rated "M".

As for the second order priorities, these have followed a similar criteria as for functional requirements, enhanced the core functionality but not disable it should the requirements not be fulfilled, and not dramatically hinder the look and feel of the platform. A good example of this is the navigation menu: It should be there, it would be a great support for the user and greatly ease their navigation through the platform, but if this menu is not existent, the user should still be able to gather their recommendation from the SBuMSS tool.

Lastly, the few requirements rated "C" have been selected as the lowest level of priority as they could serve as a nice "bonus" for the user's journey in the platform, but if they were not to be there they also would probably not be missed greatly. A good example of this is the display of the number of filtered materials based on functional properties. Regardless of if it is possible to display this number, the sever inside the application should still be able to perform said filtering in order to attain its recommendation.

5.2 System Design Diagrams

To continue describing the design work done during the first half of this chapter, the report will proceed to dive deeper into resources that aid visually to the representation of this concept. This will include a series of diagrams within the framework of UML that engineers commonly use to represent their design ideas prior to development. These diagrams will include:

- Context and Data Flow Diagrams
- Use Case Diagrams
- Sequence Diagrams
- Flow Diagrams
- System Architecture

These diagrams will help give more context to the functionalities of the proposed software system. Explaining who are the different entities involves in its functioning, how this entities communicate with each other, the different tasks that the user can perform within this system, as well as what the overall components of the system are.

5.2.1 Context Diagram

The context diagram, is also referred to as the Level 0 Data Flow Diagram. This entails the highest level of representation of what data transfers occur within the system [26]. As such it represents the elements and entities that take part in the

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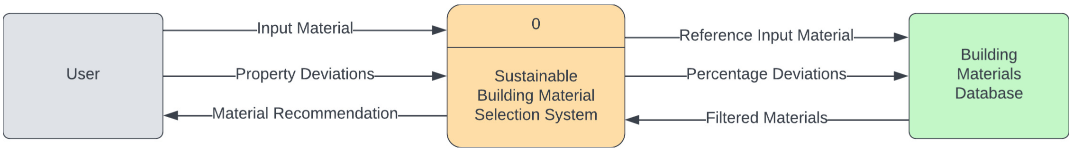

Figure 5.1: Context Diagram, designed by the author

operation of said system without going into details of their internal functionality and setting boundaries for the system. In the case of this report context diagram, shown in figure 5.1, it contains the following elements:

- Gray box on the left to represent the users interacting with the platform
- Central orange box that represents the application, containing the server and user interface
- Green box on the right representing the building material database that feeds the application
- Series of black arrow lines describing the high-level flow of data being exchanged during the functioning of the system.

With these elements the diagram attempts to establish a general conceptualization of the system data exchanges. In the next subsection a detailed Data Flow Diagram will be presented.

5.2.2 Data Flow Diagram

A data flow diagram (DFD) visually represents the movement and exchanges of data that happen within a given system. It represents how data moves between different components, processes, and entities [56]. Standardized symbols are utilized to represent different components of the diagram such as entities, data stores, or processes. Figure 5.2, showcases the data flow diagram designed for the Sustainable Building Material Selection System. Color coding was utilized to represent different processes that are associated with each other, with the lighter colors representing sub-processes. The diagram showcases different components with symbols as described below:

- Entities (External Agents) - These are represented with two large gray boxes and 3 green boxes. They represent elements external to the system that interact with it. This includes the user, server and databases feeding into said server.
- Processes - Represent the activities and exchanges that occur within the system. They are all represented with round edged boxes that have a lined

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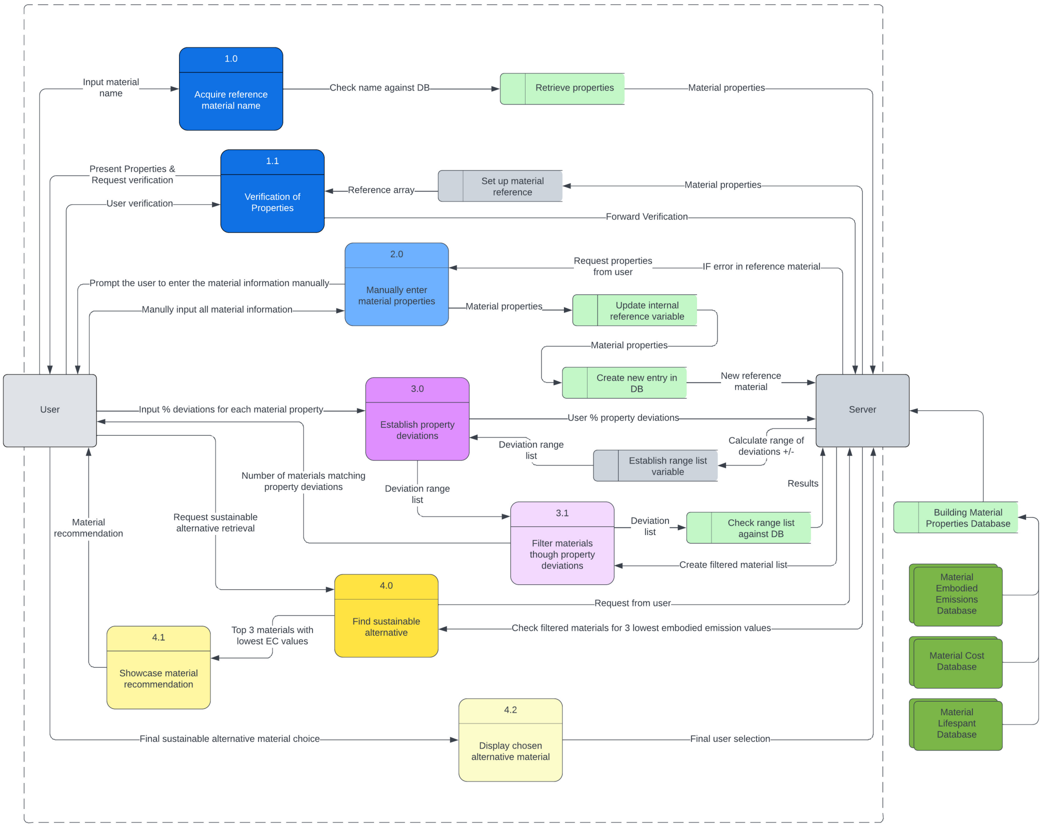

Figure 5.2: Data Flow Diagram, designed by the author

header. Example of these processes include acquiring a set piece of data, populating an internal variable, or otherwise performing a specific task.

- Data stores - represented in open-ended rectangular boxes on two different colors. Data stores help represented at which a certain piece of data is stored and where. The gray boxes relate to internal variables saved and populated by the server, whereas the green boxes represent data that is retrieved or stored in the server's database.

- The black lines in between help visualize the exchange and describe what action is taking place at each step of the process.

Overall the diagram on figure 5.2, provides a detailed look into the data exchanges within the system. Thanks to the arrangement of the elements and the color coding utilized it is possible to get a somewhat chronological description, from top to bottom of the diagram, of the data flow in the system.

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5.2.3 Use Case Diagrams

A use case, represents an action that can be taken by an system user to interact with the system itself [43]. A use case diagram helps to visually represent all the use cases within a system in the same diagram, showcasing the overall system interaction [43]. In order to create a use case diagram for the proposed solution, first a list has to be elaborated with all the different use cases that will occur during the functioning of this solution, hereafter said list of use cases can be found:

Table 5.4: Use Case UC-1 Diagram

ID	Use Cases
UC-1	Access the recommender system
UC-2	Input a reference material
UC-3	Verify material information
UC-4	Manually enter material properties
UC-5	Set up property deviations
UC-6	Filter materials based on property deviations
UC-7	Find sustainable alternative within filtered materials
UC-8	Present Recommendations
UC-9	Select recommendation

The use case diagram will help to showcase which actors are involved for each of the use cases mentioned above and how the interactions between those actors and the use cases take place. This will help create an overall idea of the journey the user undergoes when navigating the software platform. Additional descriptions of each of the use cases, following the UML model, can be found in the annex of this report, specifically in annex A

The figure 5.3, shows the use case diagram designed to represent the user journey in the SBuMSS system. This diagram consists of the following elements:

- Actors are represented in this graph with two stick figures. They refer to external entities to the system that interact with it. In this case, two actors are displayed, the user who is the one navigating the platform, and the server which in this case will be the back-end of the platform including the database and interacting from the other side.
- Use cases are represented with blue circles, each containing the code and title for the use case they refer to, as per the list 5.4 above. These use cases help capture the system's behavior from the user's perspective and describe the interactions between actors and the system.
- Relationships are represented through different sets of lines and help explain the interactions between the actors and the use cases and thus who is in-

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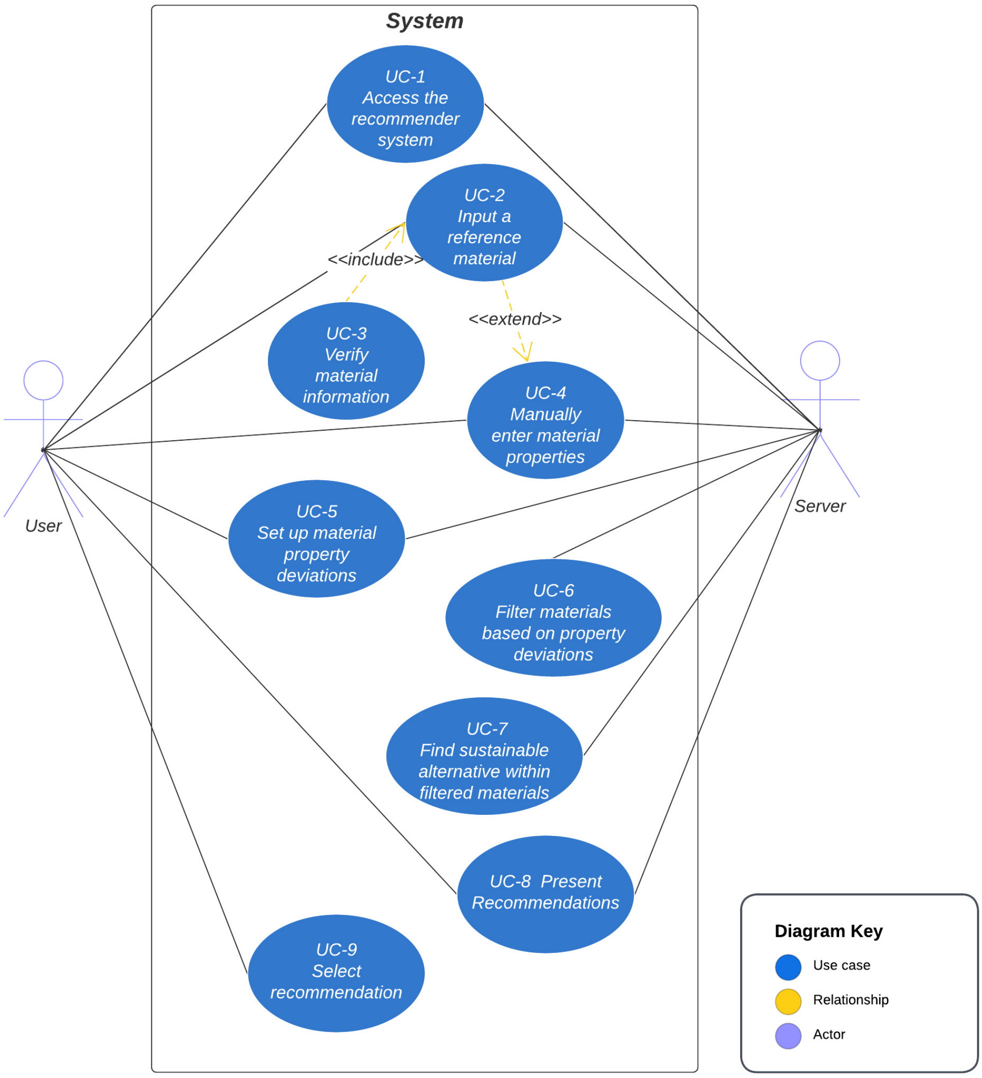

Figure 5.3: Use Case Diagram, designed by the author

volved at which step. The solid black lines represent a direct relationship between the actor and the use case. Two dotted lines exist:

– The first line with the text "<include>", which indicated a use case that relies on the previous execution of another use case to take place. In this case verification of the material information will only take place if said information has been inputted by the user.

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  - The second dotted line reads the text "<extend>" and it refers to a use case that appears if a certain condition has taken place. In this case manually entering material information is only required if the user has not been able to find their material input in the database after use case UC-2 has been executed.

- The system boundary, depicted using a box around the set of use cases. It represents the scope of the system being modeled. The boundary defines what is inside the system and what is external to it.

5.2.4 Sequence Diagram

The sequence diagram somewhat serves as a middle ground to combine the data flow diagram and the use case diagram, but with the element of time. It represents the dynamic behavior of the system and captures the sequence of events or method calls that occur during a particular scenario or use case [55]. Actors and external entities are contrasted with each other and their interactions in the system are set within a common timeline. Figure 5.4 depicts the sequence diagram designed for the proposed solution. This diagram utilizes color coding to differentiate between the actions of the user, the server and the database and is composed of several elements which include:

- Actors and entities are in this case represented with a stick figure (user) and two colored boxes for the server and database

- Lifelines help create a connection between each of the entities participating in the system over the extension of the diagram, and they are represented using dotted lines that stem from each of the aforementioned entities.

- Activation boxes are shown in this graph as colored rectangles with round edges. They help showcase the extend over time that each interaction by the entities take place under, from start to finish. These therefore are the main elements used to create the visual representation of the interactions over time.

- Messages depict the interactions or communications between objects in a sequence diagram. They are normally represented in one direction to indicate where it originates and where it goes to. The nomenclature of using numbers with a colon in between was used to further which sequences of elements take place right after each and are as such connected to each other. Two types of messages are depicted in this diagram

  - Forward messages - Indicate interactions where one actor sends data or interacts with another actor. Drawn in a single solid black line

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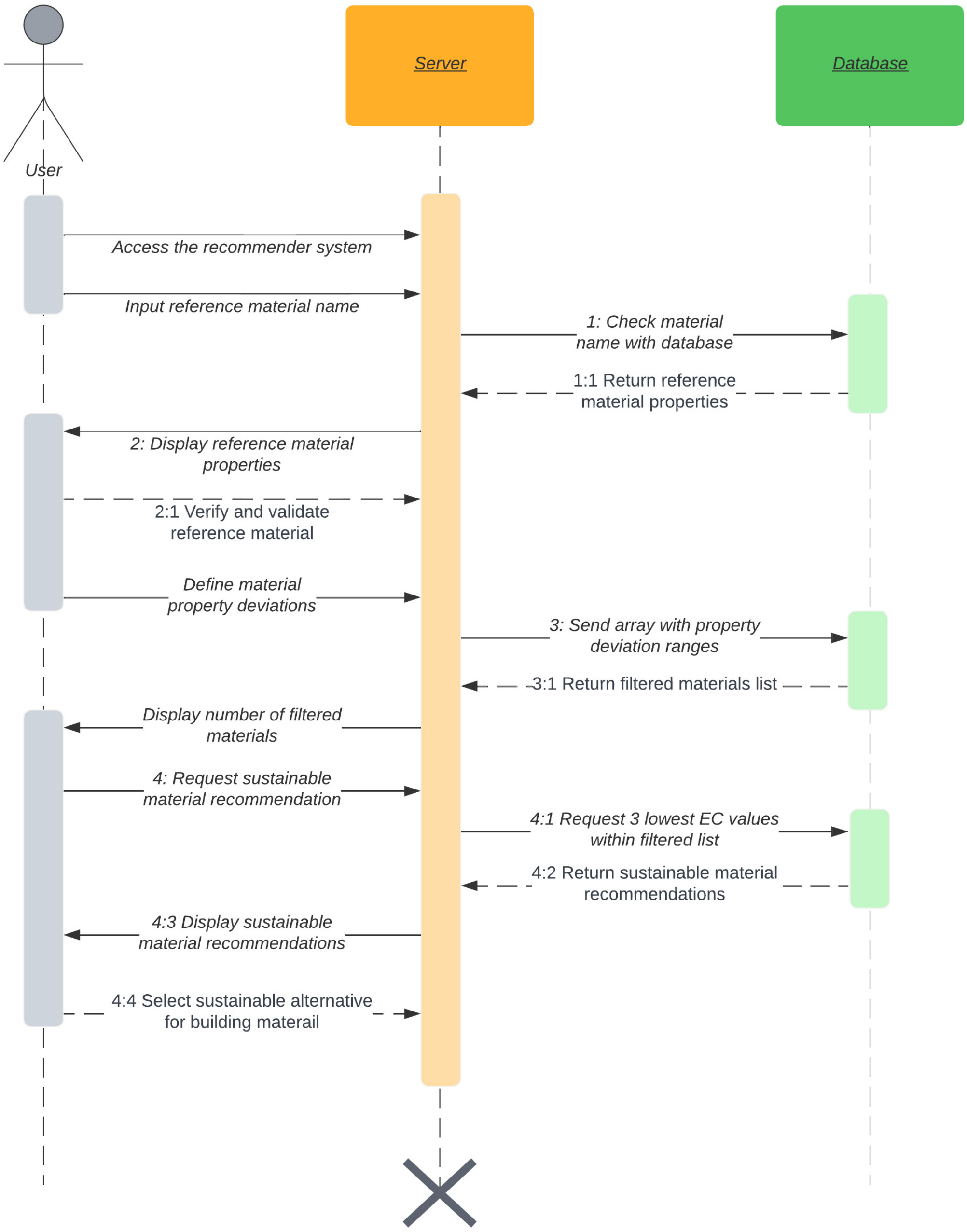

Figure 5.4: Sequence Diagram, designed by the author

– Return messages - In this case indicate messages that are returned in response to a given message. An example of this is "1:1 Return reference material properties" which occurs after the system has checked the input

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material name with the database.

5.2.5 Flow Diagram

A flow diagram, also known as a flowchart, is a graphical representation of a process or workflow [57]. In the case of the proposed system, its flow diagram can be found on figure 5.5. This diagram helps to depict in very high-level detail the steps taken by a user to go through the SBuMSS platform from start to finish. This helps gain an idea of the normal steps that a user will take since they enter the platform all the way until they are ready to exit. Since the proposed platform is designed to be straightforward and minimalist, the flow diagram This simple diagram is composed of multiple components:

- Start and end symbols are depicted using round shaped rectangles in a dark red color. They represent the beginning and end points of the flow diagram. The start symbol indicates where the process starts, while the end symbol represents the final step or completion of the process.
- Process are represented using full rectangular boxes in a light yellow color. This refer to the specific actions taken by the user, throughout the flow process.
- Decision symbols are diamond shaped boxes. They help depict points of inflexion where either the user has to make a choice, or in this case two alternative routes appear depending on the outcome of a specific action. Such is the case for the input of reference material, if the name is found in the existing the database information on that material is a straightforward process. However, if the name is not found the system must ask the user to enter said information manually and proceed to make a new entry in the database for the user.

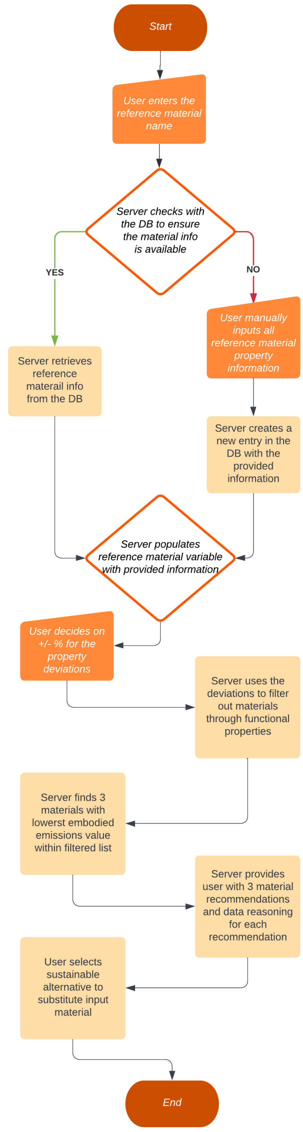

Figure 5.5: Flow Diagram, designed by the author

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- Inputs are represented using skewed orange boxes. This represent instances in which inputs of data are put into the system, which for the case of this diagrams represents moments in which inputs from the user are required to continue, such as deciding the deviation values for the functional properties.

- Flow arrows or connectors, drawn with solid black lines, are used to connect the different symbols and indicate the flow or sequence of steps in the process. The arrows show the direction of flow, from one symbol to another, indicating the order in which the activities are performed.

5.2.6 System Architecture

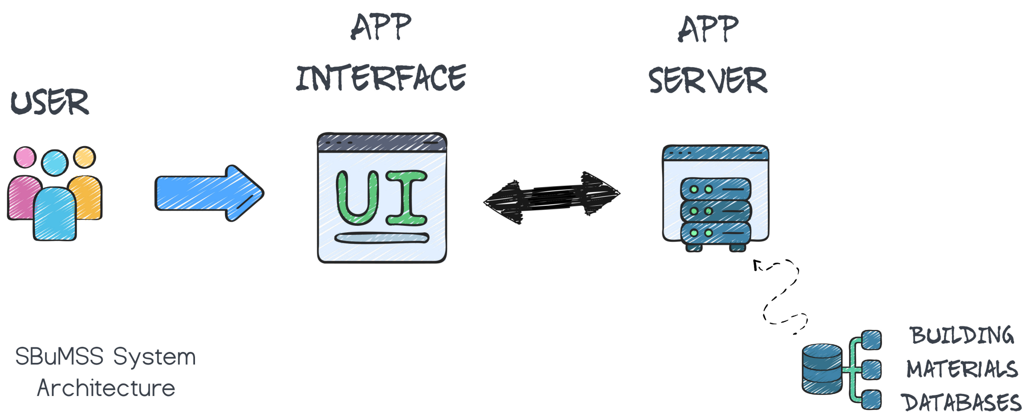

Figure 5.6: Sustainable Building Material Selection System, System Architecture diagram, designed by the author

In order to provide a high-level overview of the physical or digital assets involved in a defined system, system architecture diagrams are used. These diagrams help to visually represent the overall structure, components, and relationships within a system or software application [74]. It showcases the arrangement of different system elements and how they interact with each other to fulfill the system's requirements and functionality [74].

For the case of this proposed solution, given its minimalist nature, the diagram will be rather simplistic. Figure 5.6, showcases said diagram, using hand drawn style iconography borrowed from the Flaticon website [30], to represent the SBuMSS system architecture.

These diagram is composed of several elements from left to right: First are the users who interact with the platform, as described earlier in this chapter in table 5.1. Then a blue arrow shows the users interaction with the next element, which is the applications graphical user interface. Afterwards a two sided arrow showcases the ongoing communication between the front end GUI and the back-end server in this application. Finally the application's server (back-end) is depicted, and connected via the dotted line to the database that is implemented, containing different information on properties of building materials.

5.3 Development Stages

To begin the second half of this chapter, pertaining the development of the Sustainable Building Materials Selection System, the report will begin by deep diving into the stages that went into developing the elaboration of the final prototype. To do this, it will begin by describing the different prototype iterations that were developed. This will allow to create a detailed overview of the different features that were tested and how they enabled further design decisions towards the final prototype.

As described in the system architecture diagram above in figure 5.6, the back-end server of the system operates using external databases that contain the building material information. These database acquisition and implementation will also be described in a subsection below.

Prior to diving into the development stages, the resources used to develop this solution will be presented. The final prototype of the Sustainable Building Material Selection System was developed utilizing the Python coding language. This language covered both the front and back end sections of the application. Python was selected as it served as a relatively lightweight language that enables the fast development of full stack applications. Python also features a number of libraries that enables the effective handling of large data streams and databases. The following libraries were included into this system's development. Below some of these key libraries will be listed and briefly described:

- **pandas** data management library. As described per its developers is "a fast, powerful, flexible and easy to use open source data analysis and manipulation tool, built on top of the Python programming language" [62].

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- **Pillow** (PIL Fork) - Python imaging library. As described per its developers "adds image processing capabilities to your Python interpreter" [3].
- **Customtkinter** based on the Tkinter GUI Python library. It is, as described per its developers "a modern and customizable python UI-library based on Tkinter" [73].

To sum up, this section will help providing a timeline of how the process of deciding the Sustainable Building Material Selection System came to be. Emphasizing how each prototype iteration enabled the author to apply learnings and make educated decisions that contributed towards outputting the final prototype iteration.

5.3.1 Prototype Iterations

As stated above, this subsection will present the series of prototypes that were developed on the road to attaining the proposed solution for this project. A list roughly outlining those prototypes can be found below:

1. Back-end K-neighbors prototype
2. Back-end basic terminal recommendation
3. Front-end Tkinter interface
4. Front-end combined functionality Customtkinter approach
5. Front-end multi-class interface
6. Full-stack final solution prototype

Back-end K-neighbors prototype Early in the ideation of this project, the author designed a simple terminal interface to prove the viability of the topic idea to create a sustainable building material recommender. This consisted of a simple terminal interface, with a small hard coded database of material information. During this iteration the goal was to explore the potential of implementing machine learning algorithms into the solution.

The hypothesis was that implementing machine learning would enable creating an automated recommender system. It was theorized that this would allow to create a more comprehensive recommendations for the user and train an algorithm to better understand how to reduce the environmental impact of a construction project. So, for this early prototype a k-neighbors algorithm was implemented. In short, this focused on understanding grouping of data, in this case building

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material properties. The classifier would use proximity of data points to find the alternative materials with lower embodied carbon emission values.

The goal for the prototype was attained, the recommendation were not strictly fitting. The algorithm suggested replacing reinforced concrete with clay, which granted it can have lower embodied emissions, it does not fulfill the same functional properties. This led to deciding that other additional building properties would be considered, which was explored in the next prototype iteration.

Back-end basic terminal recommendation During the early phases of the project, when initial solution designs were taking place, an assessment of the potential machine learning implementation was done. This included early literature review onto similar models approaching the treatment of building material data through machine learning. During this assessment it was analyzed that it was difficult to pinpoint a "learning" aspect to the process being developed.

Machine learning would add a level of complexity that was unnecessary to accomplish the proposed goal for the system. This feature was therefore discontinued and left for potential future work, which will be discussed later in the discussion in Chapter 6.

Following the learnings from the previous iteration, a design decision was made here to implement multiple building material properties in the recommendation to ensure, useful outputs. Afterwards further literature research was conducted, along with elaborating the first design diagrams for the proposed solution. The first being the flow diagram as presented in figure 5.5, as this helped define the core functionalities that should be developed for the proposed solution.

The second prototype iteration focused on fulfilling this functionality in a basic interface. To accomplish this an initial building material database had to be developed, which will be explained further in the subsection 5.3.2 below. This database included information on some functional properties as well as embodied emissions values for each material for over 500 materials. With this, it was possible to develop a simple terminal-based model to accomplish said functionality. Using the Pandas library, to take in a material input, some property deviations, and combine it to make recommendations of sustainable material alternatives.

Front-end Tkinter interface Now that the back-end model for the solution had been developed, it was time to look towards the graphical user interface. The first

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step was to create a mock-up of what the GUI could look like. To do this, the Figma design tool was used [29]. This tool enabled quick design of interface mock ups to help solidify the ideated concepts. This coincided with the company visit to the JAW Sustainability office in London, which allowed to run the new GUI designs by the company for validation and to further brainstorm next steps.

In order to validate these ideation, the concepts had to be elaborated into a prototype. To accomplish this, Tkinter was decided as the desired library for implementation. This was due to its simplistic nature which would allow the development of a full application for a development team that was mostly short-staffed, driven by the author as the only developer. With this tools in hand a simple interface to input the material and print the recommended material was created, thus fulfilling the third prototype iteration.

Front-end combined functionality Customtkinter approach To fulfill the goal of building a full-stack platform for sustainable selection of building materials, further prototype iterations were needed. Furthermore, to fulfill some of the non-functional requirements regarding the style and aesthetic of the platform, the Tkinter library was not enough. Even though this library could provide the functionality for a front-end GUI, it could not fulfill the requirements of style, as it looked very basic.

This is where the Customtkinter library was discovered. This library allowed to to create stylistically gratifying interfaces, based on the Tkinter functionality. This meant that the transition from one to the other could be straight-forward. For the fourth prototype iteration, a multi-page interface designed with Customtkinter would be the development goal.

The goal was to be able to create basic page interfaces that could link the back-end functionality to the front-end interface, without necessarily making a very aesthetic interface at this point. This goal was accomplished as the interface could retrieve information to patch through to the back-end functions, to output recommendations. However, with the problem that all the front-end code was on the same page, and therefore its readability was difficult.

Front-end multi-class interface Moving forward it was important to keep iterating on some of the errors found in the previous prototype iteration. In order to maintain a clean organization in the code, each of the pages with their own functionality was divided into multiple classes, and therefore establishing the need for

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object oriented Python code. Each of those classes featured a different step of the Flow chart model. Each of these classes will be explained more in depth in the Implementation section 5.4.

In designing the interface, a flaw was found with the Customtkinter library, which came through the implementation of buttons. In Tkinter is possible the use Python tuples to enable button widgets to activate multiple functions at once. The same however was not possible for Customtkinter, as each button widget is only able to execute once individual function. This meant that the interface had to be designed using more button widgets that originally desired.

After the prototype development was finished it was once again validated with JAW Sustainability to assess some of the design decisions. These included decisions such as what additional functional material properties to consider in the recommendation. In said discussion it was decided that the functional properties should be commonly comparable amongst the different materials. This applied for a property such as strength, as this is a difficult parameters to compare among materials of radically different types, and additionally engineers already have a rough idea of what they want their specific strength values to be in a project, and therefore a deviation of this property would not be relevant. This is how the three functional properties used in the solution were decided: material viable applications, cost and lifespan. These properties were able to be compared amongst greatly different materials was still providing a good functional assessment.

Full-stack final solution prototype Lastly, after multiple prototype iterations had been successfully developed, it was time to develop the final demo prototype for the proposed solution. By this time all the UML design diagrams had been created, ideation phases along with the collaborator company JAW were finalized, and a clear idea of what the functionality of the system had to be was clearly defined.

For this final prototype iteration, the focus was to implement all the functional and non-functional requirements marked with priority "M", and as many of those marked with "S" and "C" as possible. This also included adding quality of life changes, such as the explanations at the beginning of the platform, to help clear out what the platform's purpose and functionality was. With all these changes implemented, the software platform was deemed ready for demoing and the development process therefore concluded for now.

In the next Chapter 6, a discussion will be presented of what future work would be developed into this platform moving forward. Additionally, in the final Annex

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C of this report, all the source code files for the final prototype can be found for consultation.

5.3.2 Databases

Before finally describing the implementation of the final solution prototype, the report will shortly describe the process for acquiring and building the databases that feeds the application server, as described in the system architecture figure 5.6. This would be built to harbour all the information regarding each property of the material. It will go on to take precedent as the main source used by the model to compare reference materials and make recommendations for alternative materials. As such this database was compiled onto an excel sheet featuring the following data points:

- Unique identifiers for each material
- Material name
- Embodied carbon emissions values
- Material cost
- Material lifespan
- Viable applications of the material
- Material strength (initially, but was later removed)

ICE Database & other Functional Property Databases In order to populate the database with information on each of the properties it was important to refer to the literature review to find relevant external databases. This is how the author found the Inventory of Carbon and Energy, also know as the ICE database [27]. This database was collected as a result of the research of two professors in the University of Bath, Dr Craig Jones and Professor Geoff Hammond, throughout their work at the Sustainable Energy Research Team (SERT) [27].

The database compiled information on over 500 material, pertaining their environmental impact measured in embodied carbon emissions. The database itself was the result of combining multiple other databases found by the professors during their research. It later led to the formation of Circular Ecology, the environmental consultancy company ran by the same author [25].

This database allowed to build two vital aspects, the repository of industry material names used in the industry and their embodied emission values, which will

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be the main factor in the system's recommendation calculations. Looking at the functional material properties, the ICE database alone was not enough. In order to find information about the viable applications the BICS classes [9], from the RICS organization, presented above in the table A.1 were used.

Lifespan and cost were a bit more difficult to find data on as it depends on factors such as the supplier prices, as well the process of manufacturing and transportation for that specific material. The Greater London Authority guidance set an industry standard for LCA analysis using a lifespan unit of 60 years for the building. Depending on the material a lot of them adhere to this unit as well [6]. Finally, material cost was too dependent on the supplier and thus not able to find an effective database to implement. Hence, this values were hard coded to prove functionality of the demo prototype and in future work should be replaced with real values.

5.4 Implementation

To finalize this design and development chapter, the report will proceed to describing the process of implementation of all the design insights and ideas discussed throughout the last sections. This entails deep diving into the Sustainable Building Material Selection System, its functionality as presented in each of its pages, and the overall purpose of each design decision that was implemented. These descriptions will also include mentions to which functionalities relate to the fulfilled requirements from the earlier section 5.1 on requirements specification.

Since the platform was designed as a multi-page interface, each featuring different functions that contribute to the overall functionality of the system, each page will be described individually. This design choice enables the fulfillment of requirement REQ-NF-11. These pages include:

1. Homepage
2. User Input page
3. Database validation page
4. Manual entry page
5. Functional properties deviations page
6. Material recommendation page
7. Results page

The intention behind this is to provide a clear overview of the developed platform, showcasing the results of this project's implementation. Screenshots will be provided for each of the pages to showcase what the system in action looks like. A short discussion of the value creation intended behind this platform will be provided at the end of the chapter, to open up to the final discussion and conclusion chapter that will be featured afterwards.

Side Menu Before diving into detail about each of the pages, some time will be spent describing the common property to all pages, the side menu. This interface was designed to feature the platform logo and name, as well as a series of buttons to help navigate the platform. From top to bottom the different pages of this interface are named in order, associated to individual buttons. All of the buttons are the same color of green, except for the button that correlates to the page currently being displayed.

A function was developed to keep track of the page being displayed and change the color of the associated button to a shade of brown. This was done to visually indicate for the user where in the platform they are. Each of the buttons has the added functionality of enabling the user to navigate to the indicated page. In doing so the user can quickly navigate back to a previous page or move to one further from its current one.

Lastly a drop down button can be seen that allows switching the visual of the whole interface from a "light" to a "dark" theme. This can be useful to prevent the sight of the users from becoming hindered by long exposure to the interface. The colors used to designed the sidebar menu became the cornerstone palette for the rest of the interface, to fulfill requirement RFQ-NF-10. Additionally, the general purpose behind the sidebar menu itself is to fulfill requirement REQ-NF-12.

5.4.1 Home Page

The first page in the platform serves as a welcome interface and introduction to the system. Its minimalist display features a header welcoming the user to the system. Alongside, a text box and image can be found that contains instructions on the purpose of the platform as well as its overall functionality and workflow. The image contains the different logos of each of the pages accompanied by a small description of what the page contains.

All of this information is intended to help a new user understand what to expect and how to navigate the SBuMSS platform. Moreover, this enables the fulfillment of requirement REQ-NF-06. Lastly a button enables the user to exit this

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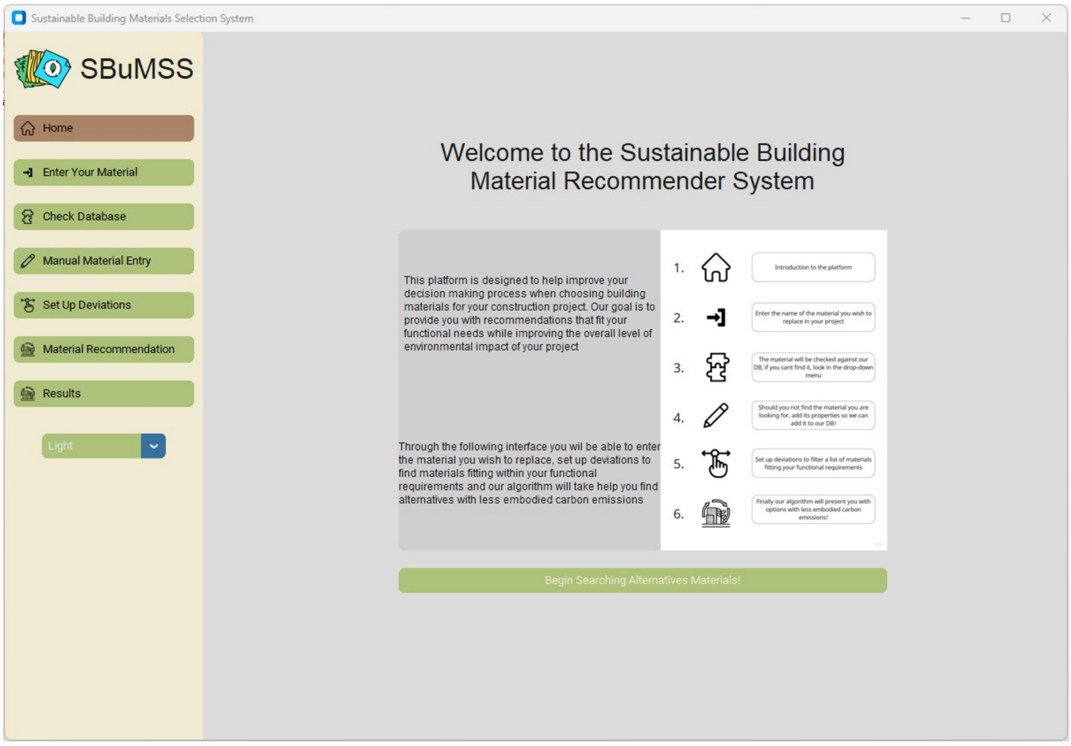

Figure 5.7: SBuMSS Screenshots - Home Page

page and continue onward onto the user input page.

5.4.2 User Input Page

The second page in the platform is the one purposed to retrieve the input material from the user. This functionality works so that the user introduces the name of a material, which will later be searched for in the back-end database in order to retrieve information on its properties.

This instance of the interface contains a label that requests the user to enter the material name in the given entry box. For the example shown a name existing in the database was selected "Aggregates and sand, from recycled resources, no heat treatment, bulk, loose". This will be the reference material for the remainder of these examples. Underneath the entry box two buttons can be found:

The first button is set to run the internal function that takes the inputted material name from the user, and looks it up within the server's database, in search of a match with its material properties. The second button enables the user to navigate onward to the database validation page.

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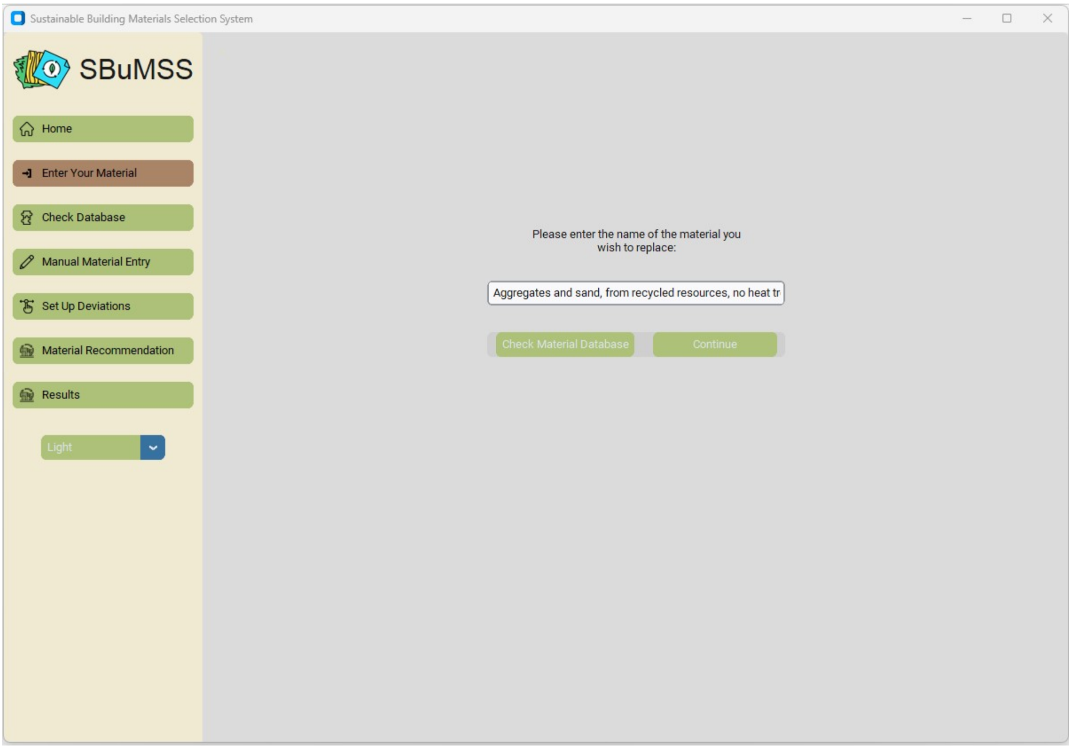

Figure 5.8: SBuMSS Screenshots - User Input Page

5.4.3 Database Validation Page

The third page in the platform is intended towards the validation and otherwise alternative approaches to establishing the reference material. A button at the top of the interface allows the user to update the entry boxes with the information the algorithm found on its database check. Should the material inputted be existent in the database, the property information will be displayed here. This will include the name, embodied carbon values, material cost, lifespan and viable applications. Should the information displayed be correct, the user can simply press the button labelled "Yes" and proceed onward to the functional properties deviations page.

However, if the information is not loaded correctly or otherwise found, two options remain. The first option is to look to the drop down menu on the right where a list of all the materials available in the database can be found. The user can click one of this materials and it will be set up internally as the reference material. Alternatively, if this method does not prove fruitful either, the user can click the button displaying "No" and proceed to the manual entry page.

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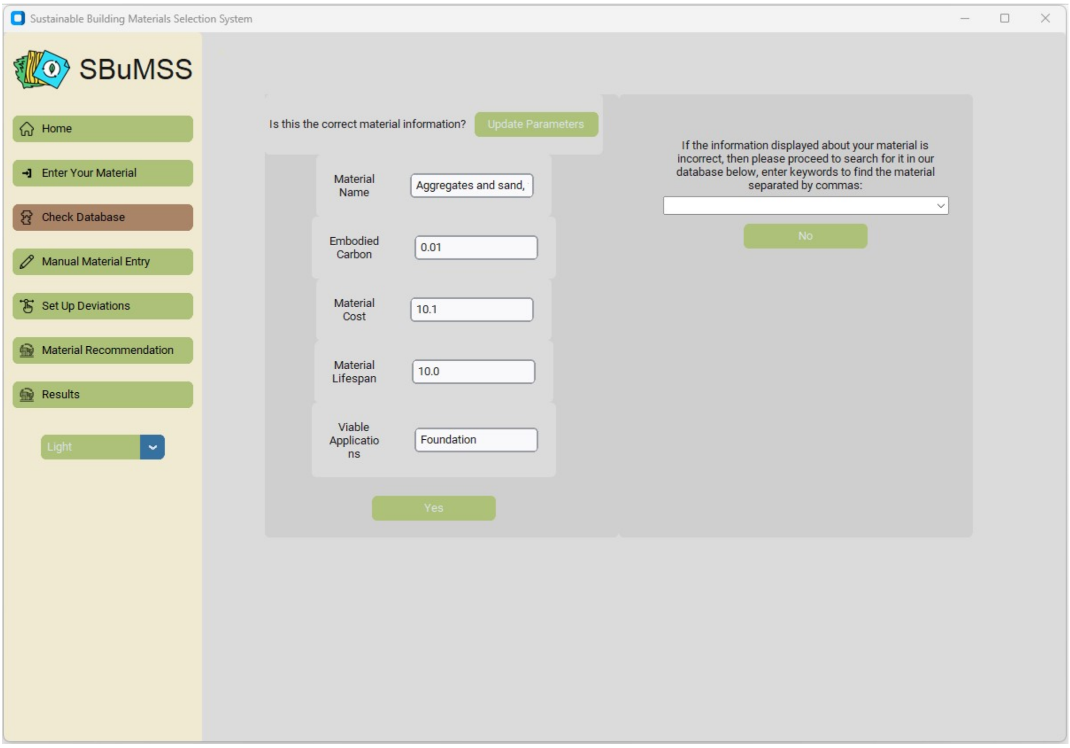

Figure 5.9: SBuMSS Screenshots - Database Validation Page

5.4.4 Manual Entry Page

In the event that the user was not able to find the reference material they were seeking to input either through the look up function for the entered name or through the material name list, this page will be their next stop. The purpose of this page is simple, allowing the user to manually enter the building material information into the database.

This instance of the interface contains several entry boxes that allow the user to input the material information. Similarly to the previous page this refers to the name, embodied emissions, cost, lifespan and viable application of the material. Once the information has been entered, three buttons take action:

The first button enables the server to update the internal variable assigned to the reference material with the entered information. The second button enables the user to add the entered material to the server's database, in the external Excel file. Lastly, the third button enables the user to navigate onward to the functional properties deviation page.

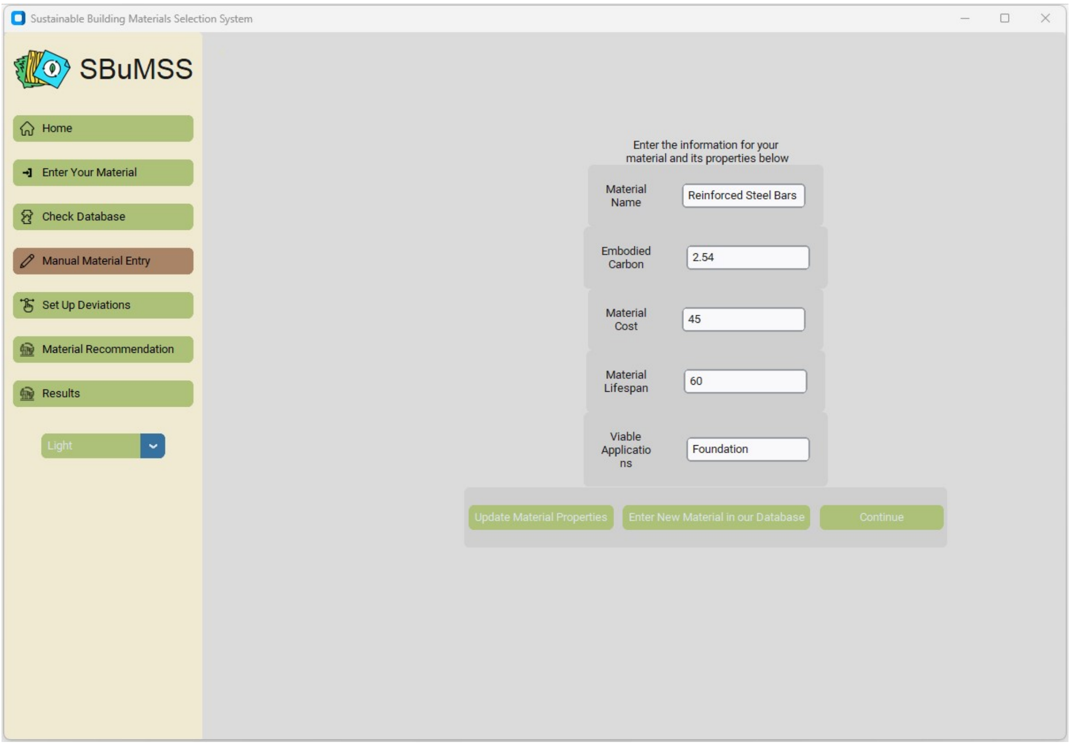

Figure 5.10: SBuMSS Screenshots - Manual Entry Page

5.4.5 Functional Properties Deviations Page

The fifth page in the SBuMSS interface relates to the additional properties for the recommendation. In fact, it is the functionality in this page that enables fulfilling the first research sub-question in this report. This instance of the interface is divided in two halves. On the left side we see first a drop down menu, this is set to allow the user to select which viable application they want for the recommended material, by default it will be the same one as the input material.

This is followed by two different slider widgets. Each of them is assigned to a different property of the material, namely the cost and the lifespan. The user will interact with each of the sliders to set up the $\pm\%$ values that will represent the functional property deviations. What this means is for each of the properties, it is the percentage above and below from the reference material that the user wishes the server to filter materials in. In other words, this enables the user to select a range of values for functional properties that are not just embodied carbon emissions, for the later recommendation algorithm to consider.

By doing this the system prevents the error that was found in early prototypes,

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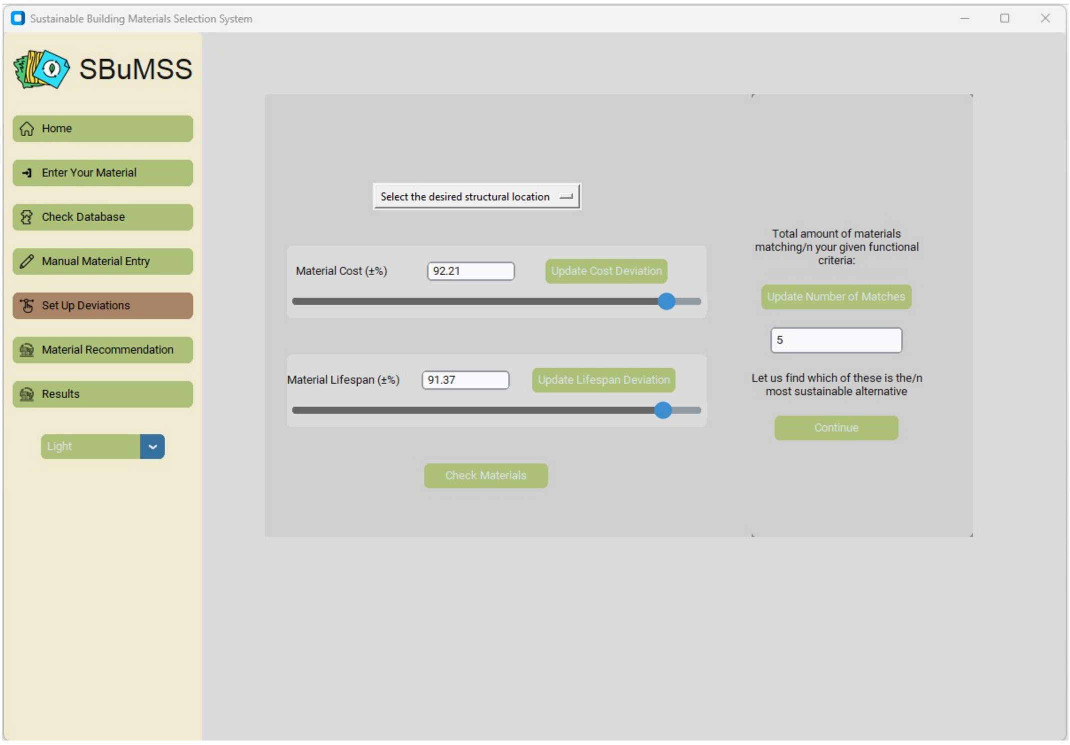

Figure 5.11: SBuMSS Screenshots - Functional Properties Deviations Page

where the recommendations would become somewhat nonsensical, with the algorithm suggesting replacement materials that could simply not fulfill the same functions as the input material. After the user has set their preferred deviation values, the "Check materials" button runs the server function that filters materials from the database based on the given functional property ranges.

Proceeding onto the second half of the page, the first button enables to update the entry box below with the number of filtered materials outputted from the previous step. This allows the user to see how many materials match their preferred deviation ranges. Lastly, the button below enables them to continue onward onto the material recommendation page.

5.4.6 Material Recommendations Page

The sixth page in this interface is the material recommendations page, which is intended to run and display the results of the sustainable recommendation function. This page features three widget menus with images and several entry boxes and labels as well as individual "Select" buttons. prior to these three menus, two buttons stand:

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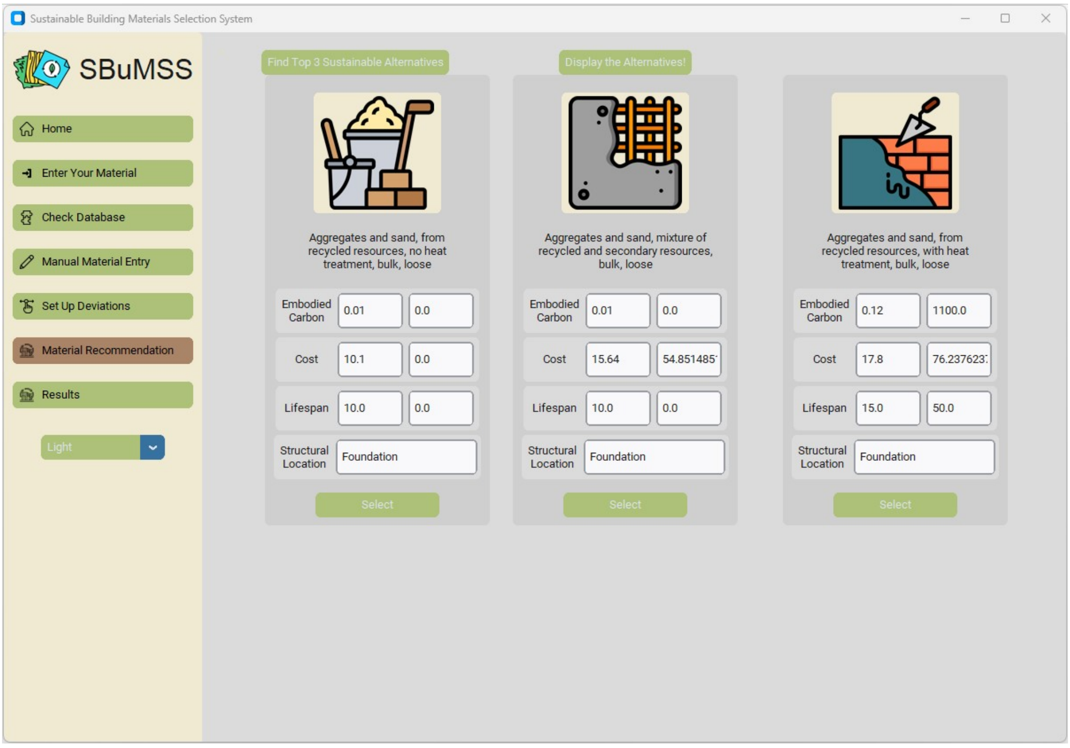

Figure 5.12: SBuMSS Screenshots - Material Recommendations Page

The first one allows the system to internally run the function for recommendation. This function looks through the list of filtered materials acquired in the previous page, comparing the materials to each other. It then finds the three materials with the lowest embodied carbon emission values and sets them as output for the recommendation.

The second button then allows the user to display the three output materials in their individual widget menus, including all their properties information. Each of the properties features next to it an entry box with a calculation of the actual percentage deviation between the reference material and the given material for each of the properties. Finally a select button can be found at the end of each of the widget menus that allows the user to chose the corresponding material as their final selection.

5.4.7 Results Page

The final page in this interface serves only to display the final material selection information. A series of widgets and labels similar to those found on the database

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validation page, will display the information of the material the user selected in the previous page, thus concluding the functionality of the Sustainable Building Material Selection System.

5.5 Testing

In order to validate the implementation of the SBuMSS system, a testing section will be presented. This section will continue to reassess the initial lists of requirements specified in the previous section 5.1. The assessment will focus on describing which of the requirements were tested and implemented into the final platform iteration. In doing so, the report will present results of what the design goals had set out to be, and what ultimately became of these goals. Each of the two tables of requirements that were presented earlier in this chapter, will be presented again, indicating those that have been tested/implemented.

Table 5.5: Table describing the fulfillment of functional requirements for the Sustainable Building Material Selection System

Fulfillment of Functional System Requirements		
ID	**Description**	**Implemented/Tested**
REQ-F-01	The system must be able to take in an input material name from the user	✓
REQ-F-02	The system must be able to retrieve the material properties based on the input name from the user	✓
REQ-F-03	The system must be able to provide a recommendation for a sustainable alternative material, for the given input	✓
REQ-F-04	The system must contain an extensive database with information about different material properties	✓
REQ-F-05	The database must contain information about embodied carbon emission values for each material	✓
REQ-F-06	The database should contain information about other building material properties pertaining each material	✓
REQ-F-07	The user must be able to manually enter new material information if input reference material is not already available	✓
REQ-F-08	The system should be able to add manually entered information about a material into the existing database	✓

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Continuation of Fulfillment of Functional Requirements 5.5		
ID	**Description**	**Implemented/Tested**
REQ-F-09	The user could be allowed to select building materials from a list if they do not have a material to input themselves	✗
REQ-F-10	The system should be able to establish an internal value to track the input material from the user as the reference material	✓
REQ-F-11	The system should allow the user to define ranges of percentage deviations for functional material properties	✓
REQ-F-12	The system should be able to filter out materials based on the user-defined deviation ranges	✓
REQ-F-13	The system should be able to find most sustainable materials among functionally a filtered list of materials	✓
REQ-F-14	The system will not feature an in-platform web shop to enable the direct purchase of recommended materials	✓
REQ-F-15	The system's user interface could feature a dark and light mode design for ease of reading for the user	✗

Table 5.6: Table describing the fulfillment of non-functional requirements for the Sustainable Building Material Selection System

Fulfillment of Non-Functional System Requirements		
ID	**Description**	**Implemented/Tested**
REQ-NF-01	The application design must be overall lightweight and minimalist	✓
REQ-NF-02	The system must be able to compare sustainable metrics of building materials in order to make recommendations	✓
REQ-NF-03	The system should consider other functional material properties when making decisions on material recommendations.	✓
REQ-NF-04	The system should be designed in a modular way so that new functionalities or changes can be easily implemented	✓
REQ-NF-05	The system must contain a clear and concise user interface that enables intuitive interactions with the user	✓

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Continuation of Fulfillment of Non-Functional Requirements List 5.6		
ID	**Description**	**Implemented/Tested**
REQ-NF-06	The system should contain an introductory text in the first page describing the purpose and functionality of the platform	✓
REQ-NF-07	The system could contain in-page instructions to help guide the user on how to navigate each page	✗
REQ-NF-08	The server must present the final results of its recommendations to the user in a clear manner	✗
REQ-NF-09	The results could include metrics on the screen to compare the output recommendations properties with those of the input material	✓
REQ-NF-10	The system could be designed using a defined colour pattern to showcase an aesthetic visual appeal	✓
REQ-NF-11	The application must be divided into multiple pages to prevent overcrowding the user with information	✓
REQ-NF-12	The application should contain a navigation menu to help the user understand in which step of the process they are at all times	✓
REQ-NF-13	The system should contain simple widget for user interactions, such as sliders to enable setting up percentages for functional property deviations.	✓
REQ-NF-14	The system could display the amount of materials that fit the functional deviation ranges set by the user	✓
REQ-F-15	The system could display the final material selected by the user in a separate page for clear presentation of results	✗

As described in the implementation section 5.4 above, and as seen by the tables 5.5 5.6 of requirements in this section, most requirements were implemented in the final prototype of the system. Only a few requirements remained unfulfilled at the time of publishing of this report:

- REQ-F-09 - This feature was not able to be finalized. The dropdown menu listing all names available in the data was included. However the functionality to filter, select and establish this as the reference material failed to be included.
- REQ-F-15 - Even though the functionality of a button that can switch between light and dark mode was implemented, the alternative color scheme, and widgets designs for the dark mode where not fully implemented, as it was ultimately not prioritized.

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- REQ-NF-07 - The introductory page instruction were implemented, however instructions for each individual page in the interface was not featured due to lack of time.
- REQ-NF-15 - Despite a results page being implemented, the functionality to extract information from the user selection and furthermore adding said information to the last results page was not implemented, due to difficulties with populating of the corresponding internal variables.
- REQ-NF-08 - Following the previous requirement not being fulfilled, it it difficult to claim that the results were ultimately presented in a clear and concice manner, and therefore this requirement was also deemed unfulfilled.

Chapter 6

Discussion & Conclusion

The final chapter of this report will proceed to present the final discussions and conclusion on the work performed during the execution of this master thesis project. The previous chapters have attempted to paint a comprehensive overview of the identified problem, namely the need the software tools that can support the reduction of environmental impact in the construction industry. An understanding of the context of this complex market and the methodology taking to approach tackling this problem. What the level of state of the art is and how it can inspire the proposed solution for this project. Finally, the process and decisions behind the design and development of the final solution proposed for this project.

The goal for this chapter will be to extract all the learnings in regards the initial goals and expectations for the project, reflecting on its execution. This will include reiterating back to the initial research question defined in Chapter 1, and reflecting if and how these questions were addresses throughout the report.

This content will be divided into two main sections: The first discussion section will reflect on the process and outcome of this development project. This will include discussing an estimate measure of the potential environmental impact of the proposed solution if it would be implemented into the market and used by stakeholders. Then, the ideas for where could this platform go in terms of further development moving forward will be exposed.

The second section will proceed to conclude on the overall accomplishments of the project. By structuring this section around the research questions stated earlier in the report will be beneficial. This will allow the section to round off the structure of the report in a way that permits assessing whether the initial goals and hypothesis set out at the beginning where accomplished, and how. This will include reasoning on what could had also be made better if it had to be done again.

6.1 Discussion

Starting with the discussion section, we will cover the topics as described in the introduction of this chapter, starting with measuring the potential impact. This refers to that of implementing the tool in the market and how it affect in terms of reducing the environmental footprints of some of the activities in the construction industry. Lastly, this will serve as a good transition to move the discussion towards what future development and features could be implemented into the platform should this project continue into the future.

6.1.1 Measuring Environmental Impact Potential of the Proposed Solution

To begin this discussion, it is of interest attempting to quantify the results of this project's proposed solution further. To do this, the following discussion will be proposed: It is possible to estimate, in somewhat general terms, what sustainable impact the software platform could have if it were implemented in the market. This could be done through calculation, say perform an assessment similar to an LCA and estimate some emission reduction calculations. However, at this stage of the report this would be to complex to estimate, without real market interactions. Instead, the report proceed to analyzes this from a more conceptual perspective.

As we have seen in this report, the impact in terms of carbon emissions in the construction industry is very large and equal parts complex. The improvements and optimizations done thus far have mostly focused on improving the energy consumption and decarbonisation of the energy grid. This has enable great decreases in the volume of operational emissions. Leaving embodied emissions to become the next critical challenge. In order to tackle this embodied type of emissions, the first step is to create better awareness amongst stakeholders of the options available to them in terms of sustainable alternatives for building materials.

The reason for this is that by making changes in the life cycle of a material, to encourage more environmentally-friendly practices is the best path forward to reducing its embodied emissions. Software tools are becoming increasingly available in the market, at the moment mainly coming from different university and research groups, that attempt to fill in this knowledge and awareness gap. This is where the Sustainable Building Material Selection System comes into play. It has been designed with the purpose of supporting stakeholders and industry professional in the process of selecting more sustainable options for their building materials. Its core functionality to retrieve material input from a user and return a recommendation for sustainable alternatives, automatically, makes it a valuable tool to

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implement into its users ongoing operations.

This is why its environmental impact potential comes from different fronts: For instance, by providing recommendations for materials with similar functional properties, but less embodied carbon emissions, it is supporting a direct reduction of those emissions. What the exact value of that emission reduction is, is difficult to estimate at this point. However, what can be said is that not only does it reduce emissions directly but in doing so it also increases the user's awareness in regards to sustainable practices in the industry.

This is specially important, considering the nature of the platform. As it can be implemented since very early stages of the project, this can mean establishing an high environmental awareness level. since the start of the project, supporting the design decisions to be more sustainable from the start. Moreover, presenting a minimalist design allows it to be easily shared among different types of stakeholders, which can in turn encourage further collaboration among them. This collaboration being harboured under the scope of reducing environmental impact means that this can create long-lasting impact, and establish new relationships between stakeholders, based around sustainability.

Creating innovation and impactful change in any industry is difficult. This is specially the case for industries that are well established, the construction industry being one of these industries. Reiterating back to the value engineering model, if you can prove that sustainability can have great monetary and functional value for stakeholders on top the environmental impact, the road to implementing green practices is paved. Henceforth, the more tools that appear that can provide such a service, and demonstrate these values, the easier it will become to spread sustainable change in the industry in the future. An example of this can be the preservation of natural materials that can happen through the optimized selection and use of building materials. Not only can this greatly reduce waste management and its effects on the environment, but it can also prove an effective budget-friendly method.

Lastly, if the use of software platforms that create awareness and support users in the implementation of sustainable building materials increases, this can encourage a market transformation. Trends can be established towards sustainable material practices, and with enough following this can encourage policy and regulatory change. As we have seen with the many examples of institutions in the UK market such as the GLA or RIBA who are creation regulatory policies and plans to reduce the overall environmental impact of the industry in the years to come. The higher up the environmental message goes in the industry ladder, the higher chance there

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will be to reduce the impact of one of the highest emitting industries in the market today.

It is important to do further research and encourage further collaboration industry-wide to gain a deeper understanding of this topic and of how sustainable impact can effectively spread globally across the sector. This also means understanding which practices and building components are harmful for the environment and should be discontinued.

6.1.2 Future Work

Following the insights about the potential impact of this tool in the market, the report will finish off this discussion by covering different ideas and concepts that could be explored moving forward, if this project were to continue. These ideas derived either of concepts that were initially explored but due to limited resources were not able to be executed, or simply those that were not relevant early in the functionality process but could become so moving forward.

The first activity that would have to be done, moving forward with this project, would be a usability test and validation of the platform with users. Due to the limited time after the development of the platform, prior to delivering this report, these tests were not able to be performed. However, they would bring tremendous value as they would allows to test assumptions included into the design of this platform. Additionally this would enable to test new functionalities and receive feedback from the users to improve the platform moving forward. Moreover, it would help fulfill the fifth step of the Design Science Research Methodology, which could led to providing even more accurate results in a consecutive report.

Moving forward, to be able to provide a better service through this tool, the server database would have to be improved. This would mean finding additional databases to populate the building material properties with more data and information. Including things like accurate costs estimations, that could be sourced from databases similarly to the ones used in other software platforms like One-Click LCA [51]. This could also entail establishing collaborations with industry partners to be able to provide information from partner suppliers directly.

This could lead to developing extra pages following the results of the material recommendation, that could feature said partners. The idea could be to include a page after the results with a list of suppliers that can provide the final material selection. This could include a comparison in prices between the different suppliers, as well as information on where they are located, or some key insights into their

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environmental impact, such as what type of transport that supplier utilizes. This could lead to an additional functionality that could calculate an estimate of the transport emissions that would be produced from delivering the material from the supplier to the construction site of the user. This could help bring further transparency to the environmental impact of the entire process.

As previously mentioned, machine learning was initially considered but discarded due to the hindrance it could have brought to the early prototype development. However, moving forward this approach could be re-explored. This could be done by adding a user database functionality to the platform, where users could register their profiles, information about their projects, their material preference, keep track of recommendations they have seen in the past and even purchase histories. This information could then be used to improve upon the recommender system with a machine learning algorithm. This algorithm could use content based filtering to take in these vast amounts of data and process it to define a set of preferences and conditions for the user in their material selection processes. Using these as labels to help identify potential materials that could fit the user in the future, and developing that profile further, the more the user would interact with the platform.

Section 4.2.1 of this report presented several insights including that of implementing external tool into the proposed software platform. Due to the limited development resources this feature was not considered for the scope of this project. It would however be an interesting idea to explore moving forward. How can the software platform be developed in a manner that allows it to be implemented into external services. This would greatly increase its value towards being implemented in established and ongoing operations.

Finally, to make all of this functionalities in the tool actionable in the market, a business and commercial analysis of the platform would have to be performed. This would focus on better understanding the competitive landscape, as well as what potential business model could fit this service. An initial hypothesis is that this could serve as a two-way SaaS model in which you charge the users a monthly fee to access the platform. Potentially even defining different features for users in different payment tiers. Conversely, the platform could charge suppliers to access the platform, featuring their products on the platform and getting direct access to large customer bases, with the SBuMSS system acting as the middleman. This could further encourage collaboration between different stakeholders in the industry, while always harbouring the pursuit of reducing environmental impact of the construction industry.

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6.2 Conclusion

To finalize this report, this last section will present the conclusions and thoughts of the author in regards to overall approach and results of the research presented in this report. In order to give this section a good structure to base it from, the report will reiterate the research questions that were formulated at the beginning of this report. This allows an assessment of the work here presented based on its initial expectations, and testing the initial assumptions of the hypothesis. However, first the report will analyze the sub-questions, in order to finalize with the main problem formulation, therefore answering the main research question posed in this report last.

How can additional material parameters be accounted for to perform the material recommendation? Early in the development of this, a collaboration was established with an external company, London-based environmental consultant JAW Sustainability. It was through this collaboration that much of the knowledge presented in this report was acquired, one of these insights being the existence of the Value Engineering framework. Early prototype iterations of the solution presented solution that despite reducing environmental impact of the material, could not uphold its functional properties. This is when Value Engineering came into play, providing a framework to base the design from, to understand how could both functional and environmental goals be fulfilled at the same time.

This took the research on a journey to understand, first of all what the idea of functional properties meant. What are the aspects of a building material that can be compared to each other, between materials that are inherently different from each other. The research led to the conclusion that although very difficult, this question could be answered with three properties: material cost, life span and its viable applications. These properties were general and common enough to all building components that it could operate as a scope to compare them all by.

Furthermore, it was important to take the user's needs into account. This led to a design decision pivotal to the functionality of the final platform. Allowing the user to define a range of "deviations" for each of these properties, that could fit their needs. This meant that the user could directly provide the platform with constraints of what kind of material was needed to fit their exact operational needs.

In summary, to answer this research question, the author discovered that it was important to establish a framework where environmental impact could be the core value provided to the user, but that this should also provide the user with some assurances. Moreover, these assurances would come in the form of ensuring

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functionality, and that the recommendations provided could as much reduce the environmental impact of the building as they could ensure that the building would function as intended.

What type of emissions should be targeted to reduce the overall environmental impact of the industry? The second sub-question led the author into gaining a deeper understanding of what does environmental impact actually mean, in this industry? How is it measured? The answers to these questions proved to be a bit more difficult than a simple metric. Each construction project is different, with varying locations, building types and components, but also needs and regulations. This meant that multiple metrics exist to measure environmental impact, Global Warming Potential and carbon emissions prevailing above all. As was seen in earlier chapters of these reports, the measuring of carbon emission impacts takes assessments through the entire life cycle of the building, and some emissions are easier to reduce than others.

Following the trends of the industry, reductions in operational carbon emissions have been prevalent in the years leading up to this work. As these reductions have been enabled through the implementation of renewable energy sources and optimization of energy consumption in buildings. As one side of the scale lightens up, naturally the other side will come weighing down, and this is the case as well for embodied emissions. As shown in figure 2.4, as energy optimization keep spreading further, we will see a trend of the percentages of embodied emissions increasing on the overall impact assessment.

This led to the decision of pursuing a design challenge that would directly relate to embodied carbon emissions, namely through the reduction of the impact of building materials. As these emissions are difficult to reduce after the construction of the building, improving the decision making process in regards to building material selections is key. Therefore, by providing a service that could automate the process of recommending sustainable building materials, the platform could enable a decrease in the impact of embodied carbon emissions, and proof useful towards the upcoming challenge this industry is starting to face.

What environmental impact can this software tool have on the construction industry? The answer to this particular question was mainly presented during the first half of this chapter, therefore for this section the report will proceed to summarize those points. As stated there, its not possible to give an exact calculation of the reduction in terms of emissions at this point. However, insights were drawn as to what the environmental impact this tool could have:

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- Increase environmental awareness among stakeholders for options available in terms of sustainable building processes and building components.
- Foster collaboration among different stakeholders in the industry on the basis of a sustainability scope.
- Cultivate a sustainability mindset across construction project since the very early stages of the project, encouraging to think about this impact from the start.
- Direct reduction of the embodied carbon emissions emitted by users of the SBuMSS platform, through the recommendation of lesser impactful material options.
- Showcasing monetary and functional value adherent to promoting sustainable options in the industry. In doing so, fostering further spread of environmental notions in the industry with effective validation.

It is this insights that provide great promise to the potential implementation of a platform like the Sustainable Building Material Selection System into the market. This also goes to show the role technology can play in fostering the spread of environmental awareness across multiple industries and sectors.

How to develop a sustainability focused recommender system to promote alternatives for building materials with less embodied carbon emissions? Finally, to answer the main question formulated when venturing into the development of this project. Throughout the extent of this report, the author has attempted to provide a deeper understanding of the intricacies that involve implementing environmental and sustainable practices into an extensive industry, such is the construction world. Additionally, attempting to paint the picture around the value technology-based solutions in this field. But to answer the question of how to develop a system that can support this type of sustainable decision making, several steps are required.

For starters it was necessary to gain a deeper understanding of the industry context, to give foundation to the work. Extensive research and literature review, supported in addition by the industry partner, led to the finding of extensive information and sources to help create a deeper understanding of this identified problem. That research was later extracted into insights that could guide the design process for a proposed solution. By understanding the state of the art level of technology in this area, it is possible to understand what work and what does not.

Therefore this design process was guided by not only an understanding of the current solutions available, but also domain knowledge from experts, extracted

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through interviews and brainstorming design sessions with the industry partner. Armed with these insights and a series of visual materials and diagrams that could support and help narrow the process and functionalities required from the platform down, the design of the final solution was executed. By establishing a series of functional and non-functional requirements, it was possible to create a sort of "to-do" list of what needed to be accomplished and how.

The implementation process took up the largest portion of time in this project, navigated under the frame of agile development. This led to the development of the solution taking place over multiple prototype iterations. At each step testing functionalities and assumptions and taking learnings on to the next phase, always improving upon what was before, to get to the final prototype iteration. Some initial ideas were discarded, such as the use of machine learning, and some development expectations were overcome, like the initial goal to focus on the back-end side of the software platform, that at the end ended up becoming a full-stack development focus instead. This led to the result of bringing out a fully functioning proof-of-concept platform that could be ready for testing.

The testing was performed in the basis of the initial requirements, reiterating through the list to understand the level of fulfillment. In this case 25 of the original 30 requirements were fulfilled. Most importantly all those marked of highest priority were fulfilled, demonstrating the core functionality of the platform. In order to understand its potential implementation value better, further usability testing would be required to be performed with users, to understand better if the platform would indeed suit their needs. Gathering all of the learnings and insights into this report, throughout the extent of the project enabled not only the presentation of this work for its evaluation, but also prompted the author to reflect back in all the steps and decisions made along the way, and how each insight at each step of the way led to which decision and in which way molded the process of developing this project.

To conclude developing a sustainability focused recommender system for sustainable alternatives of building materials is a complex process. It requires a deep understanding of the market, its stakeholders and their respective needs. Moreover, of the environmental implications present in the construction industry and how those mold policy-making and regulation. It requires an extensive process of designing the platform so it would fit in projects that are ever-changing and evolving, each with their own particular needs. It is however a process that can lead to the creation of a tool to greatly support the implementation of sustainability in a critical industry, and that has the potential to greatly benefit the environment at a global scale.

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Annex A

Additional Resources

Table A.1: This table presents the complete list of viable applications for materials following BCIS Elements model. [9]

BCIS Elements by RICS	
Main Category	**Sub-categories**
1. Facilitating Works	1. Toxic/Hazardous/Contaminated Material Treatment 2. Major Demolition Work 3. Temporary Supports to Adjacent Structures 4. Specialist Groundworks 5. Temporary Diversion Works 6. Extraordinary Site Investigation Works

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Continuation of BCIS Elements Table A.1	
Main Category	**Sub-categories**
2. Substructure	1. Foundations up to and including the damp proof course. 2. Lowest floor assembly below the underside of the screed or the lowest floor finish. 3. Basement excavation. 4. Basement retaining walls up to and including the damp proof course.
3. Superstructure	1. Frame 2. Upper Floors 3. Roof 4. Stairs and Ramps 5. External Walls 6. Windows and External Doors 7. Internal Walls and Partitions 8. Internal Doors
4. Internal Finishes	1. Wall Finishes 2. Floor Finishes 3. Ceiling Finishes

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Continuation of BCIS Elements Table A.1	
Main Category	**Sub-categories**
5. Fittings, Furnishings & Equipment	1. Fittings 2. Furnishings 3. Equipment
6. Services	1. Sanitary Installations 2. Services Equipment 3. Disposal Installations 4. Water Installations 5. Heat Source 6. Space Heating and Air Conditioning 7. Ventilation Systems 8. Electrical Installations 9. Fuel Installations 10. Lift and Conveyor Installations 11. Fire and Lightning Protection 12. Communication, Security and Control Installations 13. Specialist Installations 14. Builder's Work in Connection with Services
7. Prefabricated Buildings & Building Units	1. Prefabricated Buildings 2. Building Units

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Continuation of BCIS Elements Table A.1	
Main Category	**Sub-categories**
8. Work to Existing Building	1. Minor Demolition and Alteration Works (Strip Out) 2. Repairs to Existing Services 3. Damp-Proof Courses/Fungus and Beetle Eradication 4. Façade Retention 5. Cleaning Existing Surfaces 6. Renovation Works
9. External Works	1. Site Preparation Works 2. Roads, Paths, Pavings and Surfacings 3. Soft Landscaping, Planting and Irrigation Systems 4. Fencing, Railings and Walls 5. External Fixtures 6. External Drainage 7. External Services 8. Minor Building Works and Ancillary Buildings
10. Main Contractor's Preliminaries	1. Employer's Requirements 2. Main Contractor's Cost Items
11. Main Contractor's Overheads and Profit	1. Main Contractor's Overheads and Profit

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Continuation of BCIS Elements Table A.1	
Main Category	**Sub-categories**
12. Project/Design Team Fees	1. Consultant's Fees 2. Main Contractor's Pre-Construction Fees 3. Main Contractor's Design Fees
13. Other Development/ Project Costs	1. Other Development/Project Costs
14. Risk (Client's Contingencies)	1. Design Development Risks 2. Construction Risks 3. Employer Change Risks 4. Employer Other Risks

A.1 UML Use Case Tables

This section of the annex will contain a additional resources to support the UML Diagrams section featured in Chapter 5. These will include a series of tables that described each of the use cases featured in 5.4. This will help to provide a deeper understanding of the steps involved in each use case. To begin, the report will restate the full list of use cases, followed by UML-formatted tables describing each use case:

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ID	Use Cases
UC-1	Access the recommender system
UC-2	Input a reference material
UC-3	Verify material information
UC-4	Manually enter material properties
UC-5	Set up property deviations
UC-6	Filter materials based on property deviations
UC-7	Find sustainable alternative within filtered materials
UC-8	Present Recommendations
UC-9	Select recommendation

Table A.2: Use Case UC-1 Diagram

UC-1	Access the recommender system
Pre-Condition	The user has accessed their computer
Post-Condition	The user is prompted to enter their reference material name
Basic Path	1. The user clicks on the application icon to open the recommender system 2. The system presents the "Home" page with introductory information about the platform 3. The user clicks on the "Begin Searching Alternative Materials!" button and continues onto the "Enter your Material" page

Table A.3: Use Case UC-1 Diagram

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UC-2	**Input a Reference Material**
Pre-Condition	The user has accessed the system
Post-Condition	The system has checked the input name against the database
Basic Path	1. The user clicks on the empty entry box 2. The user inputs the name of the material they want to replace 3. The user clicks on the "Check material database" button 4. The system checks the provided name against the database to find the material information 5. The user clicks on the "Continue" button and continues onto the "Check Database" page

Table A.4: Use Case UC-2 Diagram

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<table>
<tr><th>UC-3</th><th>Verify Material information</th></tr>
<tr><td>Pre-Condition</td><td>The user has entered a reference material name</td></tr>
<tr><td>Post-Condition</td><td>The system has verified with the user that the reference material information is correct
Exceptionally the user is prompted to manually enter the materail property information</td></tr>
<tr><td>Basic Path</td><td>The user clicks on the "Update Parameters" button atop the page
The system updates the entry boxes with the information of the reference material properties
The user clicks on the "Yes" button and continues onto the "Set up Deviations" page</td></tr>
<tr><td>Alternative Path</td><td>The user is unsatisfied with the property information provided
The user clicks on the drop down menu on the right side of the screen
The system presents multiple material options for the user to choose
The user selects a material, to be set as the new reference material</td></tr>
<tr><td>Exceptional Path</td><td>The system is not able to display information as the reference material does not exist in the database
The user clicks the "No" button on the right side of the screen and proceeds to the "Manual Material Entry" page</td></tr>
</table>

Table A.5: Use Case UC-3 Diagram

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UC-4	**Manually enter material properties**
Pre-Condition	The user has failed to find the correct material information
Post-Condition	The system has updated the reference material information and added the new entry to the database
Basic Path	1. The user clicks on the the first entry box and manually enters the material name 2. The user repeats this process for the next 4 entry boxes 3. The user clicks on the "Update Material Properties" button 4. The system updates the internal reference material list with the provided values 5. The user clicks on the "Enter New Material in our Database" button 6. The system creates a new entry in the database with the information provided by the user 7. The user clicks on the "Continue" button and continues onto the "Set Up Deviations" page

Table A.6: Use Case UC-4 Diagram

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UC-5	**Set up property deviations**
Pre-Condition	The user and system have successfully established the reference material
Post-Condition	The system has registered the functional priority deviation range desired by the user
Basic Path	1. The user clicks on the drop-down menu to select a desired structural location 2. The user slides on the first widget to set up the material cost ±% 3. The user clicks on the "Update Cost Deviation" to update internally the percentages 4. The user slides on the first widget to set up the material lifespan ±% 5. The user clicks on the "Update Lifespan Deviation" to update internally the percentages

Table A.7: Use Case UC-5 Diagram

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UC-6	Filter materials based on property deviations
Pre-Condition	The user has registered the deviation range
Post-Condition	The user is presented with the number of functionally filtered materials
Basic Path	1. The user clicks on the "Check Materials" button 2. The system will proceed to run the internal function to filter materials based on the set deviations ranges 3. The system will add the filtered materials to an internal list variable 4. The user clicks on the "Update Number of Matches" button 5. The system will display the number of matches it found on the entry box on the right

Table A.8: Use Case UC-6 Diagram

UC-7	Find sustainable alternative within filtered materials
Pre-Condition	The deviations and filtering of materials have been established
Post-Condition	The user will navigate to the final page where material recommendations will be displayed
Basic Path	1. The user will click on the "Continue" button to proceed to the "Material recommendations" page 2. The user clicks on the "Find Top 3 Sustainable Alternatives" button 3. The system will internally look through the internal filtered list 4. The system will find the 3 materials with the lowest embodied emissions within the filtered list

Table A.9: Use Case UC-7 Diagram

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UC-8	**Present Recommendations**
Pre-Condition	The system has been calculating the best sustainable alternatives for the input material
Post-Condition	The user is presented with the sustainable material options
Basic Path	1. The user clicks on the "Display the Alternatives!" button 2. The system fills the first column of entry boxes with material information for the best sustainable alternative 3. The process is repeated for the other two materials on the two remaining columns 4. The system calculates and displays the % amounts in deviation between the given property and the same property in the reference material.

Table A.10: Use Case UC-8 Diagram

UC-9	**Select recommendation**
Pre-Condition	The user has been presented with the three sustainable alternatives for the given material
Post-Condition	The user selects its final material choice
Basic Path	1. The user has read the information of all the different materials 2. The user chooses its desired material and clicks on its corresponding "select" button 3. The user proceeds onto the final "Results" page 4. The system displays the information for the selected material in the boxes of the final page.

Table A.11: Use Case UC-9 Diagram

Annex B

Interview Transcripts

This annex will contain a series of transcripts for interviews conducted with relevant industry experts to better understand the context the project operates in and how the tool developed in this project can be best applied.

B.1 AAU Build Department: Regitze Kjær Zimmermann

The first interview was conducted on March 13th with Regitze Zimmermann. Regitze works as a PhD student at the BUILD Institute in Aalborg University. The goal for this interview was to utilize Regitze's domain knowledge to gain a better understanding of the context behind decision making for building materials, and attempt to identify gaps or problems that could be addressed through the use of software. Below can be found the transcript for the interview:

JACOBO : So yeah, so the idea was to basically make a little, a little piece of software that could could help with this process and could enable a little wiser decision making in materials specifically, with regards to sustainability and carbon emissions,

REGITZE : an open source tool for this company?

JACOBO : Well I, that's where I'm figuring out I think, at the big at the moment, it hasn't been set in either direction. So they haven't said, Okay, we want this for us exclusively. Because they also see the potential of this being a product that can then be open sourced, or even sold to, to a third party or something like this. So. So for now, I'm just trying to figure out if I can develop it. And then once once, once that part is finished, we can see if there's a business potential to it. But yeah, let me just start by asking you a little bit, if you want to introduce yourself and your background a little bit where you come from?

REGITZE : Yeah, my name is Regitze. I'm, I'm a PhD student here at built Insti-

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tute. And before that, I was a research assistant here as well. And before that, I'm a trained civil engineer from the Technical University of Denmark in architectural engineering. And so I haven't worked in industry, I've actually gone from universities to, to this building Research Institute. And I've worked with lifecycle assessment of building circular economy. Yeah, impact assessment of buildings.

JACOBO : So does that mean you've been doing calculations? Like doing the LCA calculations and these kind of things yourself? Or projects? Have you been?

REGITZE : What do we have is actually a tool for doing that exact assessment of buildings. So we have this very simple tool as well and for the industry. And what we do is, and the history of our department is to work very closely with the industry and with the policymakers. So we have developed this tool together with the with the agency and for the industry for free for them to use. So a lot of my work has also been with this tool.

JACOBO : So you haven't been working with tools like SEMA Pro or any of these big LCA software's?

REGITZE : I have, but I haven't so much in my work here. But I know them, but it's been a while since.

JACOBO : So it's been more about developing your own tool and seeing how that kind of accommodates to the industry?

REGITZE : it's a very practical approach. We have here. Yeah,

JACOBO : super cool. Super cool. And so what is exactly the build department and kind of what would you say is your responsibility within within the department? Because I have an idea of you guys are working within construction, and you're doing a lot with with materials, but I'm not exactly sure what the department as a whole is doing.

REGITZE : It's also doing a lot of different things. So there's a bit of history that here, we used to be the Building Research Institute, and then it became a part of the university. And then, two or three years ago, it was joined together with some people up in Aalborg who was also doing stuff about indoor climate, etc. But yeah, so we do everything concerning buildings, and I'm sitting in the research groups called sustainability of buildings. And we're looking at sustainable certifications of buildings. So one of my colleagues helped introduce the DGMB system in Denmark, which is, like the most standard certification. It's like the, the German system, which was then transformed to the Danish and specifically where we work with the environmental sustainability of building, which includes these lifecycle assessments where we have the tool and where we work with circular economy, etc. So that's more like our research, I guess, but everyone else works with indoor climate, energy,

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structures...

JACOBO : Okay, cool. Cool. So it's so I, how much of the work is related to policy? Specifically, how much of it is related to like calculations of carbon emissions? Would you say because it sounds like it's more maybe policy related or that you're working towards those kind of stakeholders more often.

REGITZE : Yeah, but a lot of those are to calculate emissions and they, so it's a lot of power. We have a lot of work with calculating on case buildings. So we get a lot of case buildings, and then we do calculations on how how do we build things performed today and then I tried to set some examples for what could we have been F as benchmarks in the building regulation. And then, of course, the policymakers has to figure out what they want to do with that, but but we sort of develop a lot of this data that they use. We both do a project for the agency, but also for private fundings.

JACOBO : Okay, cool. But so we'll just say that, then what you're doing is more related, or studying all cases of buildings that have been built and see how you can improve those then to apply to future projects? Are you already kind of on the stage of using your tools to improve buildings that the may be building new now and so on? So are you more on the retrofitting?

REGITZE : Well, I think the first work has been a lot with new construction, because that's like the easiest place to start. They fit into to the certification schemes, et cetera. But now, recently, both the industry is asking for refurbishment or retrofitting projects. And it's also something I'm looking at in my PhD project is how to consider them.

JACOBO : Okay. Because what is your topic for the PhD?

REGITZE : It is a bit about?

JACOBO : Yeah, I love that. This is the question that you always ask PhD students, and everybody always takes a second to how do I explain this?

REGITZE : It is like with implementation in the industry. So what do they need to make it easier for them to implement lifecycle assessment in their? In their daily work? So both work a bit about building information modelling and, and the information available there? And I've, I'm working with the renovation projects and, and how we can calculate on those.

JACOBO : Okay, that actually leads me to ask you an interesting question. So I guess, because you're figuring out how to implement LCA in daily work, I guess that that also gets requires a level of understanding where people are at in terms of sustainability in the industry. Right. So what would you say, kind of stakeholders in the construction industry are in terms of knowledge of sustainability? Is this something that everybody is aware of? is somewhat aware of but starting to look into it? Or?

Regitze : I think we've had a recent very steep incline in in knowledge, because I don't know if you know, but they from 2023, to from this year, there are requirements in the building regulation to live up to a maximum co2 emissions of new buildings. So the past year, it has been like a big topic in the building industry. But of course, there are many people who are, who don't know anything about it yet. But there are also a lot of people who see this as an opportunity to be ahead on the news knowledge and, and be able to sell this this task of doing the lifecycle assessment. Okay, so there has been a gradual growth in terms of like 10 years ago on 2012, I think we have the DGNB systems with a sustainable certification. So there we started, like a knowledge build up of lifecycle assessment of buildings, slowly, but now in recent years, it has gone a lot faster.

Jacobo : I guess this is kind of the sense in a lot of industries. I think the construction industry is not the only one that's going through this. But yeah, I've also kind of noticed that I mean, Denmark is a pretty good example, in general for, I think, awareness and sustainability. But I was also curious to see how that's engaging, or one thing is to know about it, one thing is to implement it. And so it's good to know that they're doing a lot of policy to do that. So one thing I wanted to get a sense of is I've been also having some other conversations with people in the industry to get a, an understanding of two main things. So on the one side is the idea of what are the stages that are involved in a construction process? When I do research, there's a lot of different opinions on this. And there's a lot of different I mean, I know it's not a one standardised process, because all construction projects are different and so on. But just I'm trying to build a general idea of what are some of the stages that are involved in most construction processes, or with the hopes of understanding where does the decision making for materials come into play in those different stages and then And then the decision making process itself, which we can get into a bit later. But so what would you say? I mean, it's a big question. I know but but just to get an understanding of some of the standardised process, steps that go into, like, you know, from a client saying, I have this need for a building until the building is up in the, in the foundations, right. So, to understand that process a little bit more.

Regitze : Yeah, but I think I'm maybe not the expert on that, because I've never been out in trying it. But of course, there's a design process. And there are some different stages, but it all depends on like the type of building the type of contracts they have. So sometimes it's very like divided there is an architect, there is an engineer, there is an entrepreneur. And then they have some different tasks. And other times, they are all sitting together, or the entrepreneur has both the architects and the engineers, and he's doing everything and and those stages can overlap. So I think it can depend a lot on the project. But of course, there are like some different stages, typically. And I think it is a challenge to get it in, in the early stages, or at least to to have it ended up also being what is chosen in, in the end

JACOBO : this is kind of the sense I've gotten so far that it like whatever you set out to do at the beginning is never going to be the same thing as you end up having with the end. And I mean, it makes sense, right? It's also very dependent on a lot of external factors that you can control from city regulations to mean even the weather is a factor and you know, so things get delayed, but you've mentioned architects, engineers, entrepreneurs, so is that kind of all of the stakeholders that are involved in normally in a construction project, and other sorts of contractors and some No,

REGITZE : yeah, the contractors, the client.

JACOBO : Yeah, I guess the developers is well known? Or is that the same as intrapreneur? Is that the same world?

REGITZE : I'm not sure I'm not so good with the English terms I listed. The developer who would you say is that the person who owns the

JACOBO : From my understanding developers are normally companies that tend to buy the like, they buy the lot, and then they arrange the different stakeholders to make the project happen. That's kind of my understanding. So like, for example, I think I will I think I that's where I get a little bit blurry. Because I also I'm not really sure I think that the client or the client is on putting on the money. But I think the developer helps facilitate for the client, right, this Yeah, more of the project management side of things. Yeah. That's kind of what I understand is. Fair enough. That's fair. So within your word, how much do you would you say, you know, now about the decision making with process when it comes to link building materials? Yeah. How that normally goes? Again, it's a big question. I know. But just to understand a little bit. Guess my goal is, who is involved in making decisions for materials? Is there a specific point in the process where it's more important, more relevant, to make those decisions or is it equally as important, when you're deciding where the building's gonna go as when you're starting to build the building?

REGITZE : I think yeah, I think I don't want to say specifically when its decided, because it's not my expertise. So what we are talking about in my department is to, of course, always included in the data, because that's where it will make an impact on the project, but but how they actually implemented is different. That is also something that I could ask them.

JACOBO : And do you think sustainability is becoming a factor when it comes to selecting building materials? Or are people just looking at money? And that's basically the main factor is cost and how can we reduce costs,

REGITZE : No like the big pensions, houses, and other big groups of money, they are working towards more sustainable goals in their investments, and of course, this contributes as well. Now with the Building Regulations, it becomes important for everyone, right, it's like a thing, we have to meet this goal. So it's similar to the energy regulation that we sort of have to also in the early stages, make some sort of calculations to say okay, we can actually make it within the limit value, but again, this process is only starting and there's none of this none of the buildings being built right now that needs to will live up to this. It's only like the building that now has to send in their building permits, etc. So we're still in that stage of it being implemented, but in DGNB and stuff, they have to do like an early calculation of the LCA.

JACOBO : Okay. And that includes the raw material extraction, manufacturing of the materials transportation, also the electricity usage of the building, I guess, I guess it's the entire

REGITZE : Yeah, the energy use. So they would typically do the calculation for the energy use of the building, there's like a standardised way of doing that they will make like a simple model in the early stages, and they can use the same results from there in the tool that we have for the lifecycle assessment. And it uses like, finished data or like aggregated data. So you have the raw material extraction and production process in one stage or A1 to A3. So it's, it's all dumped in there.

JACOBO : And that is what then is considered as the embodied carbon emissions, mostly right? Or does the embodied carbon also include...

REGITZE : It also includes end of life and there's also replacement. So we calculate out over 50 years of service life of the building, and then we have service life for the materials, you have to estimate the service level for the materials that included and then you can have the replacements during those 15 years.

JACOBO : Is embodied carbon emissions the main way of looking at carbon emissions within this context? Because I know embodied carbon emission tries to combine, as we've said, all these stages into one, right? So is that the best way of doing it? Or is it sometimes more important to break it down into what of those emissions is raw material extraction, what is transport and what is end of life?

REGITZE : I think you have to document them separately. But of course, it's the aggregated number that has a limit value. So, of course, you could always aggregate the limit values also and say, okay, it's important that we should also reduce impact today so we reduce the production of the product. So we

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make sure that right now, we also reducing and not just planning to not have so many replacements or end of life.

Jacobo : So we've been discussing a little bit the decision making process. And I think one of the things where I've been a little unclear is on the factors that are relevant in this decision making. Just so I give you a bit of an insight, the tool I'm trying to develop, I want to keep it simple, I don't want it to become a tool that's too complicated, because I feel like that key of is the simplicity and making it fast, something that you can kind of have adaptable throughout the process. And as you said, it's a very changing process. So if it becomes kind of open ended, it's easier to adapt to different type of projects, right. But because of this project is so different I'm trying to understand what is the common thread between them right, and so my mind led me to think of the factors that are influencing the decision making. So I'm trying to compile a list of which are those factors. So obviously, I want, like sustainability is my main drive for the tool. So I want my main decision factor to be carbon emissions embodied carbon emissions specifically. But I don't know if you can tell me some of the other factors that you think are relevant when when they're deciding between this cement or that other cement or things like that.

Regitze : I guess that's the complexity of it. That different materials have different properties. So if you take an insulation material, you need to look at the U-value or the lambda value of the product. So see how well it, it actually insulates. So you have to define some sort of functional unit for all your different material types to be able to compare them.

Jacobo : But is there some properties that are common to most materials? It doesn't have to be all I mean, I understand that, for example, insulation is very different than cement for a facade, right? So if we're looking at the facades, windows. For example, I found this resource for a triangular kind of pyramid that is listing all of this embodied carbon emissions and in a way, from my understanding, allowing consultants to make a choice if they're looking for alternatives, but then I don't know if there are similar charts with other properties that are being used or if it's only embodied carbon emissions that have been framed in this way.

Regitze : I think this is only production. Well, I was just grabbing this on my way out. So in this tool that we have, we have also like made different layers of a building. So it was easier to put together because a facade can consist of a lot of different materials and cladding materials, you maybe need both the cladding material and you need the fastening materials. So we sort of lumped some materials together and created different groups. So for instance, a wall would be like a middle layer of like the load bearing and insulating layer here and then we had like cladding outside and internal cladding on the inside.

So that's a way of sort of defining some some functions of different layers and using that to, to compare

Jacobo : Okay, and what are some of the functions that you take into account when you build this groups of materials?

Regitze : Well, you have to have some structure. I guess in the middle layer, we have the insulation materials, we can take the U-value and then you have the load bearing material and yeah, we talked to some structural engineers about what was typical, okay, this was typical in like this high end building, you actually have this thickness and this strength of concrete.

Jacobo : And the strength is what's measured in pounds per inch, right? DPI I think its the measure or?

Regitze : MPa, Mega Pascal.

Jacobo : And then the thickness you mentioned, what's the other unit?

Regitze : Yeah, so how much material you use

Jacobo : Is that for the density of the material? Or just to see how much you require?

Regitze : No, so...it's been so long since i have looked at this. But you say like, C20 and C25. But yeah, then you have the cladding, I don't know what you can say about that, I would just look at different how different manufacturers make it.

Jacobo : This is the list I've compiled so far, where I think some of the things that I see are shared between materials is, as I said, raw strength of the material, obviously, and the cost, and they seem to be the most ,in my head, the most common ones, there's aesthetic, which is a very difficult thing to measure, but I know where this comes into play as to deciding what goes into a certain material, the aesthetics of the district, but also the city. So that also goes were linked with building locations where it's going to be so then of course, then of course the lifespan of that material, and then where in the building the materials gonna go. So as we said, the inner facade or the cladding...so all of these things, and these are some of the things I found to be common between most materials that properties that are being considered but I don't know if this is the right track or if there's something more key that I'm missing.

Regitze : I'm just thinking like do those compare because I'm the things I was talking about was like, what are the requirements for building a building? If you take these different materials, you have to make sure that they can insulate the building enough if you have to choose from different types of materials.

Jacobo : That's good, because that's that's also helping me test my assumptions of

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seeing if I'm thinking of the right things for choosing a material. So insulation is probably one of the key the most important aspects, no?

REGITZE : Yeah. But I guess you can, yeah, it's, I guess it's parameters everything.

JACOBO : I'm breaking this down into a very engineering mindset, of course, trying to make this work, but

REGITZE : I'm just in my head, it's like, okay, you have to first compare things that are comparable. And that's what I'm talking about. And then there is like, different parameters. Okay, this didn't cost more. And this has, it's not as pretty, but like the first. Yeah, the first you have to do is compare things that are comparable. And that's what I was talking about.

JACOBO : So it's really good that you say that, because that's kind of the first step of what I want for my tool, the way I wanted to operate normally, or why I'm thinking is going to work is that the user, whoever this user is, will be coming in with an input material, say, Okay, I want to use this type of cement for a wall that goes in this part of the building in this location, right. And then with that information, gets checked with the database to see if that material exists, and then extracts the information, right. So maybe some of these properties, maybe other properties, depending on the material. And then the first step is to, to kind of, because I'm making recommendations, I want to do it in kind of two steps. The first step being, let's find materials that, as you say, are comparable to this, because when I did a first iteration of this, yeah, I mean, obviously, Clay, for example, is has less embodied carbon emissions than cement. But you cannot make a pillar of clay, the same as you would make a pillar cement, right? So then my first goal was, okay, how, what properties do I have to look at? So I set up a threshold of okay, these things are comparable, you know, you asking for cement, and I'm gonna give you 15 materials that are comparable to cement. And then when I've selected the list of 50 materials, then I can start looking at emissions and say, okay, and these are the ones that are less anything. So what would you say? Are those the properties that make materials comparable? Is there some that are common to most materials, or is it very case specific, and it has to be as comprehensive as what you have here to be able to make a comparison.

REGITZE : The easiest thing is insulating materials, because that's like the U-value. So those are sort of easy to compare. But then load bearing structures, you can have different types of load bearing structures. So those are like different, maybe completely different systems. So you might have a column and beam system, but you might also have like just a wall system. So there are like different systems you can choose between. But if you talk about Denmark, we typically do it a lot the same and we use a lot of concrete structures in sort of the same thicknesses. So you could go far from using maybe some standard structures like that. And you can also make some column beam structure for office buildings or something. But for residential, you could also maybe choose like, okay, we're only looking at residential houses here. And that would typically just be concrete walls. And we only building up to five stories, because that's also what you typically do. And there are also some requirements that work for everything up to five structures. So you just have to stay in within those rules. And that's quite kind of what we did here with using the standard.

JACOBO : Okay. Where would otherwise normally stakeholders go seek out this information? So if they like, is there a place where all of these kinds of relations and standardizations are listed that they go check? Or is it just because they have the knowledge because they've studied and have competences on this?

REGITZE : So are you talking about lifecycle assessment, or how they want to design their building?

JACOBO : More about the specifically the choices you've made here, right, so you from my understanding here, you've compiled a list of materials and what matches with to each other and some comparable structures, right? So is this the only resource that now exists? Has this kind of comparison? Or is there? Or is this based off of some other databases that have been used?

REGITZE : Well, there's the the costs, there's like a cost system, which has a lot of standards, they are like, expert in making standard structures and putting costs on them. So in there, you can see a lot of like standard structures. I think a lot of the contractors and they will have a standard way of building up their structures. So they have like standard structures to use and architectural firm will also have a little bank of like technical ways they built up a structure. So this is also something that they can individually do the different companies how they do it, typically. And you can also read, how you build a building in Denmark, we have these guides, and here, you can probably also find a lot of these structures.

JACOBO : Yeah, okay. So normally, in the process of selecting a material, I guess that it requires a consultant to come in that has this knowledge or access to this knowledge and then helps guide the engineers or the the architects or the entrepreneurs in the process, or are they equipped to?

REGITZE : Okay, well, I think the architect will typically draw something like this. And in the architectural firm, they also have these persons who are not architects, they are trained in making like, they're not civil engineers, but they know how to draw structures and do like simple calculations on structures. So they have some help there, and how to dimension the thickness and stuff

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of different things. So they will actually draw everything at the architectural firm and sort of decide something. And then that's the typical process, then later on, the engineer will come on and say, Okay, we think this should be, I don't think this is so typical, but they could say, oh, I think we should not we should do a different kind of structural system, and then they will change it to the way they want. I think they will also always change some things, but not like completely different. And they will do the hard calculations and dimensions. But it will typically be the architect, because it is so standard the way that we built in Denmark. So they will just say, Okay, it's a concrete house, we do it like this but if they want to build a wooden house, they can again, look at this, oh, how do we typically build wooden buildings? How do the constructions look? Okay, it's something like this, and then they will draw this?

JACOBO : Yeah. Because I mean, I can imagine that also, different stakeholders have different interests. Right. So and engineers always gonna go for functionality, I imagine. Yeah, trying to get the most optimized electricity use and so on, right? Whereas the architect is going to want to make it look good.

REGITZE : Exactly and maybe the architect can be sometimes a bit more ambitious, I think also engineers nowadays, but of course, they are also like they are responsible for it not falling apart and living up to also energy standards and all of these things. So they they want to make sure that this is done correctly. And where architects can maybe want to do a bigger window here and etc. and the engineer has to, yeah.

JACOBO : So what type of what type of software do you think is normally now involved in this processes of deciding building materials? Is there any software that is being used? Or it's all kind of by hand going through lists and using the knowledge that they have to?

REGITZE : Yeah, I think they typically in Denmark, everyone draws in this Revit tool. And in there they can have like, created their families, and they have like standard structures in there that they can use.

JACOBO : Cool, and that goes along with what you were saying earlier about Denmark, doing a lot of standardized, kind of a lot of some standard structuring for all things.

REGITZE : Yeah, we have a typical typical way of using a lot of concrete. And yeah, so that's so there is just like a standard.

JACOBO : I've been here for a while it's true that concrete. It's a big thing in Danish buildings.

REGITZE : Yeah, but now there's also a lot of people talking about wood buildings that's also coming up.

JACOBO : I mean, it's not like burning is going to be such an issue here in Denmark, you don't have that many fires in the in the summer, fortunately, so I guess wood could be a good transition.

REGITZE : But again, the building code is maybe somehow difficult when you're using wood structures, but that's also development, how can we adapt it to not just say no to all wood structures or like today, we have to cover all the wood in like, like gypsum material that cannot burn and stuff. But typically, if it's a structural element, it cannot really burn that easily. But I think they're working on it right now, I don't know how far they are.

JACOBO : How different Do you think these processes are between different countries? So Denmark, you've spoken a lot about it, with it being quite standardized in some ways. And there being quite a lot of interest in sustainability as well. Do you think that's the same for most countries in Europe? Does it vary very differently? The focus of my, for example, my thesis is going to be mostly in the English environment and understanding the English environment. So yeah, just to get a sense of, you know, how representative is this information for most construction projects? Or is it so specific to Denmark, that doesn't play anywhere else?

REGITZE : I don't know so much about how it is with these different stages and stuff in other countries. But I think overall, it's similar but different.

JACOBO : Adapted, I suppose. Moreso than changed.

REGITZE : Yeah, but of course, there are different traditions of how to build in other countries, using a lot more steel in other nations and wood structures also in Austria and other countries. So there are different traditions. But are you asking about the design process, or the choosing material process?

JACOBO : Both I mean, I guess it's both. It's the design process but it's also the material juicing process. I mean, for me, the most relevant is probably the latter than the first but yeah,

REGITZE : but yeah, it depends a lot if you have a tradition of so in Denmark, we don't build so much high rises, but a lot of different other nations build a lot of high rises. And that is just a completely different way of building with a lot more steel typically. So in that way, there are different traditions, and there are huge companies that just specialize in that.

JACOBO : Okay. All right, let me see, I don't want to take too much more of your time. But I guess the final thing I would like to know about is, from your understanding where do you see, is there any lacks in this process, as of right now, especially when it comes to choosing materials, is there anything that you feel it's missing, that could be improved? Or is there a major problem that you've identified in your, in your work saying, Oh, I wish we could do this or that or this, you know, this part of the material selection process was more streamlined or I don't know.

Regitze : I think like we talked about it is very standardized. And there are a lot of rules that are also made in Denmark to ensure that we built in a safe way in terms of fire and structural ability and stuff. But those are also rules that sometimes goes against reusing materials and using more biogenic material, etc. So we do have a challenge right now in incorporating all of these more sustainable alternatives because our rules are conservative, but of course, because we don't want fires, etc, in our buildings, but there is a process in that. And so also maybe the cost because a lot of things are maybe standardized in the ways that we've built because it also cost a lot to it might cost I don't know so much about costs. So I don't want to say that it's necessarily like that. Actually some project that's like the biggest or at least it used to be the biggest wood structure right over here in Denmark. And they build it because it was cheaper than then the concrete structure. So it's not because it's always cheaper.

Jacobo : So what you were saying before about rules being conservative. Does that mean that it requires a little bit more dynamism a bit more like innovation in this process? Like, would you hope that people would be a bit more open to different ways of doing things?

Regitze : Yeah, yeah, designing in different ways. Yeah.

Jacobo : And so, on that note, what would you say, you've been working with software yourself, and you've been developing some some software's more for LCA, as you mentioned, but what do you think is the role of software in this industry now? Like, do you think that the industry is open to technology to enter maturing?

Regitze : Yeah, I think they are.

Jacobo : And so what how do you see that's going to kind of empower the sustainability part of things.

Regitze : I think there's still a lot of challenges with the people working with BIM models, as I said, but there's a lot of challenges still, with the accuracy of the BIM models, which was some of what I looked into. But I think, you know, I think there are different needs in different groups of the building industry. So there are smaller companies, and there are bigger companies, and all the bigger companies are right now, a lot of them at least are developing their own tools to implement, whereas maybe the smaller companies maybe buys from, in the future future might buy from these bigger companies the software or they use free software, such as the ones that we have. But I think that a good thing will be to work for free tools for for the smaller companies, or

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at least, that they somehow doesn't have to be free, but that they somehow are able to use easy. Some very easy or how do you say, intuitive tools to choose materials, because they are not going to be experienced it in SimaPro, or something like that they need something easily.

JACOBO : Cool. That's very good to know. Do you think this is this links up to circular economy? So earlier, you were saying that some of the policies might drive away from retrofitting or reusing materials and so on? Do you think that, it's a very leading question, but do you think that if people start to trust the software's, and the software's are the ones suggesting for this kind of reuse materials, do you think that's going to make it easier for people to start thinking about this? Or do we need to have first a change of mindset of saying, Oh, actually, we should use reusable materials before anything else can help.

REGITZE : But I think we have some rules today, which makes it difficult to reuse materials. So those of course has to be developed. And then they're just the mindset but I feel like a lot of people are open to using different materials but it's just of course a new industry and yeah, and maybe conservativism we know these materials, we know that they aren't good. We don't know what these new materials do. But with good reason. Because we have had recently a big scandal in some some new material that was used that had to be removed from a lot of buildings because they caused some damages with moist in the buildings. So we also need to know what these new materials, the consequences of using new materials. So we need no more knowledge or a way to regulate this, I guess.

JACOBO : Super cool. All right, this was a lot of very useful information. I mean, I know it's big questions, and I know it's difficult to also just kind of organize the mind to get all of it out. So for that I apologize. But I thank you so much for for your

REGITZE : You're welcome, I'm just like I'm not in the industry. So it's it can be difficult to to answer the questions that I feel like a more you should ask the industry. But yeah, I hope it helps.

JACOBO : No, it does. It does me Nothing for me was, it's a very good way of getting a sense. I mean, I come completely new to this industry. Yeah, I'm new to construction. So, you know, I'm learning all of this vocabulary. I didn't even know what cladding was, you know. So like, it's. So first step is also to get into the good to understanding. But it's good. Also for me to confirm things I've heard from different sources, right. So what they were saying about, about, yeah, the specificity, specificity to each project, the stakeholders what they want. And it really seems to me like, I'm trying to break it down into simple terms, what I'm choosing a building material is, but inherently,

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they're just not really possible. Because it's never a simple thing.

REGITZE : No, exactly. So it's a it's a challenging project.

JACOBO : Yeah, I think so. I mean, I think I'm on the way to kind of find some some ways of making it a little bit easier to adapt to different aspects. But as you say, it needs to be intuitive. It needs to be adaptable. And it's the only way that people are gonna buy using tools like this, otherwise, they're gonna be like, Why would I use this If I know I can do this on my own, right?

REGITZE : So I think they are screaming after, after good easy tools. But again, they also want to then use that to maybe to somehow, like, it's all this data flow is also just a chance, because they also want to use it then to in the end make their How do you say like, what they have to deliver to the municipality to say that? Okay, we are under the limit value for co2. So yeah, it's a big question. Should we just have something easy to begin with? And then later on a more specialized tools that we can use for the municipality? Or should it be the same tool that you can use throughout the process?

JACOBO : From my side, I think I'm trying to build this early, early one, I think also, I'm picking very specific scenarios, because as we establish, it's not the same issue building this part of the wall as this part of the wall, is this part of the wall? All right. So because there's so many variables, I'm trying to kind of close it down on, okay, let me see if I can do this for, let's say, an insulation material that goes in the facade of a building in this specific region, and then have it so kind of specified down to exactly where it is that it's easy to test out and lets you set U-values.

REGITZE : Yeah. But I also think if you talk with an architect, they will probably tell you that in the early stages, it's more like they're doing like volume testing, where they don't necessarily know what the materials are or this structure concept. And then they're maybe trying, okay, should it be? Should it be a wooden building or concrete building like, those overall decisions? Okay, do it go this way or that way? And then first, maybe very much later, they're looking at the insulation material?

JACOBO : Yeah. Yeah, so it's not that all the materials are equally as relevant at all stages obviously and you have to prioritize?

REGITZE : No, but yeah, but the insulation material can, of course, be important. So it wouldn't be nice to also somehow have it in the calculations. But yeah, it all depends on. Yeah, how you want to do it, because it could be nice to have a very advanced calculation. But of course, for the architect, it's only a choice of wooden building or concrete building, but then maybe you have like some sort of uncertainty margin. Okay, so the wooden building would look like this, and the concrete building would look like this. But then there's like an uncertainty and maybe quite much, depending on which insulation material to choose and etc, all the other materials.

JACOBO : It's about reducing uncertainty, I suppose and trying to as much as you can. All right cool! Well, I will not take up more of your time. Thank you so much.

B.2 JAW Sustainability: Lord Matthew Louis Higgs

The second interview was conducted on March 30th with Matthew Higgs. Matthew works as associate director at JAW Sustainability. The goal for this interview was to utilize Matthews's domain knowledge to gain a better of the context of the construction industry in the UK, how far sustainability work in this industry had come, what the future hold for the city of London and policy reforms to improve its sustainability goals. Additionally, it was intended to gain an understanding of the current methods being utilized to select building materials, and where software tools to automate this process may find their space in this industry. Below can be found the transcript for the interview:

JACOBO : I'm here with Matthew Higgs, associate director at JAW sustainability. Matthew, do you want to introduce yourself, tell me a little bit about what's your role in the company is and what do you do?

MATTHEW : Sure thing. I'm Matthew, Lord Matthew Louis Higgs, associate director of JAW stainability. And I lead up the building materials team. As a team, we mostly complete building LCAs for refurbishment and new build projects. We also perform pre redevelopment or pre demolition audits on refurbishment and sites that have been cleared for new builds. And we also handle a large portion of the circular economy work that is done for larger projects within London. Although not exclusively, but that's one of the only areas in which such things are a legal requirement.

JACOBO : So I take it your your work involves a lot of understanding regulation, it involves a lot about doing calculations on different stages of a building's construction and different understandings of the carbon emissions throughout the process of the building?

MATTHEW : You are correct. We do various different levels of estimation and calculation, particularly for lifecycle assessment. And how much of that is estimation and how much of it is reality is largely based on the design the stage at which that assessment is undertaken. So earlier design stages will have to use assumptions either taken from regulatory or guidance documents or from our own repository of projects, for example, that we work with the same client on multiple projects, and they tell us that the buildups are going to be largely the same, then we can use old building models to make early estimations for things like foundation massings, or structural frame massings. And that's not the most accurate way of doing it, obviously. But prior to the engagement of a structural engineer, who actually uses building physics calculation engines to determine the massings of those things, it's about as good as we can do. Once we move into the later stages, and that information is available, we update the calculations to use the technical design information. And then later post construction, we use information from material delivery notes that we use to calculate the actual emissions of embodied emissions of the building. And then compare those things.

Jacobo : So, since you are very, you work a lot on sustainability within within the industry and within the construction industry. What would you say is the role that sustainability is currently playing in the construction industry?

Matthew : I think if you'd have asked this question a couple of years ago, the answer probably would have been quite different. In London, which is one of the few places in the UK at least, where there is a serious regulatory environment surrounding sustainability and buildings, both from the operational side with energy efficiency measures, be they based on building fabric or building systems. That's I mean, that is a legal requirement, there is a minimum standard that is set across the entire UK and London has a standard which goes further beyond that and requires a 30% improvement as a minimum baseline over the UK standard. So that is something that has to be done in order to gain planning permission. And then even after planning permission, you have to prove that in order to be able to sell or rent your building to use it for its intended purpose. That is not the case with embodied carbon that's only for operational carbon emissions. Most work towards embodied carbon is market driven currently, and that is likely to change I expect but currently there are people like LETI, the London energy transformation initiative, the GLA, the Greater London Authority, have published targets for so that I should perhaps go back one step and say that London as a whole has something called the London plan, which is output by the GLA. And this sets forward targets to push developments within London, amongst many, many other things. But I'm only talking about the sustainability parts of it, there's a whole host of other stuff in there, a push towards net zero by 2050. And until very recently, the understanding throughout most of the building industry was that net zero was equal to operational net zero, which is not the case and is now more widely being understood to not be the case then operational net zero would be that you minimise the energy use throughout your building, you maximise the generation of renewable electricity on your site. And you offset whatever remains relatively flimsy that is now largely being expanded to include embodied emissions. Although I have to say that the general principles have not changed it is minimise what you do on like maximise what you can do on site with regards to reductions in energy use and embodied carbon and then offset whatever is remaining have kind of gone off on a tirade here, what was the question?

Jacobo : No, I'm just trying to get a sense on the standing of sustainability in the construction industry. And it sounds like in London specifically, it is quite a kind of quite an important topic when it comes to this industry. And they're really regulating on it right?

Matthew : Very much so and I would say that it varies from from developer to developer and also from engineering firms from architecture firms, even from client to client, whether or not it's something that they choose to engage in for its own merits or whether or not they choose to perform the regulatory minimums required we generally push for above average. But at the end of the day, we do not have the power within the design team to really affect the design we provide information. And what is done with that information is largely down to the client. Be they the contractor or the architect or the structural engineer or whoever is paying for the building, it varies. I would say throughout the construction industry as a whole in the past, sustainability has largely been seen as a thorn in the side poor or however the metaphor goes. But I do feel that that is changing. It is more and more being understood that there is a net benefit both in terms of potential profit and in perception of your business as a whole. Nobody wants to get tarred with the brush of being unsustainable these days. But similarly, specifically, returning to the topic of building materials, if you can reduce the amount of concrete required for your structural frame, if you can physically cut the mass required through either effective building design, or even just reducing wastage by using precast materials or whatever, then you're reducing the overall like the overheads of the project as a whole. And so if it's well done, there is a solid business case for introducing sustainability as well as the fact that also if something is operationally very efficient, and that is a high selling point, to the point where in 10, 20, maybe years, you won't be able to sell a terrible building with a gas boiler in it. I mean, they won't even exist. At least not in this city. The point being that I think slowly it is taking time and it has taken time. But slowly over time, it is becoming more apparent that not only is this something that you have to do, but it is also something that if you actively engage with in the correct way can provide win wins for everybody. Environment for the people purchasing the buildings or renting the buildings and for the people who are developing and selling them.

Jacobo : So what are the obstacles ahead to be able to, like is there any obstacles that are preventing sustainability from being implemented further and if so, what are they?

Matthew : Many some of them are as simple as cost and timelines, the building industry, the construction industry as a whole is very deadline focused very deadline driven. This comes from the general way that it is set out in order to get planning permission. Particularly in London again, there are various review panels that you have to undergo, and they occur every X amount of months, I don't remember off the top of my head how often it is. And if you miss that, then you're you cannot get your planning permission for another X amount of months, I think it's three. And pushing a timeline back by three months means that every person who was contracted to a specific timeline is probably going to have some cut part of their fee retained or will have to pay some kind of fine to the whoever has contracted them. And so it's very deadline driven, very money driven. And these things, even if they might, let's say you through two weeks of extra modelling, you could reduce the volume of a reinforced concrete frame by 10%. And monetarily, if you miss your planning deadline, then it may still be a net loss financially. And so there are always financial hurdles

Jacobo : So money and time are common hurdles?

Matthew : Two big hurdles yeah. There's also just a general mentality and this is what has started shifting, but it is still prevalent in large sectors of the building industry. Like I said, it's being eroded faster in London because of the regulatory environment. But throughout the rest of the country, and I cannot speak to Europe as a whole. The construction industry moves slowly, the people work in it for 60 years of their life, and they want to build buildings at the end of their career in the same way that they did in beginning of it often. And so there is a phase shift that has to occur a paradigm shift that has to occur. And sometimes people get stuck in their ways and these people happen to be the directors of large contractors or whoever it may be that is in control of determining what the sustainability strategy of the project will actually be. So we provide information ideas and quantifications to back it up. But we do not have the final say as to what the sustainability strategy on a building is.

Jacobo : You give advice and they have to decide whether they want to implement said advice or not,

Matthew : We consult yes, precisely.

Jacobo : So you've talked about both embodied carbon emissions and also operational carbon emission. So, I wonder if you could just very briefly give an insight into the differences and is there a one that is more important now, is there a trend towards one or the other?

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Matthew : Certainly, as I said before the has been for several years now, I think pushing five years a push towards what is referred to as net zero, especially in again in London, under the London plan. There has been this push towards net zero and that has been at this so far very focused on operational emissions and regulated operational emissions at that. So regulated emissions are anything relating to the heating, cooling or ventilation of your building. And unregulated emissions are everything else your fridge TV, your oven. And that has been a significant push and it has for the large part worked the regulatory environment in London is now so stringent that you will not be able to meet the operational carbon reduction targets if you use a gas boiler. And so a new building in London will not use a gas boiler and as a result, because it will use mostly air source heat pumps. Air source heat pumps require that the building fabric is tightly sealed require that the U-values are significantly low enough to retain that heat because it uses relatively low grade heat depending on the system between 30 and 60 degrees. And so that has been a very significant and a very successful push towards the reduction of operational emissions at the same time you've also had a general greening of the grid. So an increased amount of energy production is being produced by renewable and "renewable" sources, be it solar farms wind farms or the "renewables" being biomass or in some cases biogas. There's a very large power station. Want to say I can't remember the name a bit, but I'll let you know later, begins with the de Drax, Drax power station, used to be a coal plant now largely burns pellets, biomass pellets. And that is, for better or worse not the point of this conversation, counted as renewable energy. And so the way that the carbon is calculated for that means that there has been a significant reduction in the kilogrammes of co2 equivalents produced per kilowatt of energy produced. And so if you look at charts showing the whole lifecycle carbon emissions building, you will see that over time, the amount percentile, the amount that is derived from the operation of that building, or at least the operational energy of that building, has reduced and that is partially because the gross amount has reduced due to the greening of the grid. But that is, it is still part of a whole. And the reason that the gross amount has reduced is because the operational part of that whole has been reducing. And the reason that the materialistic parts the embodied emissions have increased is because as part of the whole, they are not reducing where they both reducing it at commensurate speeds, then the percentages would remain the same. And they'd grossly reduce, so what would have previously been roughly 50-50 would have remained 50-50, but that pie chart would have just gotten smaller. That hasn't happened, the wedge that is a portion to operational emissions has gotten smaller, showing that the advances in the reduction of operational emissions is progressing significantly faster than the

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reduction in embodied emissions.

JACOBO : So if the next step then is to tackle embodied carbon emissions, how does that connect to meaning in your work, for example, with building materials? How does that connect to building materials? Is there a way to make them more sustainable?

MATTHEW : Yeah, there's a few different ways to do it. A lot of guidance documents roughly outline this, but like the Cliff Notes version of it is, you can reduce the amount of materials that you use. So as I mentioned before reducing structural frames, perhaps using something called Brick slips instead of full bricks, which is essentially the shaving from a front of a break. And so you turn one break into four bricks lips, and you glue them all to the front of the building. Obviously, not structural, so you can reduce the amount of materials you use. Alternatively, you can use materials which for one reason or another, have a lower level of embodied carbon this could be because their production method, produces less carbon than a typical alternative. So an example of that would be, although it's not ready for market yet, it's kind of ready for market but not in the quantities required. You have green steel that is made using electric arc furnaces, which can be entirely powered by renewable energy, vastly reducing the co2 per kilogramme or tonne of steel as opposed to traditional barium which would use coking coal to get the high heat. Or you can. An example for concrete would be the reduction of the use of Portland cement, which is a typical binder used in most if not all concrete. And by replacing that with the essentially recycled materials but they're mostly waste materials outputs from either steel production or some other forms of production fly ash and grant ground granulated blast furnace slag are the two most common ones. And you remove some of the cement you introduce these two things and they act as a binder as well. And so by removing what's known as a virgin material, something which has to go through a full process of being extracted from the ground, process, transported etc. If you utilise a waste product from something else, then you offset the emissions and all of that virgin production. And so for every kilogramme of fly ash that you use in concrete, you offset the carbon emissions of a kilogramme of Portland cement. and Portland cement is quite intensive,

JACOBO : Right. So it's about being smart with the usage of your materials and kind of, it's not really retrofitting as such, but it's kind of reusing, repurposing, upcycling some materials that otherwise would be taken as waste and using them again as building components.

MATTHEW : Those are examples of making existing materials that are already utilised heavily within the construction industry greener. You can also use alternative materials, it's still a relatively young industry, but things like cross

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laminated timber, proving that they, up to certain heights and within certain building applications, they can be used as structural framing for structural framing systems. And although depending on how you calculate the embodied carbon, even if you just look at it logically outside of guidance documents and things of this kind, which determine whether or not you can include or exclude biogenic carbon, which is a whole thing. What is sustainable steel? There was a finite amount of steel within the planet and theoretically infinite amount of wood. And so that those are kind of three options, you can make a single material better, you can reduce the amount of the materials or you can utilise a different material that fills the same functional role

Jacobo : And making the material better, as you said, by reinforcing certain aspects of it that might not be as strong to make it more sustainable, right?

Matthew : That is the example with concrete. Yes, I mean, steel is steel, regardless of how you produce it. So if you produce green steel, then it's still steel. But yes, so making existing materials greener often involves either using recycled materials. So for example, gypsum, which is all plaster and plasterboard essentially, is an inherently recyclable material plasterboard is a pressed layer of gypsum with I mean, it might it might be foil backed if it's fire retardant or something like that. And likewise, the gypsum there might be impregnated with something else, but the materials inherent to that are 100% recyclable. And so if that material is all collected at the end of a project and back to a manufacturer who can process reprocess it, then you are offsetting a significant part of the whole lifecycle emissions of that product because that product no longer has to be extracted from anywhere. And so whilst you might still have, you will still have lifecycle emissions from the deconstruction of the building it came from transport to a reprocessing facility, the energy required for the reprocessing and then transport back to a site and reconstruction into a new building, you have still skipped out several of the earliest stages of whole lifecycle emissions being the extraction of raw materials and the transport of those raw materials to a suitable site. And the extraction of raw materials is often very energetic, you only have to think about mining, strip mining, making quarries, things like this, like a lot of materials that we particularly with the cases of sand and earth born materials are, it's an incredibly energetic and therefore carbon intense process to extract those materials from the beginning. And also there is then the whole thought of like waste and ecotoxicity and stuff like that everything you put in a landfill eventually goes back into the sky. Whereas everything that you take from the surface of the planet and then put back onto the surface of the planet is going to keep that carbon out of the atmosphere for longer. Which overtime compounds. So if you can create this, I mean, the idea is called the circular economy if you can create a world in which a break never goes to

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landfill and it's never crushed for aggregate and as long as it doesn't lose its value and remains a break then the lifetime of a brick is 120 years plus. So then that the carbon that was required to make that brick, everything that went into it, it has a much longer lifespan and you are offsetting the production of new bricks by reusing it so all of these things compound into reducing the overall systemic carbon production of the industry.

JACOBO : Okay, I want to take it a step back now that we've been covering this and then try and gain a bit of an understanding of the bigger picture, because I want to understand kind of where some of the decision making that comes into building materials comes into place and so on. So, from your knowledge, what are kind of the steps in a very generic sense that go into a construction project since the need for the building is identified until the building's put up in the foundations.

MATTHEW : okay. I mean, you can roughly split this into RIBA stages, they stages one through six,

JACOBO : RIBA being the association of...?

MATTHEW : Royal Institute of B, something architects, I forget what the B stands for

JACOBO : the royal entity or other legal entity that kind of regulates the stages.

MATTHEW : It's not all that, like they have no regulatory power. But they are a group of building professionals essentially, who have been doing this for centuries now and largely aware of the industry in ways that a lot of other people are not, and they have set out this, it's called the RIBA plan of works. And it just outlines kind of how a building is produced from initial conception of the idea we need. There are students here, Portsmouth University is building a campus in blah, blah, blah, place, there is no accommodation for the students, we should build some student accommodation. At that point, someone, whoever the client is will begin contacting people like architects, who will produce various ideas for what this building might look like and then it goes through and it gets more and more granular. As you move through with the general idea of the building, you need to know how it's going to stand up. Structural engineers, once you know how it's going to stand out, you need to know how much that's going to cost, quantity surveyors. And somewhere within this process, generally in that kind of area was where we would come in. And we would at the same time as a quantity surveyor, it's telling you how much a building is going to cost, we will also be telling you what the carbon embodied carbon count is. But material selection actually begins quite early on, even a client can have an idea that they want their building to be green. And that limits the material selection possibilities.

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An architect can have an idea that they want. They want the building to be a specific shape, which necessitates a specific type of structure. And then that is a material selection. And so whilst specific material specification probably occurs further down the line of RIBA stages, maybe a little bit of 2, mostly of 4, 2 being conceptual design, where the building is kind of roughed out. And 4 being technical design, which is when you have the likes of mechanical and electrical engineers, specifying where ducts and pipes and cabling is going to run and where unit and rooms are fully fleshed out, and you have an idea of how hot the room is gonna get because you know, where the sun rises and where the window points, calculate those things. So that's 4. And that's when things will come very in depth. But the material selection, in its essence begins much, much earlier than that. Because I mean, even simple things like we want the basement on this building means that you're already making decisions that will affect the quantity of materials because basements require deeper foundations that require retaining walls to keep the building out and all that sort of thing. If you have if you design a building, which is not rationalised, which means that things don't line up internally, then you increase the required amount of structural frame to transfer the load from overhanging areas that were just falling, like gravity would just pull them down to Earth. You have an increased requirements to structural frame to make sure that doesn't happen and the building standards and as you increase the mass of the structural framing have to increase the mass of the foundations and so so on and so forth. And so decisions that affect the materiality of the building are occurring throughout the entire process. But typically, we become involved at a stage where too many decisions have been made for us to affect things like material licence or authority so that we can't come in and say we just don't have the basement because they've already a portion of that space. So we would normally come in somewhere late design stage 2 maybe. And then we would do the design stage 2 work they would apply for planning permission and then there would be some condition and we will probably come back at stage 4 and do it all again and then post construction we will do it again so that we could compare the actual results to our initial assessments.

JACOBO : Does that mean that it's difficult to pinpoint a specific stage within this, you know, so there's six stages in RIBA?

MATTHEW : Yes, but 5 is construction and 6 is handover. So the design of the building is kind of, okay.

JACOBO : So those stages 1-4, from your knowledge, could you say there's a place where decision making on building materials weighs more than other stages? Or is it kind of evenly distributed? Does it depend on the stakeholders in-

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volved? You mentioned Architects, Engineers...

MATTHEW : So it can vary based on the stakeholders involved, as I said, if there is a very specific idea for what a building should be, or should what it should look like or what functionality it has to have, then those choices will all affect the materiality of the building, as far as like actual specification of selection of materials like manufacturing, selecting a manufacturer for your installation, stuff, all that stuff will be done in stage 4, for the most part. But the the materials in a broader sense, not so specific, not selecting a specific manufacturer, will occur in, an awful lot in design stage 2. But decisions that affect those materials will be made even earlier than that, when the building doesn't even exist in someone's head.

JACOBO : Okay. So it's very early on in the process

MATTHEW : Its when the process begins. But I would say that as you go through it up to design, stage 4, you select more and more and more. And so probably between 2 and 4 is where the majority of the conscious decisions are made.

JACOBO : And then. So with that in mind, how are this link materials been selected? What are the different methodologies from again, from your knowledge that are being used to be able to cover this?

MATTHEW : Some of it is, it depends on what the function of the material is. So if we're looking at facades, things that are outward facing, or interiors, things that are inward facing, a lot of that would be driven by aesthetics, and performance. So for example, in London, there's a lot of brick. That's a conscious choice by most objects. There's also a lot of glass. And so it depends on what kind of building you're making. But this is what I was saying about material selection and how it can occur incredibly early as if you're building a building within an area of London, whether a lot of brick buildings, you're not going to be or rather, you're going to be penalized for trying to make a glass skyscraper. That's genuinely not Well, thought off. There is a lot of heritage in the city. And as such, there are a lot of limiting factors regarding how you design a building. What was the question again?

JACOBO : I asked you what are the current methods that you're using to select the building materials?

MATTHEW : Right, yes. So some of it will be performance based, some of it will be based on aesthetics, the materials in between the exterior and interior that will mostly largely be performance based. And a lot of it is just determined by status quo. Concrete works, steel works. They're also readily available, availability is a significant driver as well. So knowing that you have enough of that material within your reach to produce your building steel and concrete around readily abundant, something like cross laminated timber is not,

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which means it is a much bigger incentive towards using materials that you know, the materials that you've done, and then some of it is just simply awareness. Architects are not structural engineers. And so they might not be aware of structural materials. So yeah, I would say awareness, a certain level of just business as usual. But yeah, like drivers, specifically things that people are looking for when they're looking at material will be if it's out, whatever I'm facing probably has something to do with aesthetics, at least, but also a lot about durability, lifetime.

Jacobo : And, regardless, availability is always important.

Matthew : Availability is always going to be important cost will always be important, because at the end of the day, as I said previously, as well as being very deadline driven the building industry is a massive money spender. And that's why an awful lot of people are in it. It's because these buildings will and can make money. But there's a lot of value engineering that occurs in there a lot of minimizing the output so that the profit is maximized.

Jacobo : And you mentioned awareness. So how does, like if we go to practical terms, how does the selection actually happen? Is it an architect will hire a consultant that comes in and reports: This is the list of materials that are available and this is what you can use? Well, but is it more the stakeholder themselves go and research databases of materials are unavailable? Are the suppliers actively kind of promoting their materials? And so what are like how do I if I wanted to build a building? How do I know where to look for materials and how to choose?

Matthew : Where to look? I mean, that is something that is specified generally a little further down the road. And so various subcontractors, there's a lot of something called design and build that goes on, which is where something like rough material specifications will be sent out. And then whoever is building the building will source the materials themselves.

Jacobo : Yeah, I mean, I'm not talking so much about the sourcing itself that I understand this is more about the knowledge right?

Matthew : So that is, again, I think, largely based on the status quo, like most structural engineers will have or even architects and developers as a whole, very few people who build large buildings do one and then never another. They even house builders and things like this, like, there are several large developers that exclusively build semi detached and detached homes. And they will have a specific, they will have their framework, this is what we do this is how we build buildings. And so an awful lot of that is not necessarily ignorance, but an unwillingness or a lack of awareness with regards to alternatives.

Jacobo : Okay, so it's, it's a lot about this is how I already do it, the specialization of an architectural firm towards specific types of buildings specific type of materials, and then they use for those buildings and then operating within that comfort zone, as opposed to maybe kind of looking at options that might be off their comfort zone.

Matthew : It's easy to become blinkered, and if something works, then you will continue to do it.

Jacobo : Okay. But is there any tools that are out there that are helping people know how to use like, what materials they can look for? And like? Is it is it large databases that you know you get with your LCA software programs or is it not software based?

Matthew : There are databases of materials largely made up of something called EPDs. There are also some other databases that contain other types of material information. But I would say that they are mostly not utilized for specification they are more utilized as repositories for specific information. their strengths and lifetimes and stuff of materials there will be more used technically, I guess, as opposed to like for for the purpose of calculation. The EPD database that are utilized for building LCA is would not be used by a subcontractor or an architect to specify materials. For a start your problems of access. As a second point, you have that these material databases that contain hundreds if not 10s, if not hundreds of 1000s of products. And trawling through them is a nightmare. As far as non software based tools, and there are some, some tools out there for specification of materials, but I've played with a couple of them and found them generally to be relatively lackluster, There is a website, I forget its name, I'll send it to you in a bit where you can kind of look for materials in there, there are some filters and stuff.

Jacobo : So it sounds like a lot of the methodology or the tools used to select materials is either knowledge based. So you go you have a rough idea of what type of feeling you want. Yeah, and you go to specific stakeholders that are good at making such a building happen, and so they will have the knowledge. But otherwise there are some tools just not that many that have information broader than that specification where you can access to find certain conditions. Is that correct?

Matthew : But I think in general, it doesn't quite work that way. I think it's not that you would say I want my building to have concrete frame, I will go to someone who made who designs concrete frames, it would you would say, I want my building to not fall down, you would go to a structural engineer, and depending on what their preference is, you would get your structural frame made of steel or concrete? Or maybe if there was significant drive from further up the chain from the architects or from the client themselves, then

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they would explore alternatives. But then, yeah, they would do calculations based on things like strength, wind loading, and stuff like this, like general loading of buildings, like your structural engineers, focus is not typically and has never typically been embodied carbon, it is making a building stand up.

Jacobo : So does this then you see a gap that could be filled? Or is there is there something missing in this process of building to a selection?

Matthew : I mean, sure, and I think this is probably why there is this lag behind operational emissions to embodied emissions, is because the process of determining how you reduce those emissions is still being developed. And it is a time of flux within the regulatory environment, and within the building industry as a whole. And it is becoming known that it is more important for these things to be accounted for. And it is only really now that it is being figured out how we account for them. And so I think, as far as tool development goes, the reason that there are not particularly many out there at the moment is because prior to this, it was never considered necessary. And that perhaps in 10 years, we will look back at this time all the time, five years ago and think my goodness, how did we ever do this?

Jacobo : So it's because the focus has been more operational than than embodied that this is happening then?

Matthew : I think so. And I think it will rectify itself in relatively short order, one way or another

Jacobo : I have one final question. So if I would tell you there is a tool, or there would be a tool that can support stakeholders in making some of these decisions and understanding sustainable building materials? Where would you see relevance for such a tool? So something like what stages of the construction project you can follow the RIBA stages, if you'd like, what would you say, like where would you see a gap for such a tool?

Matthew : Again, I would say that it's probably stages 2 and 4. But that's not necessarily because of the types of design that occur. Those stages are more to do with the stakeholders that are involved in those stages. Stage 2, you have architects largely leading the design. And they are people for whom kind of add to which would allow for greater understanding of the possibilities and potentials of materials that they could use would be useful, because then it's not their primary focus. And it's not how architects are trained, they're trained in building forms, mostly there are degrees out there for sustainable architecture and stuff like that. But in the UK, if you do one of those, you're not classified as an architect, and you need to study for three more years to get your license. And so it's systemically not encouraged. And so I think architects as a whole would be a good target, which is why RIBA stage 2 is relevant for any tool that were coming down to material selection. And then the other one that I would say, would it and the other group of individuals in the stakeholder that I think it would be useful for would be structural engineers, because they the structural frame of the building has such a large impact on the total embodied emissions, that anything that could simplify the process of them determining it, assuming that they are considering and body carpet, which again, is becoming more and more likely by the day, it's becoming more and more important that they do consider those things. Anything that can lay out in simple terms, what materials or what level of cement replacement or because then as the benchmarks improve, we will we will gain more of an idea of what each building element itself has to aim for. And so anything that can simplify that process and say alright, well look for each meter cubed of this type of concrete that you use, you're going to produce x, y, z amounts of produce, but there will be x, y, z amounts of body carbon, I think that's going to be very useful for them just to streamline their entire process. Because it's going to be something that they'll have to consider rather than them designing a frame and then sending that design to a person like me, who will look at that design and calculate the embodied carbon and send it back to them and say, Alright, we probably need to cut some of this, can you design another one and blah, blah, blah, can you maybe, or even if I look at it, and say, Alright, fine, but if you make it out with 20%, cement replacement, or if you have it 40% Cement replacement, then we get this amount of reduction, blah, blah, blah, blah, blah, is that possible, and then then during the loading calculations again, and then blow back and forth, and back and forth. If they can calculate the massing of the frame, and then look through materials and say, Well, this is the embodied carbon of 20%, cement replacement, 40%, etc, etc, then it cuts out the middleman as I said, construction is very deadline orientated. And so the more you can streamline that process of both materials selection and an understanding of the embodied carbon within those materials, then as long as you can ensure that the material selected is still meets the functional requirements, and you can lay out the embodied carbon of that you streamline that entire process, and it becomes it removes one of the major barriers to, to the inclusion of these things, which is that it takes time to do the analysis and to make sure that you get it right, anything that you can do to streamline it to speed up that process, even to cut out people like me to, to a certain extent, it's great if you ensure, not ensure you cannot ensure, but you encourage the industry as a whole to take those materials under their wing and to utilize them all.

JACOBO : So to summarize, the question would then not be so much when is this relevant or where but for whom? And the reason why it's because you're targeting two main value points as you're putting them, right. So one on

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the one side, being able to have a tool that shortens timespan of making these decisions and speeds things up. But also on the provides, as we spoke earlier, a lot of this is knowledge based, so then it provides knowledge to these people right and in and enhances them without necessarily exactly...

MATTHEW : Provides access to information that they may not have otherwise found. Because it sits in a database that they have no particular reason to look at. Or streamlines the process by allowing them to quickly look at the impact of altering those materials. Two things that I think are very valuable. Knowledge and speed.

JACOBO : Yeah. Perfect. Well, that's what I have for you today. Thank you so much for taking the time to sit with me

MATTHEW : I just want to say that you're doing an excellent job.

Annex C

Solution Source Code

This annex will contain all the different source code files for the final iteration of the Sustainable Building Material Selection System as explained in Chapter 5 of the associated report.

C.1 Main Class: App

```
from PIL import Image
import customtkinter as ctk
from Homepage import Homepage
from UserInput import UserInput
from DBMatching import DBMatching
from ManualDBInput import ManualDBInput
from PropDeviations import PropDeviations
from MatRecommend import MatRecommend
from Results import Result
import pandas as pd


def change_appearance_mode(new_appearance_mode):
    ctk.set_appearance_mode(new_appearance_mode)


class App(ctk.CTkFrame):
    def __init__(self, master=None):
        super().__init__(master)
        self.master = master
```

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```
self.master.title("Sustainable Building
    Materials Recommender System")
self.master.geometry("1200x800")

# define a set of variables that will be
    utilized at different stages throughout the
    other classes
self.mat_properties = ["", "", "", "", "", ""]
     # [0]uniqueid, [1]name, [2]ec, [3]cost, [4]
    lifespan, [5]viable application
self.filtered_materials = []
self.recommendations = [["", "", "", "", ""], [
    "", "", "", "", ""], ["", "", "", "", ""]]

# import the database to be used
self.df = pd.read_csv('building_materials_DB.
    csv', delimiter=',')

# ------------------------------------NAV FRAME
    -----------------------------------------------


self.nav_frame = ctk.CTkFrame(self, fg_color="#
    F0EAD2", width=225, height=800)
self.nav_frame.grid(row=0, column=0, sticky="ns
    ")
self.nav_frame.grid_propagate(False)

# create grid inside navigation frame
self.nav_frame.grid_columnconfigure(0, weight
    =1)

# create logo image widget
self.logo_img = ctk.CTkImage(light_image=Image.
    open("images/sbm_logo.png"),
                              dark_image=Image.
                                 open("images/
                                 sbm_logo.png"),
                                  size=(64, 64))
self.logo_label = ctk.CTkLabel(self.nav_frame,
    image=self.logo_img, compound="left", text="
```

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```
    SBM Recommender",
                                     padx=10)
self.logo_label.grid(row=0, column=0, padx=10,
    pady=10, sticky="ew")

# create buttons in navigation frame to switch
    between pages
# home nav button
home_icon = ctk.CTkImage(light_image=Image.open
    ("images/home_light.png"),
                                 dark_image=Image.open(
                                     "images/home_dark.
                                     png"), size=(16,
                                     16))
self.nav_btn_home = ctk.CTkButton(self.
    nav_frame, text="Home", text_color="black",
    image=home_icon,
                                         compound="
                                             left",
                                         command=self.
                                             show_home,
                                              hover=
                                             True,
                                         hover_color="
                                             #6C584C",
                                             border_spacing
                                             =5, anchor
                                             ="w")  # ,
                                              state="
                                             disabled"
self.nav_btn_home.grid(row=1, column=0, padx
    =10, pady=10, sticky="ew")

# user input nav button
uin_icon = ctk.CTkImage(light_image=Image.open(
    "images/input_light.png"),
                                dark_image=Image.open("
                                    images/input_dark.
                                    png"), size=(16, 16)
                                    )
```

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```
self.nav_btn_uin = ctk.CTkButton(self.nav_frame
    , text="Enter Your Material", text_color="
    black", image=uin_icon, compound="left",
                                     command=self.
                                        show_user_input
                                        , hover=
                                        True,
                                     hover_color="
                                        #6C584C",
                                        border_spacing
                                        =5, anchor=
                                        "w")  # ,
                                        state="
                                        disabled"
self.nav_btn_uin.grid(row=2, column=0, padx=10,
     pady=10, sticky="ew")

# database matching nav button
dbmatch_icon = ctk.CTkImage(light_image=Image.
    open("images/match_light.png"),
                              dark_image=Image.
                                 open("images/
                                 match_dark.png")
                                 , size=(16, 16))
self.nav_btn_dbmatch = ctk.CTkButton(self.
    nav_frame, text="Check Database", text_color
    ="black", image=dbmatch_icon,
                                         compound="
                                            left",
                                         command=
                                            self.
                                            show_db_matching
                                            ,
                                         hover=True
                                            ,
                                            hover_color
                                            ="#6
                                            C584C",

                                            border_spacing
                                            =5,
```

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```
                                                      anchor="w"
                                                         )  # ,
                                                         state="
                                                         disabled
                                                         "
            self.nav_btn_dbmatch.grid(row=3, column=0, padx
                =10, pady=10, sticky="ew")

            # manual input nav button
            manin_icon = ctk.CTkImage(light_image=Image.
                open("images/manual_light.png"),
                                          dark_image=Image.open
                                             ("images/
                                             manual_dark.png"),
                                              size=(16, 16))
            self.nav_btn_manin = ctk.CTkButton(self.
                nav_frame, text="Manual Material Entry",
                text_color="black", image=manin_icon,
                compound="left",
                                                   command=self
                                                      .
                                                      show_manual_input
                                                      , hover=
                                                      True,
                                                   hover_color=
                                                      "#6C584C"
                                                      ,
                                                      border_spacing
                                                      =5,
                                                      anchor="w
                                                      ")
            self.nav_btn_manin.grid(row=4, column=0, padx
                =10, pady=10, sticky="ew")

            # property deviations nav button
            pdev_icon = ctk.CTkImage(light_image=Image.open
                ("images/deviation_light.png"),
                                         dark_image=Image.open(
                                            "images/
                                            deviation_dark.png"
                                            ), size=(16, 16))
```

```
self.nav_btn_pdev = ctk.CTkButton(self.
    nav_frame, text="Set Up Deviations",
    text_color="black", image=pdev_icon,
    compound="left",
                                  command=self.
                                     show_prop_dev
                                     , hover=
                                     True,
                                  border_spacing
                                     =5,
                                     hover_color
                                     ="#6C584C"
                                     , anchor="
                                     w")
self.nav_btn_pdev.grid(row=5, column=0, padx
    =10, pady=10, sticky="ew")

# material recommender nav button
matrec_icon = ctk.CTkImage(light_image=Image.
    open("images/rec_light.png"),
                           dark_image=Image.
                              open("images/
                              rec_dark.png"),
                              size=(16, 16))
self.nav_btn_matrec = ctk.CTkButton(self.
    nav_frame, text="Material Recommendation",
    text_color="black", image=matrec_icon,
                                    compound="
                                       left",
                                    command=
                                       self.
                                       show_mat_rec
                                       ,
                                    hover=True,

                                       hover_color
                                       ="#6
                                       C584C",
                                       border_spacing
                                       =5,
                                    anchor="w")
```

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```
        self.nav_btn_matrec.grid(row=6, column=0, padx
            =10, pady=10, sticky="ew")

        # results nav button
        result_icon = ctk.CTkImage(light_image=Image.
            open("images/rec_light.png"),
                                    dark_image=Image.
                                        open("images/
                                        rec_dark.png"),
                                        size=(16, 16))
        self.nav_btn_result = ctk.CTkButton(self.
            nav_frame, text="Results", text_color="black
            ",
                                              image=
                                                  result_icon
                                                  ,
                                              compound="
                                                  left",
                                              command=
                                                  self.
                                                  show_results
                                                  ,
                                              hover=True,

                                                  hover_color
                                                  ="#6
                                                  C584C",
                                                  border_spacing
                                                  =5,
                                              anchor="w")
        self.nav_btn_result.grid(row=7, column=0, padx
            =10, pady=10, sticky="ew")

        # Add Options menu to change appearance mode
        self.appearance_mode_menu = ctk.CTkOptionMenu(
            self.nav_frame, values=["Light", "Dark", "
            System"],
                                                         fg_color
                                                             =
                                                             "
                                                             #
```

```
ADC178
"
,

command
=
change_appearanc
)

self.appearance_mode_menu.grid(row=8, column=0,
     padx=20, pady=20, sticky="s")

self.nav_buttons = [self.nav_btn_home, self.
   nav_btn_uin, self.nav_btn_manin, self.
   nav_btn_dbmatch,
                    self.nav_btn_pdev, self.
                       nav_btn_matrec]

# ------------------------------------MAIN
   FRAME
   -----------------------------------------------

# create main frame to hold the pages
self.main_frame = ctk.CTkFrame(self, bg_color="
   #DDE5B6", fg_color="#DDE5B6", width=975,
   height=800)
self.main_frame.grid(row=0, column=1, sticky="
   nsew", padx=20, pady=20)
self.main_frame.grid_propagate(False)

# configure grid layout of the main frame
self.main_frame.grid_rowconfigure(0, weight=1)
self.main_frame.grid_columnconfigure(0, weight
   =1)

# create instances of each page
self.page1 = Homepage(self.main_frame, self)
self.page2 = UserInput(self.main_frame, self,
   self.mat_properties, self.df)
```

```
        self.page3 = DBMatching(self.main_frame, self,
            self.mat_properties, self.df)
        self.page4 = ManualDBInput(self.main_frame,
            self, self.mat_properties, self.df)
        self.page5 = PropDeviations(self.main_frame,
            self,  self.mat_properties, self.df, self.
            filtered_materials)
        self.page6 = MatRecommend(self.main_frame, self
            , self.recommendations, self.df, self.
            filtered_materials, self.mat_properties)
        self.page7 = Result(self.main_frame, self, self
            .recommendations, self.df)

        # dictionary to associate pages with respective
             buttons
        self.menu_buttons = {
            self.page1: self.nav_btn_home,
            self.page2: self.nav_btn_uin,
            self.page3: self.nav_btn_dbmatch,
            self.page4: self.nav_btn_manin,
            self.page5: self.nav_btn_pdev,
            self.page6: self.nav_btn_matrec,
            self.page7: self.nav_btn_result,
        }

        # show the initial page
        self.show_page(self.page1)

        # pack and show the main application frame
        self.pack(fill="both", expand=True)

    def show_page(self, page):
        """Show the given page and hide all other pages
            """
        for p in [self.page1, self.page2, self.page3,
            self.page4, self.page5, self.page6, self.
            page7]:
            if p == page:
                # p.tkraise()
                # p.parent = self.main_frame  # Set the
                    parent to main_frame
```

```
                    p.grid(row=0, column=0, sticky="nsew")
                    self.menu_buttons[p].configure(fg_color
                        ="#A98467")
                else:
                    # p.parent = None  # Hide other pages
                    p.grid_remove()
                    self.menu_buttons[p].configure(fg_color
                        ="#ADC178")

    def show_home(self):
        self.show_page(self.page1)

    def show_user_input(self):
        self.show_page(self.page2)

    def show_db_matching(self):
        self.show_page(self.page3)

    def show_manual_input(self):
        self.show_page(self.page4)

    def show_prop_dev(self):
        self.show_page(self.page5)

    def show_mat_rec(self):
        self.show_page(self.page6)

    def show_results(self):
        self.show_page(self.page7)


# Driver Code
if __name__ == "__main__":
    root = ctk.CTk()
    app = App(root)
    root.mainloop()
```

C.2 Sub-Class: Homepage

```
import customtkinter as ctk
```

```
from PIL import Image


class Homepage(ctk.CTkFrame):
    def __init__(self, master=None, app=None):
        super().__init__(master)
        self.app = app
        # self.configure(fg_color="#DDE5B6")

        self.label = ctk.CTkLabel(self, text="Welcome
           to the Sustainable Building Material
           Recommender System",
                                  font=("Guidole
                                     Regular", 28),
                                     wraplength=500,
                                     justify="center")
        self.label.grid(row=0, column=0, padx=(200, 0),
             pady=(100, 20), sticky="nsew")

        self.frame = ctk.CTkFrame(self)
        self.frame.grid(row=1, column=0, padx=(200, 0),
             pady=(20, 0), sticky="nsew")

        self.intro_lbl = ctk.CTkLabel(self.frame, text=
           "This platform is designed to help improve
           your decision making process when choosing
           building materials for your construction
           project. Our goal is to provide you with
           recommendations that fit your functional
           needs while improving the overall level of
           environmental impact of your project", font
           =("Guidole Regular", 12), wraplength=300,
           justify="left")
        self.intro_lbl.grid(row=0, column=0)

        self.intro_lbl2 = ctk.CTkLabel(self.frame, text
           ="Through the following interface you wil be
            able to enter the material you wish to
           replace, set up deviations to find materials
            fitting within your functional requirements
            and our algorithm will take help you find
```

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```
            alternatives with less embodied carbon
            emissions", font=("Guidole Regular", 12),
            wraplength=300, justify="left")
        self.intro_lbl2.grid(row=1, column=0)

        guide = ctk.CTkImage(light_image=Image.open("
            images/guide.jpg"), dark_image=Image.open("
            images/guide.jpg"),
                              size=(256, 362))
        self.guide_btn = ctk.CTkLabel(self.frame, text=
            "", image=guide)
        self.guide_btn.grid(row=0, column=1, rowspan=2)

        self.btn = ctk.CTkButton(self, text="Begin
            Searching Alternatives Materials!",
            text_color="#F0EAD2",
                                      fg_color="#ADC178",
                                         hover=True,
                                         hover_color="#6
                                         C584C",
                                      command=self.
                                         show_user_input)
        self.btn.grid(row=2, column=0, padx=(200, 0),
            pady=(20, 0), sticky="nsew")

    def show_user_input(self):
        self.app.show_page(self.app.page2)
```

C.3 Sub-Class: User Input

```
import customtkinter as ctk


class UserInput(ctk.CTkFrame):
    def __init__(self, master=None, app=None,
       properties=None, database=None):
        super().__init__(master)
        self.app = app
        self.mat_name = None
        self.material_properties = properties
```

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```
        self.database = database

        self.label = ctk.CTkLabel(self, text="Please
           enter the name of the material you wish to
           replace:",
                                  wraplength=250,
                                     justify="center")
        self.label.grid(row=0, column=0, padx=(300, 0),
            pady=(200, 20), sticky="nsew")

        self.input = ctk.CTkEntry(self,
           placeholder_text="Material Name")
        self.input.grid(row=3, column=0, padx=(300, 0),
            pady=10, sticky="nsew")

        self.btn_frame = ctk.CTkFrame(self, width=300,
           height=50)
        self.btn_frame.grid(row=4, column=0, padx=(300,
            0), pady=20, sticky="nsew")

        self.save_btn = ctk.CTkButton(self.btn_frame,
           text="Check Material Database", fg_color="#
           ADC178", hover=True,
                                       hover_color="#6
                                          C584C",
                                       command=self.
                                          db_matching_btn
                                          )
        self.save_btn.grid(row=0, column=0, padx=10,
           sticky="nsew")

        self.continue_btn = ctk.CTkButton(self.
           btn_frame, text="Continue", fg_color="#
           ADC178",
                                           hover=True,
                                           hover_color="
                                              #6C584C",
                                           command=self.
                                              show_db_matching
                                              )
```

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```
        self.continue_btn.grid(row=0, column=1, padx
            =10, sticky="nsew")

    def db_entry_matching(self, material, database,
        properties):
        # Check if the input exists as a database entry
            already
        exp = database['ICE DB Name'] == material
        if material in database['ICE DB Name'].values:
            unique_id = database.loc[exp, 'Unique ID'].
                values[0]
            name = database.loc[exp, 'ICE DB Name'].
                values[0]
            ec = database.loc[exp, 'EC per kg'].values
                [0]
            cost = database.loc[exp, 'Cost'].values[0]
            lifespan = database.loc[exp, 'Lifespan'].
                values[0]
            application = database.loc[exp, 'Viable
                Applications'].values[0]
            props = [unique_id, name, ec, cost,
                lifespan, application]

            for i in range(6):
                properties[i] = props[i]

            return properties

    def db_matching_btn(self):
        self.db_entry_matching(self.input.get(), self.
            database, self.material_properties)

    def show_db_matching(self):
        self.app.show_page(self.app.page3)
```

C.4 Sub-Class: DatabaseMatching

```
import customtkinter as ctk
from tkinter import ttk
import re
```

```
class DBMatching(ctk.CTkFrame):
    def __init__(self, master=None, app=None,
       properties=None, database=None):
        super().__init__(master)
        self.app = app
        self.database = database
        self.properties = properties

        # create the frames to split the interface into
        self.left_frame = ctk.CTkFrame(self, width=400,
            height=500)
        self.left_frame.grid(row=0, column=0, sticky="
           nsw", padx=(50, 0), pady=(50, 0))
        self.left_frame.grid_propagate(False)

        self.right_frame = ctk.CTkFrame(self, width
           =400, height=500)
        self.right_frame.grid(row=0, column=1, sticky="
           nse", pady=(50, 0))
        self.right_frame.grid_propagate(False)

        # ---------------------------------------LEFT
           FRAME
           ----------------------------------------------

        # pair 0
        self.pair0_frame = ctk.CTkFrame(self.left_frame
           , width=500, height=50)
        self.pair0_frame.grid(row=0, column=0)

        self.label = ctk.CTkLabel(self.pair0_frame,
           text="Is this the correct material
           information?")
        self.label.grid(row=0, column=0, padx=5, pady
           =20)

        self.update_btn = ctk.CTkButton(self.
           pair0_frame, text="Update Parameters",
           fg_color="#ADC178", hover=True,
```

```
                                        hover_color="#6
                                           C584C",
                                           command=self
                                           .
                                           update_params_btn
                                           )
self.update_btn.grid(row=0, column=1, padx=5,
   pady=20)

# create frame containing label-entry box
# pair 1
self.pair1_frame = ctk.CTkFrame(self.left_frame
   , width=500, height=50)
self.pair1_frame.grid(row=1, column=0)

self.box_label1 = ctk.CTkLabel(self.pair1_frame
   , text="Material Name", wraplength=60,
   justify="center")
self.box_label1.grid(row=0, column=0, padx=20,
   pady=20)

self.box_entry1 = ctk.CTkEntry(self.pair1_frame
   , placeholder_text="Material Name")
self.box_entry1.grid(row=0, column=1, padx=20,
   pady=20)

# pair 2
self.pair2_frame = ctk.CTkFrame(self.left_frame
   , width=500, height=50)
self.pair2_frame.grid(row=2, column=0)

self.box_label2 = ctk.CTkLabel(self.pair2_frame
   , text="Embodied Carbon", wraplength=60,
   justify="center")
self.box_label2.grid(row=0, column=0, padx=20,
   pady=20)

self.box_entry2 = ctk.CTkEntry(self.pair2_frame
   , placeholder_text="Value in CO2e/kg")
self.box_entry2.grid(row=0, column=1, padx=20,
   pady=20)
```

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```
        # pair 3
        self.pair3_frame = ctk.CTkFrame(self.left_frame
            , width=500, height=50)
        self.pair3_frame.grid(row=3, column=0)

        self.box_label3 = ctk.CTkLabel(self.pair3_frame
            , text="Material Cost", wraplength=60,
            justify="center")
        self.box_label3.grid(row=0, column=0, padx=20,
            pady=20)

        self.box_entry3 = ctk.CTkEntry(self.pair3_frame
            , placeholder_text="Value in     ")
        self.box_entry3.grid(row=0, column=1, padx=20,
            pady=20)

        # pair 4
        self.pair4_frame = ctk.CTkFrame(self.left_frame
            , width=500, height=50)
        self.pair4_frame.grid(row=4, column=0)

        self.box_label4 = ctk.CTkLabel(self.pair4_frame
            , text="Material Lifespan", wraplength=60,
            justify="center")
        self.box_label4.grid(row=0, column=0, padx=20,
            pady=20)

        self.box_entry4 = ctk.CTkEntry(self.pair4_frame
            , placeholder_text="Value in Years")
        self.box_entry4.grid(row=0, column=1, padx=20,
            pady=20)

        # pair 5
        self.pair5_frame = ctk.CTkFrame(self.left_frame
            , width=500, height=50)
        self.pair5_frame.grid(row=5, column=0)

        self.box_label5 = ctk.CTkLabel(self.pair5_frame
            , text="Viable Applications", wraplength=60,
             justify="center")
```

```
self.box_label5.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry5 = ctk.CTkEntry(self.pair5_frame
    , placeholder_text="i.e., Facade, Walls, etc
    .")
self.box_entry5.grid(row=0, column=1, padx=20,
    pady=20)

# create yes and no buttons
self.yes_btn = ctk.CTkButton(self.left_frame,
    text="Yes", fg_color="#ADC178", hover=True,
    hover_color="#6C584C",
                                command=self.
                                    show_prop_dev)
self.yes_btn.grid(row=6, column=0, padx=20,
    pady=20)

# --------------------------------RIGHT FRAME
    WIDGETS
    --------------------------------------------------

# Create a list of options for the dropdown
    menu. TO BE REPLACED WITH FILTERED LIST OF
    MATERIALS BASED OFF KEYWORD
self.label = ctk.CTkLabel(self.right_frame,
                            text="If the
                                information
                                displayed about
                                your material is
                                incorrect, then
                                please proceed to
                                search for it in
                                our database below
                                , enter keywords
                                to find the
                                material separated
                                 by commas:",
                            width=350, wraplength
                                =300, justify="
                                center")
```

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```
        self.label.grid(row=0, column=0, pady=(50, 0))

        self.material_names = database['ICE DB Name'].
            values.tolist()
        # print(self.material_names)

        self.combo = ttk.Combobox(self.right_frame,
            width=50)
        self.combo['values'] = self.material_names
        self.combo.grid(row=1, column=0, padx=(50, 50),
             pady=5)
        # self.combo.bind("<<ComboboxSelected>>", self.
            filter_options)
        self.combo.bind("<<ComboboxModified>>", self.
            filter_btn)

        self.no_btn = ctk.CTkButton(self.right_frame,
            text="No", fg_color="#ADC178", hover=True,
            hover_color="#6C584C",
                                          command=self.
                                              show_manual_input
                                              ) # self.
                                              update_properties
                                              (self.combobox.
                                              get(), database,
                                               properties)
        self.no_btn.grid(row=2, column=0, padx=(50, 50)
            , pady=5)

    def update_parameters(self, properties):
        # print(properties)
        self.box_entry1.insert('end', properties[1])
        self.box_entry2.insert('end', properties[2])
        self.box_entry3.insert('end', properties[3])
        self.box_entry4.insert('end', properties[4])
        self.box_entry5.insert('end', properties[5])

    def filter_options(self, event, database):
        text = event.widget.get().lower()
        keywords = re.split(r',\s*', text)
```

```
        filtered_options = [option for option in
           database['ICE DB Name'].values.tolist() if
                                all(keyword in option.lower
                                   () for keyword in
                                   keywords)]
        self.combo['values'] = filtered_options

    def update_properties(self, material, database,
                              properties):  # in this case
                                 material will correspond
                                 to the name extracted from
                                  the combobox after the
                                 user's selection
        if material in database['ICE DB Name'].values:
            unique_id = database.loc[database['ICE DB
               Name'] == material, 'Unique ID'].values
               [0]
            name = database.loc[database['ICE DB Name']
                == material, 'ICE DB Name'].values[0]
            ec = database.loc[database['ICE DB Name']
               == material, 'EC per kg'].values[0]
            cost = database.loc[database['ICE DB Name']
                == material, 'Cost'].values[0]
            lifespan = database.loc[database['ICE DB
               Name'] == material, 'Lifespan'].values
               [0]
            application = database.loc[database['ICE DB
                Name'] == material, 'Viable
               Applications'].values[0]
            props = [unique_id, name, ec, cost,
               lifespan, application]

            for i in range(6):
                properties[i] = props[i]

            return properties

    def filter_btn(self):
        self.filter_options(self.database)

    def show_manual_input(self):
```

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```
            self.app.show_page(self.app.page4)

        def show_prop_dev(self):
            self.app.show_page(self.app.page5)

        def update_params_btn(self):
            self.update_parameters(self.properties)
```

C.5 Sub-Class: ManualEntry

```
import customtkinter as ctk
import pandas as pd
import uuid


class ManualDBInput(ctk.CTkFrame):
    def __init__(self, master=None, app=None,
       properties=None, database=None):
        super().__init__(master)
        self.app = app
        self.properties = properties
        self.database = database
        self.mat_name = None
        self.mat_ec = None
        self.mat_cost = None
        self.mat_life = None
        self.mat_apps = None

        self.label = ctk.CTkLabel(self, text="Enter the
            information for your\n material and its
           properties below",
                                 wraplength=200,
                                    justify="center")
        self.label.grid(row=0, column=0, padx=(275, 0),
            pady=(100, 0))

        # pair 1
        self.pair1_frame = ctk.CTkFrame(self, width
           =500, height=50)
```

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```
self.pair1_frame.grid(row=1, column=0, padx
    =(275, 0))

self.box_label1 = ctk.CTkLabel(self.pair1_frame
    , text="Material Name", wraplength=60,
    justify="center")
self.box_label1.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry1 = ctk.CTkEntry(self.pair1_frame
    , placeholder_text="Enter the Name of the
    Material")
self.box_entry1.grid(row=0, column=1, padx=20,
    pady=20)

# pair 2
self.pair2_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair2_frame.grid(row=2, column=0, padx
    =(275, 0))

self.box_label2 = ctk.CTkLabel(self.pair2_frame
    , text="Embodied Carbon", wraplength=60,
    justify="center")
self.box_label2.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry2 = ctk.CTkEntry(self.pair2_frame
    ,
                              placeholder_text
                                 ="Embodied
                                 carbon value
                                 in CO2e/kg")
self.box_entry2.grid(row=0, column=1, padx=20,
    pady=20)

# pair 3
self.pair3_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair3_frame.grid(row=3, column=0, padx
    =(275, 0))
```

```
self.box_label3 = ctk.CTkLabel(self.pair3_frame
    , text="Material Cost", wraplength=60,
    justify="center")
self.box_label3.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry3 = ctk.CTkEntry(self.pair3_frame
    , placeholder_text="Cost in      ")
self.box_entry3.grid(row=0, column=1, padx=20,
    pady=20)

# pair 4
self.pair4_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair4_frame.grid(row=4, column=0, padx
    =(275, 0))

self.box_label4 = ctk.CTkLabel(self.pair4_frame
    , text="Material Lifespan", wraplength=60,
    justify="center")
self.box_label4.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry4 = ctk.CTkEntry(self.pair4_frame
    , placeholder_text="Lifespan in Years")
self.box_entry4.grid(row=0, column=1, padx=20,
    pady=20)

# pair 5
self.pair5_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair5_frame.grid(row=5, column=0, padx
    =(275, 0))

self.box_label5 = ctk.CTkLabel(self.pair5_frame
    , text="Viable Applications", wraplength=60,
     justify="center")
self.box_label5.grid(row=0, column=0, padx=20,
    pady=20)
```

```
self.box_entry5 = ctk.CTkEntry(self.pair5_frame
   , placeholder_text="i.e Cladding, Roofing,
   Inner Walls, etc.")
self.box_entry5.grid(row=0, column=1, padx=20,
   pady=20)

self.entries = [self.box_entry1, self.
   box_entry2, self.box_entry3, self.box_entry4
   , self.box_entry5]

# final button
self.btn_frame = ctk.CTkFrame(self, width=500,
   height=50)
self.btn_frame.grid(row=6, column=0, padx=(275,
    0))

self.save_btn = ctk.CTkButton(self.btn_frame,
   text="Update Material Properties", fg_color=
   "#ADC178", hover=True,
                              hover_color="#6
                                 C584C",
                                 command=self.
                                 upd_prop_btn)
self.save_btn.grid(row=0, column=0, padx=5,
   pady=20)

self.exe_btn = ctk.CTkButton(self.btn_frame,
   text="Enter New Material in our Database",
   fg_color="#ADC178",
                             hover=True,
                                hover_color="#6
                                C584C", command
                                =self.
                                db_entry_btn)
self.exe_btn.grid(row=0, column=1, padx=5, pady
   =20)

self.continue_btn = ctk.CTkButton(self.
   btn_frame, text="Enter New Material in our
   Database", fg_color="#ADC178",
```

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```
                                                    hover=True,
                                                       hover_color
                                                       ="#6C584C"
                                                       , command=
                                                       self.
                                                       continue_btn
                                                       )
        self.continue_btn.grid(row=0, column=2, padx=5,
            pady=20)

    # design for function to trigger upon press of a
       button, and it will go through all the entry
       boxes in
    # the frame and retrieve the input from the user to
        store it in mat_properties

    def enter_info(self, mat_properties):
        mat_name = self.box_entry1.get()
        mat_ec = self.box_entry2.get()
        mat_cost = self.box_entry3.get()
        mat_life = self.box_entry4.get()
        mat_apps = self.box_entry5.get()

        mat_properties[1] = mat_name
        mat_properties[2] = mat_ec
        mat_properties[3] = mat_cost
        mat_properties[4] = mat_life
        mat_properties[5] = mat_apps
        # print(self.mat_properties)
        return mat_properties

    def manual_input(self, database, properties):
        # Prompt the user to fill in the relevant
           properties to add a new entry to the
           database
        # generate a random unique id number of numbers
            and letters in the format "XXXXXXXX-XXXX-
           XXXX-XXXX-XXXXXXXXXXXX" where X are the
           numbers and/or letters
        unique_id = str(uuid.uuid4()).lower()
```

```
            # Create a new entry with the generated id and
               user input properties
            new_entry = pd.DataFrame({
                'Unique ID': [unique_id],
                'ICE DB Name': [properties[1]],
                'EC per kg': [properties[2]],
                'Cost': [properties[3]],
                'Lifespan': [properties[4]],
                'Viable Applications': [properties[5]]})

            # Append the new entry to the database
            database = pd.concat([database, new_entry])
            database.to_csv('building_materials_DB.csv',
               index=False, sep=',')
            print("New entry added to database.")

        def upd_prop_btn(self):
            self.enter_info(self.properties)

        def db_entry_btn(self):
            self.manual_input(self.database, self.
               properties)

        def continue_btn(self):
            self.app.show_page(self.app.page5)
```

C.6 Sub-Class: PropertyDeviations

```
import customtkinter as ctk
import tkinter as tk


class PropDeviations(ctk.CTkFrame):
    def __init__(self, master=None, app=None,
        properties=None, database=None,
        filtered_materials=None):
        super().__init__(master)
        self.app = app
        self.properties = properties
        # print(self.properties)
```

```
self.database = database
# print(self.database)
self.filtered_materials = filtered_materials

# LEFT FRAME & WIDGETS
# create the frames to split the interface into
self.left_frame = ctk.CTkFrame(self, bg_color="
    lightgray", width=550, height=500)
self.left_frame.grid(row=0, column=0, sticky="
    nsw", padx=(50, 0), pady=(50, 0))
self.left_frame.grid_propagate(False)

# Create the Options menu that displays
    structural locations
self.str_menu_var = ctk.StringVar(self.
    left_frame,
                                  value="Select
                                     the
                                    desired
                                    structural
                                     location"
                                    ) # set
                                    the
                                    initial
                                    value
self.str_menu = tk.OptionMenu(self.left_frame,
    self.str_menu_var,
                              "Structural
                                 Location") #
                                 values=self.
                                 str_locations
self.str_menu.grid(row=0, column=0, padx=(0,
    20), pady=(100, 20))
self.menu = self.str_menu["menu"]

self.subList1 = tk.Menu(self.menu, tearoff=
    False)
self.menu.add_cascade(label="Wall", menu=self.
    subList1)
self.subList1.add_command(label="Internal Wall"
    )
```

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```
self.subList1.add_command(label="External Wall"
   )

self.subList2 = tk.Menu(self.menu, tearoff=
   False)
self.menu.add_cascade(label="Facade", menu=self
   .subList2)
self.subList2.add_command(label="Cladding")
self.subList2.add_command(label="Facade Wall")

# Create pair 1 frame
self.pair1_frame = ctk.CTkFrame(self.left_frame
   , width=500, height=50)
self.pair1_frame.grid(row=1, column=0, padx
   =(25, 0), pady=20, sticky="w")

# Create a label, entry box and slider widgets
   for pair 1
self.cost_lbl = ctk.CTkLabel(self.pair1_frame,
   text="Material Cost (  %)", width=125,
   height=20)
self.cost_lbl.grid(row=0, column=0, pady=(15,
   0), sticky="w")

self.cost_entry = ctk.CTkEntry(self.pair1_frame
   , placeholder_text=" %", width=100, height
   =20)
self.cost_entry.grid(row=0, column=1, padx=(15,
    15), pady=(15, 0), sticky="w")

self.slider1 = ctk.CTkSlider(self.pair1_frame,
   from_=0, to=100, width=475, height=20)
self.slider1.set(25)
self.slider1.grid(row=1, column=0, columnspan
   =3, pady=10)

self.cost_update = ctk.CTkButton(self.
   pair1_frame, width=75, text="Update Cost
   Deviation", fg_color="#ADC178",
                              hover=True,
```

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```
                                        hover_color="
                                           #6C584C",
                                        command=self.
                                           upd_cost_btn
                                           )
self.cost_update.grid(row=0, column=2, padx=(0,
     25), pady=(15, 0), sticky="w")

# Create pair 2 frame
self.pair2_frame = ctk.CTkFrame(self.left_frame
   , width=500, height=50)
self.pair2_frame.grid(row=2, column=0, padx
   =(25, 0), pady=20, sticky="w")

# Create a label, entry box and slider widgets
   for pair 1
self.life_lbl = ctk.CTkLabel(self.pair2_frame,
   text="Material Lifespan (  %)", width=125,
   height=20)
self.life_lbl.grid(row=0, column=0, pady=(15,
   0), sticky="w")

self.life_entry = ctk.CTkEntry(self.pair2_frame
   , placeholder_text=" %", width=100, height
   =20)
self.life_entry.grid(row=0, column=1, padx=(15,
     15), pady=(15, 0), sticky="w")

self.slider2 = ctk.CTkSlider(self.pair2_frame,
   from_=0, to=100, width=475, height=20)
self.slider2.set(40)
self.slider2.grid(row=1, column=0, columnspan
   =3, pady=10)

self.life_update = ctk.CTkButton(self.
   pair2_frame, width=75, text="Update Lifespan
     Deviation",
                                        fg_color="#
                                           ADC178",
                                           hover=True,
```

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```
                                                    hover_color="
                                                       #6C584C",
                                                    command=self.
                                                       upd_life_btn
                                                       )
            self.life_update.grid(row=0, column=2, padx=(0,
                25), pady=(15, 0), sticky="w")

            # button to enter deviations
            self.enter_btn = ctk.CTkButton(self.left_frame,
                text="Check Materials", fg_color="#ADC178",
                hover=True,
                                                  hover_color="#6
                                                     C584C",
                                                  command=self.
                                                     sim_materials_btn
                                                     )
            self.enter_btn.grid(row=3, column=0, padx=20,
               pady=20)

            # RIGHT FRAME & WIDGETS

            self.right_frame = ctk.CTkFrame(self, bg_color=
               "gray", width=250, height=500)
            self.right_frame.grid(row=0, column=1, sticky="
               nse", pady=(50, 0))
            self.right_frame.grid_propagate(False)

            self.txt_lbl = ctk.CTkLabel(self.right_frame,
                                        text="Total amount
                                           of materials
                                           matching/n your
                                           given functional
                                            criteria:",
                                        wraplength=200,
                                           justify="center"
                                           )
            self.txt_lbl.grid(row=0, column=0, pady=(150,
               10))
```

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```
        self.matches_btn = ctk.CTkButton(self.
           right_frame, text="Update Number of Matches"
           , fg_color="#ADC178",
                                          hover=True,
                                             hover_color
                                             ="#6C584C",
                                          command=self.
                                             n_matches_btn
                                             )
        self.matches_btn.grid(row=1, column=0, pady=10)

        self.matches_entry = ctk.CTkEntry(self.
           right_frame, width=150, height=30)
        self.matches_entry.grid(row=2, column=0, pady
           =10)

        self.txt_lbl1 = ctk.CTkLabel(self.right_frame,
                                      text="Let us find
                                         which of these
                                         is the/n most
                                         sustainable
                                         alternative",
                                      wraplength=200,
                                         justify="center
                                         ")
        self.txt_lbl1.grid(row=3, column=0, pady=10)

        self.btn = ctk.CTkButton(self.right_frame, text
           ="Continue", fg_color="#ADC178", hover=True,
                                 hover_color="#6C584C",
                                     command=self.
                                    show_mat_rec)
        self.btn.grid(row=4, column=0, pady=10)

    # def optionmenu_callback(self, choice):
    # print("You selected the following location:",
       choice)
    # return choice
    # extract choice and include into filtering, so it
       includes the option selected by the user
```

```
def update_cost_value(self, value):
    # Update the label with the current value of
       the scale
    self.cost_entry.delete(0, 'end')
    self.cost_entry.insert('end', str(value))
    # print(scale.get())

def update_life_value(self, value):
    # Update the label with the current value of
       the scale
    self.life_entry.delete(0, 'end')
    self.life_entry.insert('end', str(value))
    # print(scale.get())

def find_similar_materials(self, properties,
   database, cost_dev, life_dev, matching_materials
   ):
    cost_dev = round(float(cost_dev)/100, 2)
    # print ("Cost Deviation: " + str(cost_dev))
    life_dev = round(float(life_dev)/100, 2)
    # print ("Lifespan Deviation: " + str(life_dev)
       )

    cost_range = (properties[3] * (1 - cost_dev),
       properties[3] * (1 + cost_dev))
    # print(cost_range)
    lifespan_range = (properties[4] * (1 - life_dev
       ), properties[4] * (1 + life_dev))
    # print(lifespan_range)

    for index, row in database.iterrows():
        # print('Checking row:', index)
        # print ('Row:', row)
        if (cost_range[0] <= row['Cost'] <=
           cost_range[1]
                and lifespan_range[0] <= row['
                   Lifespan'] <= lifespan_range[1])
                   :
            matching_materials.append(row['ICE DB
               Name'])
```

```
            print("This is properties", properties)
            if properties in matching_materials:
                matching_materials.remove(properties)

            # Return the list of similar materials
            print(matching_materials)
            return matching_materials

        def num_matches(self, matching_materials=None):
            n_matches = len(matching_materials)
            print(n_matches)
            self.matches_entry.delete(0, 'end')
            self.matches_entry.insert('end', n_matches)

        def upd_cost_btn(self):
            self.update_cost_value(round(self.slider1.get()
               , 2))

        def upd_life_btn(self):
            self.update_life_value(round(self.slider2.get()
               , 2))

        def sim_materials_btn(self):
            self.find_similar_materials(self.properties,
               self.database, self.cost_entry.get(), self.
               life_entry.get(), self.filtered_materials)

        def n_matches_btn(self):
            self.num_matches(self.filtered_materials)

        def show_mat_rec(self):
            self.app.show_page(self.app.page6)
```

C.7 Sub-Class: MaterialRecommendation

```
import customtkinter as ctk
from PIL import Image


class MatRecommend(ctk.CTkFrame):
```

```
    def __init__(self, master=None, app=None,
       recommendation=None, database=None,
       filtered_materials=None, properties=None):
        super().__init__(master)
        self.app = app
        self.recommendations = recommendation
        self.database = database
        self.filtered_materials = filtered_materials
        self.properties = properties

        self.ec_btn = ctk.CTkButton(self, text="Find
           Top 3 Sustainable Alternatives",
                                        fg_color="#ADC178",
                                            hover=True,
                                           hover_color="#6
                                           C584C",
                                        command=self.
                                           lowest_ec_btn)
        self.ec_btn.grid(row=0, column=0)

        self.update_btn = ctk.CTkButton(self, text="
           Display the Alternatives!", fg_color="#
           ADC178",
                                            hover=True,
                                               hover_color=
                                               "#6C584C",
                                               command=self
                                               .
                                               upd_parm_btn
                                               )
        self.update_btn.grid(row=0, column=1)
        # ------------------------------------------
           FIRST MATERIAL FRAME
           ----------------------------------------------

        self.mat_frame1 = ctk.CTkFrame(self, width=250,
            height=500)
        self.mat_frame1.grid(row=1, column=0, padx=(50,
            0))
```

```
self.mat_img = ctk.CTkImage(light_image=Image.
    open("images/aggregates.png"),
                            dark_image=Image.
                               open("images/
                               aggregates.png")
                               , size=(128,
                               128))
self.img_btn = ctk.CTkButton(self.mat_frame1,
    fg_color="#F0EAD2", image=self.mat_img, text
    ="", state="disabled")
self.img_btn.grid(row=0, column=0, padx=20,
    pady=20)

self.mat_lbl1 = ctk.CTkLabel(self.mat_frame1,
    text="Material 1", wraplength=200)
self.mat_lbl1.grid(row=1, column=0, padx=10,
    pady=(0, 20))

# create nested frames for each Label-Entry-
    Entry group
# 1st group
self.group_frame1 = ctk.CTkFrame(self.
    mat_frame1, width=220, height=50)
self.group_frame1.grid(row=2, column=0, padx
    =(10, 10), pady=(0, 5))

# Each group features a label with the name of
    the property
self.prop_lbl1 = ctk.CTkLabel(self.group_frame1
    , text="Embodied Carbon", width=60, height
    =40, wraplength=60,
                              justify="center")
self.prop_lbl1.grid(row=0, column=0, padx=(5,
    0), pady=5)

# An entry for the property value of that
    material
self.prop_entry1 = ctk.CTkEntry(self.
    group_frame1, placeholder_text="EC in CO2e/
    kg", width=75, height=40)
```

```
self.prop_entry1.grid(row=0, column=1, padx=5,
    pady=5)

# And a percentage of deviation for that
    property compared to the input material
self.prop_percent1 = ctk.CTkEntry(self.
    group_frame1, placeholder_text="+/- %",
    width=75, height=40)
self.prop_percent1.grid(row=0, column=2, padx
    =(0, 5), pady=5)

# 2nd group
self.group_frame2 = ctk.CTkFrame(self.
    mat_frame1, width=220, height=50)
self.group_frame2.grid(row=3, column=0, padx
    =(10, 10), pady=(0, 5))

# Each group features a label with the name of
    the property
self.prop_lbl2 = ctk.CTkLabel(self.group_frame2
    , text="Cost", width=60, height=40,
    wraplength=60,
                                justify="center")
self.prop_lbl2.grid(row=0, column=0, padx=(5,
    0), pady=5)

# An entry for the property value of that
    material
self.prop_entry2 = ctk.CTkEntry(self.
    group_frame2, placeholder_text=" x     ",
    width=75, height=40)
self.prop_entry2.grid(row=0, column=1, padx=5,
    pady=5)

# And a percentage of deviation for that
    property compared to the input material
self.prop_percent2 = ctk.CTkEntry(self.
    group_frame2, placeholder_text="+/- %",
    width=75, height=40)
self.prop_percent2.grid(row=0, column=2, padx
    =(0, 5), pady=5)
```

```
# 3rd group
self.group_frame3 = ctk.CTkFrame(self.
   mat_frame1, width=220, height=50)
self.group_frame3.grid(row=4, column=0, padx
   =(10, 10), pady=(0, 5))

# Each group features a label with the name of
   the property
self.prop_lbl3 = ctk.CTkLabel(self.group_frame3
   , text="Lifespan", width=60, height=40,
   wraplength=60,
                              justify="center")
self.prop_lbl3.grid(row=0, column=0, padx=(5,
   0), pady=5)

# An entry for the property value of that
   material
self.prop_entry3 = ctk.CTkEntry(self.
   group_frame3, placeholder_text="Years",
   width=75, height=40)
self.prop_entry3.grid(row=0, column=1, padx=5,
   pady=5)

# And a percentage of deviation for that
   property compared to the input material
self.prop_percent3 = ctk.CTkEntry(self.
   group_frame3, placeholder_text="+/- %",
   width=75, height=40)
self.prop_percent3.grid(row=0, column=2, padx
   =(0, 5), pady=5)

# 4th group
self.group_frame4 = ctk.CTkFrame(self.
   mat_frame1, width=220, height=50)
self.group_frame4.grid(row=5, column=0, padx
   =(10, 10), pady=(0, 5))

# Each group features a label with the name of
   the property
```

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```
self.prop_lbl4 = ctk.CTkLabel(self.group_frame4
    , text="Structural Location", width=60,
    height=40, wraplength=60,
                                 justify="center")
self.prop_lbl4.grid(row=0, column=0, padx=(5,
    0), pady=5)

# An entry for the property value of that
    material
self.prop_entry4 = ctk.CTkEntry(self.
    group_frame4, placeholder_text="Locations",
    width=160, height=40)
self.prop_entry4.grid(row=0, column=1, padx=5,
    pady=5)

# self.mat1_name = self.mat_lbl1.cget("text")
self.select_btn1 = ctk.CTkButton(self.
    mat_frame1, text="Select", fg_color="#ADC178
    ", hover=True,
                                    hover_color="
                                       #6C584C",
                                    command=self.
                                       select_material
                                       )
self.select_btn1.grid(row=6, column=0, padx=20,
     pady=10)

# ---------------------------------SECOND
    MATERIAL FRAME
    ----------------------------------------------------

self.mat_frame2 = ctk.CTkFrame(self, width=250,
     height=500)
self.mat_frame2.grid(row=1, column=1, padx=(25,
     25))

self.mat2_img = ctk.CTkImage(light_image=Image.
    open("images/concrete.png"),
                             dark_image=Image.
                                open("images/
                                concrete.png"),
```

```
                                        size=(128,
                                        128))
self.img2_btn = ctk.CTkButton(self.mat_frame2,
   fg_color="#F0EAD2", image=self.mat2_img,
   text="",
                                    state="disabled")
self.img2_btn.grid(row=0, column=0, padx=20,
   pady=20)

self.mat_lbl2 = ctk.CTkLabel(self.mat_frame2,
   text="Material 2", wraplength=200)
self.mat_lbl2.grid(row=1, column=0, padx=10,
   pady=(0, 20))

# create nested frames for each Label-Entry-
   Entry group
# 1st group
self.group2_frame1 = ctk.CTkFrame(self.
   mat_frame2, width=220, height=50)
self.group2_frame1.grid(row=2, column=0, padx
   =(10, 10), pady=(0, 5))

# Each group features a label with the name of
   the property
self.prop2_lbl1 = ctk.CTkLabel(self.
   group2_frame1, text="Embodied Carbon", width
   =60, height=40, wraplength=60,
                                    justify="center"
                                    )
self.prop2_lbl1.grid(row=0, column=0, padx=(5,
   0), pady=5)

# An entry for the property value of that
   material
self.prop2_entry1 = ctk.CTkEntry(self.
   group2_frame1, placeholder_text="EC in CO2e/
   kg", width=75, height=40)
self.prop2_entry1.grid(row=0, column=1, padx=5,
    pady=5)
```

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```
# And a percentage of deviation for that
   property compared to the input material
self.prop2_percent1 = ctk.CTkEntry(self.
   group2_frame1, placeholder_text="+/- %",
   width=75, height=40)
self.prop2_percent1.grid(row=0, column=2, padx
   =(0, 5), pady=5)

# 2nd group
self.group2_frame2 = ctk.CTkFrame(self.
   mat_frame2, width=220, height=50)
self.group2_frame2.grid(row=3, column=0, padx
   =(10, 10), pady=(0, 5))

# Each group features a label with the name of
   the property
self.prop2_lbl2 = ctk.CTkLabel(self.
   group2_frame2, text="Cost", width=60, height
   =40, wraplength=60,
                            justify="center"
                                )
self.prop2_lbl2.grid(row=0, column=0, padx=(5,
   0), pady=5)

# An entry for the property value of that
   material
self.prop2_entry2 = ctk.CTkEntry(self.
   group2_frame2, placeholder_text=" x    ",
   width=75, height=40)
self.prop2_entry2.grid(row=0, column=1, padx=5,
    pady=5)

# And a percentage of deviation for that
   property compared to the input material
self.prop2_percent2 = ctk.CTkEntry(self.
   group2_frame2, placeholder_text="+/- %",
   width=75, height=40)
self.prop2_percent2.grid(row=0, column=2, padx
   =(0, 5), pady=5)

# 3rd group
```

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```
self.group2_frame3 = ctk.CTkFrame(self.
    mat_frame2, width=220, height=50)
self.group2_frame3.grid(row=4, column=0, padx
    =(10, 10), pady=(0, 5))

# Each group features a label with the name of
    the property
self.prop2_lbl3 = ctk.CTkLabel(self.
    group2_frame3, text="Lifespan", width=60,
    height=40, wraplength=60,
                            justify="center"
                                )
self.prop2_lbl3.grid(row=0, column=0, padx=(5,
    0), pady=5)

# An entry for the property value of that
    material
self.prop2_entry3 = ctk.CTkEntry(self.
    group2_frame3, placeholder_text="Years",
    width=75, height=40)
self.prop2_entry3.grid(row=0, column=1, padx=5,
     pady=5)

# And a percentage of deviation for that
    property compared to the input material
self.prop2_percent3 = ctk.CTkEntry(self.
    group2_frame3, placeholder_text="+/- %",
    width=75, height=40)
self.prop2_percent3.grid(row=0, column=2, padx
    =(0, 5), pady=5)

# 4th group
self.group2_frame4 = ctk.CTkFrame(self.
    mat_frame2, width=220, height=50)
self.group2_frame4.grid(row=5, column=0, padx
    =(10, 10), pady=(0, 5))

# Each group features a label with the name of
    the property
self.prop2_lbl4 = ctk.CTkLabel(self.
    group2_frame4, text="Structural Location",
```

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```
    width=60, height=40,
                                    wraplength=60,
                                    justify="center"
                                       )
self.prop2_lbl4.grid(row=0, column=0, padx=(5,
    0), pady=5)

# An entry for the property value of that
    material
self.prop2_entry4 = ctk.CTkEntry(self.
    group2_frame4, placeholder_text="Locations",
     width=160, height=40)
self.prop2_entry4.grid(row=0, column=1, padx=5,
     pady=5)

# self.mat2_name = self.mat_lbl2.cget("text")
self.select_btn2 = ctk.CTkButton(self.
    mat_frame2, text="Select", fg_color="#ADC178
    ", hover=True,
                                     hover_color="
                                        #6C584C",
                                     command=self.
                                        select_material
                                        )
self.select_btn2.grid(row=6, column=0, padx=20,
     pady=10)

# ------------------------------THIRD MATERIAL
     FRAME
    ----------------------------------------------------

self.mat_frame3 = ctk.CTkFrame(self, width=250,
     height=500)
self.mat_frame3.grid(row=1, column=2, padx=(25,
     25))

self.mat3_img = ctk.CTkImage(light_image=Image.
    open("images/brick.png"),
                                dark_image=Image.
                                   open("images/
                                   brick.png"),
```

```
                                                    size=(128, 128)
                                                    )
self.img3_btn = ctk.CTkButton(self.mat_frame3,
   fg_color="#F0EAD2", image=self.mat3_img,
   text="",
                                                  state="disabled")
self.img3_btn.grid(row=0, column=0, padx=20,
   pady=20)

self.mat_lbl3 = ctk.CTkLabel(self.mat_frame3,
   text="Material 3", wraplength=200)
self.mat_lbl3.grid(row=1, column=0, padx=10,
   pady=(0, 20))

# create nested frames for each Label-Entry-
   Entry group
# 1st group
self.group3_frame1 = ctk.CTkFrame(self.
   mat_frame3, width=220, height=50)
self.group3_frame1.grid(row=2, column=0, padx
   =(10, 10), pady=(0, 5))

# Each group features a label with the name of
   the property
self.prop3_lbl1 = ctk.CTkLabel(self.
   group3_frame1, text="Embodied Carbon", width
   =60, height=40, wraplength=60,
                                                   justify="center"
                                                      )
self.prop3_lbl1.grid(row=0, column=0, padx=(5,
   0), pady=5)

# An entry for the property value of that
   material
self.prop3_entry1 = ctk.CTkEntry(self.
   group3_frame1, placeholder_text="EC in CO2e/
   kg", width=75, height=40)
self.prop3_entry1.grid(row=0, column=1, padx=5,
    pady=5)
```

```
# And a percentage of deviation for that
   property compared to the input material
self.prop3_percent1 = ctk.CTkEntry(self.
   group3_frame1, placeholder_text="+/- %",
   width=75, height=40)
self.prop3_percent1.grid(row=0, column=2, padx
   =(0, 5), pady=5)

# 2nd group
self.group3_frame2 = ctk.CTkFrame(self.
   mat_frame3, width=220, height=50)
self.group3_frame2.grid(row=3, column=0, padx
   =(10, 10), pady=(0, 5))

# Each group features a label with the name of
   the property
self.prop3_lbl2 = ctk.CTkLabel(self.
   group3_frame2, text="Cost", width=60, height
   =40, wraplength=60,
                            justify="center"
                              )
self.prop3_lbl2.grid(row=0, column=0, padx=(5,
   0), pady=5)

# An entry for the property value of that
   material
self.prop3_entry2 = ctk.CTkEntry(self.
   group3_frame2, placeholder_text=" x    ",
   width=75, height=40)
self.prop3_entry2.grid(row=0, column=1, padx=5,
    pady=5)

# And a percentage of deviation for that
   property compared to the input material
self.prop3_percent2 = ctk.CTkEntry(self.
   group3_frame2, placeholder_text="+/- %",
   width=75, height=40)
self.prop3_percent2.grid(row=0, column=2, padx
   =(0, 5), pady=5)

# 3rd group
```

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```
self.group3_frame3 = ctk.CTkFrame(self.
    mat_frame3, width=220, height=50)
self.group3_frame3.grid(row=4, column=0, padx
    =(10, 10), pady=(0, 5))

# Each group features a label with the name of
    the property
self.prop3_lbl3 = ctk.CTkLabel(self.
    group3_frame3, text="Lifespan", width=60,
    height=40, wraplength=60,
                            justify="center"
                                )
self.prop3_lbl3.grid(row=0, column=0, padx=(5,
    0), pady=5)

# An entry for the property value of that
    material
self.prop3_entry3 = ctk.CTkEntry(self.
    group3_frame3, placeholder_text="Years",
    width=75, height=40)
self.prop3_entry3.grid(row=0, column=1, padx=5,
     pady=5)

# And a percentage of deviation for that
    property compared to the input material
self.prop3_percent3 = ctk.CTkEntry(self.
    group3_frame3, placeholder_text="+/- %",
    width=75, height=40)
self.prop3_percent3.grid(row=0, column=2, padx
    =(0, 5), pady=5)

# 4th group
self.group3_frame4 = ctk.CTkFrame(self.
    mat_frame3, width=220, height=50)
self.group3_frame4.grid(row=5, column=0, padx
    =(10, 10), pady=(0, 5))

# Each group features a label with the name of
    the property
self.prop3_lbl4 = ctk.CTkLabel(self.
    group3_frame4, text="Structural Location",
```

```
            width=60, height=40,
                                            wraplength=60,
                                            justify="center"
                                               )
        self.prop3_lbl4.grid(row=0, column=0, padx=(5,
            0), pady=5)

        # An entry for the property value of that
            material
        self.prop3_entry4 = ctk.CTkEntry(self.
            group3_frame4, placeholder_text="Locations",
             width=160, height=40)
        self.prop3_entry4.grid(row=0, column=1, padx=5,
             pady=5)

        # self.mat3_name = self.mat_lbl3.cget("text")
        self.select_btn3 = ctk.CTkButton(self.
            mat_frame3, text="Select", fg_color="#ADC178
            ", hover=True,
                                              hover_color="
                                                 #6C584C",
                                              command=self.
                                                 select_material
                                                 )
        self.select_btn3.grid(row=6, column=0, padx=20,
             pady=10)

    def lowest_ec(self, matching_materials, database,
       recommendations):
        # assume filtered_materials is a list of
            materials filtered by the previous steps
        filtered_df = database[database['ICE DB Name'].
            isin(matching_materials)]

        # find the three smallest EC per kg values
        smallest_ec_df = filtered_df.nsmallest(3, 'EC
            per kg')
        # print(smallest_ec_df)
        # print(type(smallest_ec_df))

        for i in range(len(recommendations)):
```

```
            for j in range(1, len(smallest_ec_df.
               columns)):
                recommendations[i][j - 1] =
                   smallest_ec_df.iloc[i, j]
        print(recommendations)

    def lowest_ec_btn(self):
        self.lowest_ec(self.filtered_materials, self.
           database, self.recommendations)

    def update_parameters(self, recommendations,
       properties):
        input_list = [properties[2], properties[3],
           properties[4]]
        print("Reference parameters", input_list)
        print("Recommendations", recommendations)
        output_list = [[rec[1], rec[2], rec[3]] for rec
            in recommendations]
        print("Output parameters", output_list)
        percent_diff = []
        for i in range(len(input_list)):
            diff_list = []
            for j in range(len(output_list)):
                if output_list[j][i] >= input_list[i]:
                    diff = ((output_list[j][i] -
                       input_list[i]) / input_list[i])
                       * 100
                else:
                    diff = -1 * ((input_list[i] -
                       output_list[j][i]) / input_list[
                       i]) * 100
                diff_list.append(diff)
            percent_diff.append(diff_list)

        print(percent_diff)

        # Each iteration will fill up the entries for
           each of the material frames
        self.mat_lbl1.configure(text=str(
           recommendations[0][0]), wraplength=self.
           mat_lbl1.cget('wraplength'))  # name
```

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```
self.prop_entry1.insert('end', recommendations
   [0][1])  # embodied carbon
self.prop_percent1.insert('end', percent_diff
   [0][0])  # % ec
self.prop_entry2.insert('end', recommendations
   [0][2])  # cost
self.prop_percent2.insert('end', percent_diff
   [1][0])  # % cost
self.prop_entry3.insert('end', recommendations
   [0][3])  # life span
self.prop_percent3.insert('end', percent_diff
   [2][0])  # % life
self.prop_entry4.insert('end', recommendations
   [0][4])  # applications

self.mat_lbl2.configure(text=str(
   recommendations[1][0]), wraplength=self.
   mat_lbl2.cget('wraplength'))  # name
self.prop2_entry1.insert('end', recommendations
   [1][1])  # embodied carbon
self.prop2_percent1.insert('end', percent_diff
   [0][1])  # % ec
self.prop2_entry2.insert('end', recommendations
   [1][2])  # cost
self.prop2_percent2.insert('end', percent_diff
   [1][1])  # % cost
self.prop2_entry3.insert('end', recommendations
   [1][3])  # life span
self.prop2_percent3.insert('end', percent_diff
   [2][1])  # % life
self.prop2_entry4.insert('end', recommendations
   [1][4])  # applications

self.mat_lbl3.configure(text=str(
   recommendations[2][0]), wraplength=self.
   mat_lbl3.cget('wraplength'))  # name
self.prop3_entry1.insert('end', recommendations
   [2][1])  # embodied carbon
self.prop3_percent1.insert('end', percent_diff
   [0][2])  # % ec
```

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```
            self.prop3_entry2.insert('end', recommendations
               [2][2])  # cost
            self.prop3_percent2.insert('end', percent_diff
               [1][2])  # % cost
            self.prop3_entry3.insert('end', recommendations
               [2][3])  # life span
            self.prop3_percent3.insert('end', percent_diff
               [2][2])  # % life
            self.prop3_entry4.insert('end', recommendations
               [2][4])  # applications

        def upd_parm_btn(self):
            self.update_parameters(self.recommendations,
               self.properties)

        def select_material(self):  # name
            # print("You chose " + name)
            print("You made a choice, yay!")
```

C.8 Sub-Class: Results

```
    import customtkinter as ctk
    from PIL import Image


    class Result(ctk.CTkFrame):
        def __init__(self, master=None, app=None,
           recommendation=None, database=None):
            super().__init__(master)
            self.app = app
            self.recommendations = recommendation
            self.database = database

            self.label = ctk.CTkLabel(self, text="You
               selected the following material:",
                                      font=("Guidole
                                         Regular", 28),
                                         wraplength=500,
                                         justify="center")
```

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```
self.label.grid(row=0, column=0, padx=(200, 0),
     pady=(100, 20), sticky="nsew")

# create frame containing label-entry box
# pair 1
self.pair1_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair1_frame.grid(row=1, column=0)

self.box_label1 = ctk.CTkLabel(self.pair1_frame
    , text="Material Name", wraplength=60,
    justify="center")
self.box_label1.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry1 = ctk.CTkEntry(self.pair1_frame
    , placeholder_text="Material Name")
self.box_entry1.grid(row=0, column=1, padx=20,
    pady=20)

# pair 2
self.pair2_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair2_frame.grid(row=2, column=0)

self.box_label2 = ctk.CTkLabel(self.pair2_frame
    , text="Embodied Carbon", wraplength=60,
    justify="center")
self.box_label2.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry2 = ctk.CTkEntry(self.pair2_frame
    , placeholder_text="Value in CO2e/kg")
self.box_entry2.grid(row=0, column=1, padx=20,
    pady=20)

# pair 3
self.pair3_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair3_frame.grid(row=3, column=0)
```

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self.box_label3 = ctk.CTkLabel(self.pair3_frame
    , text="Material Cost", wraplength=60,
    justify="center")
self.box_label3.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry3 = ctk.CTkEntry(self.pair3_frame
    , placeholder_text="Value in     ")
self.box_entry3.grid(row=0, column=1, padx=20,
    pady=20)

# pair 4
self.pair4_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair4_frame.grid(row=4, column=0)

self.box_label4 = ctk.CTkLabel(self.pair4_frame
    , text="Material Lifespan", wraplength=60,
    justify="center")
self.box_label4.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry4 = ctk.CTkEntry(self.pair4_frame
    , placeholder_text="Value in Years")
self.box_entry4.grid(row=0, column=1, padx=20,
    pady=20)

# pair 5
self.pair5_frame = ctk.CTkFrame(self, width
    =500, height=50)
self.pair5_frame.grid(row=5, column=0)

self.box_label5 = ctk.CTkLabel(self.pair5_frame
    , text="Viable Applications", wraplength=60,
     justify="center")
self.box_label5.grid(row=0, column=0, padx=20,
    pady=20)

self.box_entry5 = ctk.CTkEntry(self.pair5_frame
    , placeholder_text="i.e., Facade, Walls, etc
    .")
```

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        self.box_entry5.grid(row=0, column=1, padx=20,
           pady=20)
```