Eric Veliyulin

ExploreLCA – A Web Application for Exploring Systematised Life Cycle Assessments of Buildings

Master's thesis in Informatics
Supervisor: Sobah Abbas Petersen
Co-supervisor: Christofer Skaar, Eirik Resch
June 2021

Master's thesis

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Abstract

This study presents ExploreLCA, a web application for exploring systematised life cycle assessments (LCAs) of buildings found in the building LCA database (bLCAd) tool.

The bLCAd tool is a MySQL database for systematically organising and storing LCAs of buildings. Systematised LCAs help facilitate statistical analyses and generate reliable embodied emissions figures, which are necessary for making reliable comparisons of emissions across buildings. In its current state, there is no way to browse through the different types of building data present in the bLCAd tool without having to manually write numerous SQL queries, either through a command line interface or via a dedicated tool – this might pose a challenge to practitioners that lack the required technical competence. This study explores how systematised LCA results found in the bLCAd tool can be made accessible through an interactive web application. In this context, *accessible* means both "easy to use", "easy to understand" and "easy to get access to".

The design science research methodology was used to design and develop ExploreLCA. The application was evaluated through usability testing, questionnaires and interviews, in which the participants consisted of 33 students from the MSc in Sustainable Architecture at NTNU, and one energy and environment advisor from the architectural firm Asplan Viak. Qualitative data derived from the evaluations was then further analysed using the grounded theory method. The application's success was measured using the two primary variables of the Technology Acceptance Model, *perceived usefulness* and *perceived ease of use*.

The results show that ExploreLCA has an overall high level of perceived usefulness and perceived ease of use, indicating that the systematised LCAs of buildings found in the bLCAd tool are made satisfactorily accessible. These results suggest that ExploreLCA shows promise as a valuable application for practitioners that wish to explore access systematised LCAs of buildings in an interactive and flexible manner.

Sammendrag

Denne studien presenterer ExploreLCA, en webapplikasjon for utforskning av systematiserte livssyklusanalyser (LCA) av bygninger funnet i building LCA database (bLCAd)-verktøyet.

bLCAd-verktøyet er en MySQL-database for systematisk organisering og lagring av LCA-er av bygninger. Systematiserte LCA-er hjelper med å legge til rette for statistiske analyser og generering av pålitelige utslippstall, som er nødvendige for å gjennomføre pålitelige sammenligninger av utslipp på tvers av bygninger. Per i dag finnes det ingen måte å bla gjennom de ulike typene bygningsdata som er tilstede i bLCAd-verktøyet uten å måtte manuelt skrive en rekke SQL-spørringer, enten gjennom et kommandolinjegrensesnitt eller via et dedikert verktøy – dette kan oppleves som en utfordring av brukere som mangler nødvendig teknisk kompetanse. Denne studien utforsker hvordan systematiserte LCA-resultater lagret i bLCAd-verktøyet kan tilgjengeliggjøres gjennom en interaktiv webapplikasjon. I denne sammenhengen betyr *tilgjengelig* både "enkel å bruke", "enkel å forstå" og "enkel å få tilgang til".

Design science research-metodikken ble brukt til å designe og utvikle ExploreLCA. Applikasjonen ble evaluert gjennom brukervennlighetstesting, spørreundersøkelser og intervjuer, der deltagerne besto av 33 studenter fra masterprogrammet i bærekraftig arkitektur ved NTNU, samt én energi- og miljørådgiver fra arkitektfirmaet Asplan Viak. Kvalitative data som ble utledet fra evalueringene ble videre analysert ved hjelp av grounded theory-metoden. Applikasjonens suksess ble målt ved hjelp av Technology Acceptance-modellen sine to hovedvariabler, *opplevd nytteverdi* og *opplevd brukervennlighet*.

Resultatene viser at ExploreLCA har et generelt høyt nivå av opplevd nytteverdi og opplevd brukervennlighet, noe som indikerer at de systematiserte LCA-ene av bygningene funnet i bLCAd-verktøyet blir gjort tilgjengelige på en tilfredsstillende måte. Disse resultatene tyder på at ExploreLCA virker som en lovende og verdifull applikasjon for brukere som ønsker å utforske og få tilgang til systematiserte LCA-er av bygninger på en interaktiv og fleksibel måte.

Preface

This thesis marks the completion of my Master's degree in Informatics at the Norwegian University of Science and Technology (NTNU). The project lasted from August 2020 until June 2021. The realisation of this project would not have been possible without the help of numerous people, all of whom I wish to acknowledge.

I want to start by thanking my supervisor, Sobah Abbas Petersen, for providing invaluable support, assistance and guidance throughout the entire duration of this project – I couldn't have made it without your help.

Furthermore, I want to thank my co-supervisors Christofer Skaar and Eirik Resch – you provided me with valuable knowledge and insight into the field of LCA and sustainability in buildings, both of which I was previously completely unfamiliar with. I would also like to extend a special thanks to Eirik for giving me an in-depth demonstration of the bLCAd tool, and for always being available to help in answering all of my questions.

Next, I would like to thank Émilie Chartrand from Asplan Viak, for participating in an early, but important round of evaluation – your feedback allowed me to make great progress, and helped shape the rest of this project.

I also wish to thank Luca Finocchiaro and Matteo Tagnocchetti from the Department of Architecture and Technology at NTNU for helping me arrange test sessions with students from the Sustainable Architecture masterprogramme. Moreover, I wish to thank the students themselves, for taking the time to participate in the test sessions, and for providing precious feedback that helped me complete this project.

Finally, I want to thank my friends and family for always believing in me, and for all the love and encouragement you have provided along the way.

Takk for meg!

Eric Veliyulin
Trondheim, 11.06.2021

Contents

Figures

Tables

Acronyms

AJAX Asynchronous JavaScript and XML

CO_2e Carbon Dioxide Equivalent

CSS Cascading Style Sheets

EPD Environmental Product Declaration

FME ZEN The Research Centre on Zero Emission Neighbourhoods in Smart Cities

GHG Greenhouse Gas

GWP Global Warming Potential

HTML HyperText Markup Language

HTTP HyperText Transfer Protocol

KPI Key Performance Indicator

LCA Life Cycle Assessment

SPA Single Page Application

SQL Structured Query Language

SUS System Usability Scale

TAM Technology Acceptance Model

ZEB Zero Emission Building

ZEN Zero Emission Neighbourhood

Chapter 1

Introduction

This chapter introduces the background for this project, before presenting the problem statement and motivation for conducting this research. The objectives and research questions that direct this thesis are then formulated, followed by a review of the thesis structure, containing short descriptions of the chapters to come.

1.1 Background

The building sector is currently one of the biggest contributing sectors when it comes to global greenhouse gas (GHG) emissions [1]. In modern buildings, processes such as material production, material replacement, and material transportation make up a significant fraction of a building's total GHG emissions – these processes are collectively known as embodied emissions. In order to better quantify and evaluate a building's embodied emissions, the life cycle assessment (LCA) methodology is often used [2]. LCA means systematically mapping and assessing the environmental impacts of a product, or a building, throughout its entire lifecycle – this is achieved by dividing the environmental impacts into distinct lifecycle stages according to the European standard EN 15978 [3].

Because conducting a complete LCA study of a building produces large amounts of difficult-to-interpret data, studies are often reported with low resolution, and with little or no details about system boundaries, calculation methods, and other parameters. This makes it difficult to use the results for any further statistical applications, which in turn reduces the usefulness of the LCAs [2].

In an attempt to mitigate the challenges related to conducting LCAs at full resolution, a database tool for systematically organising and storing previously conducted building LCAs, called the building LCA database (bLCAd) tool, was developed by Resch and Andresen [4]. The bLCAd tool systematises a building's embodied emissions by organising it as a hierarchical set of building elements, themselves consisting of specific building materials, whose emissions are then further broken down into distinct lifecycle stages. By storing building LCAs using this approach, the tool is able to produce consistent, systematic data, which can help facilitate statistical analyses and generation of reliable embodied emissions figures.

1.2 Problem Statement and Motivation

As of today, the bLCAd tool contains the systematised life cycle assessments of 20 different building projects. With a growing dataset, the tool has potential to be valuable for establishing benchmarks, which can help practitioners in the planning stages of new projects. A practitioner, in this case, is someone who works in the field of architecture and sustainability.

But, in order to benefit from the LCA studies stored in the bLCAd tool, one must first be able to access them. Currently, the only way to access data from the tool is by directly connecting to the SQL database, either through a command line interface, or via a dedicated tool like MySQL Workbench[1]. One must then write custom SQL queries in order to access the specific pieces of data that one wishes to retrieve. As such, there is currently no way to explore or browse through different types of building data without having to write numerous queries – something that a potential practitioner might find challenging, should they not have the necessary technical skills. I want to propose a solution to this problem, by creating a web application that will allow users to explore and access systematised LCAs stored in the bLCAd tool in an interactive and flexible manner.

1.3 Objectives

The primary objective of this thesis is to explore how one can make systematised LCA results found in the bLCAd tool accessible through a web application – *accessible*, in this case, means both "easy to use", "easy to understand" and "easy to get access to". The next objective is to find out how a user might want to use such an application by identifying usage scenarios for it, as well as what elements such an application should include in order to be useful and easy to use. The final objective is to find out what effect such an application might have on its users' awareness and understanding of sustainability in buildings.

To accomplish these objectives, a web application called ExploreLCA has been developed. ExploreLCA connects to the bLCAd tool, and can be used to browse through and visualise data from the different building LCA studies found in the tool.

[1]MySQL Workbench: `https://www.mysql.com/products/workbench/`

1.4 Research Questions

With the aforementioned objectives in mind, and with regard to ExploreLCA, a set of research questions have been formulated to direct the thesis:

RQ1 How can systematised life cycle assessments of buildings be made accessible through a web application?

- **(a)** What are the usage scenarios for such an application?
- **(b)** What elements should be included in such an application?

RQ2 What effect would a web application for exploring systematised life cycle assessments of buildings have on its users' awareness of sustainability in buildings?

1.5 Thesis Structure

The thesis is structured as follows.

Chapter 2 - Theoretical Background

Describes the theoretical background for the project, which mainly consists of related academic papers, literature, and projects. The chapter concludes with a summary of the reviewed theory, and presents the research gaps that have been identified.

Chapter 3 - Research Method

Addresses the various research methods, theories, and models that were used throughout this project.

Chapter 4 - Implementation of ExploreLCA

Presents the web application developed in conjunction with this thesis, including the design choices made, the tools and libraries used for building it, the application architecture, and an overview of its functionality and features.

Chapter 5 - Evaluation of ExploreLCA

Describes the studies that were conducted in order to evaluate ExploreLCA. The participants of each study are presented, and the methods and activities that were used are described in detail.

Chapter 6 - Results

Presents the results from the evaluations that were conducted during this project. The results are separated into three distinct parts, and are structured after the evaluation studies that they belong to.

Chapter 7 - Discussion

Includes an interpretation and a discussion of the results with regard to the research questions, as well as an elaboration of the limitations of the study.

Chapter 8 - Conclusion

Concludes the thesis and presents recommendations for further work.

Chapter 2

Theoretical Background

This chapter presents the theoretical background for this project, and provides the context for the rest of the thesis. The chapter concludes with a summary of the reviewed theory, and presents the research gaps that have been identified.

The theory is mainly based on related academic papers and literature, which were procured through recommendations from supervisors and individuals working on FME ZEN projects. Additionally, some literature was obtained through informal searches in search engines like Google Scholar, Oria, and NTNU Open, using relevant keywords such as *LCA*, *building*, *bLCAd*, *web application*, *interface* and *usability*.

2.1 Sustainability in Buildings

The building sector is one of the biggest contributing sectors when it comes to global greenhouse gas (GHG) emissions [1]. Operational energy use in existing buildings has traditionally been the main cause for the sector's high emissions, but during recent years, developments in the area of renewable energy technologies and energy efficiency have helped push the operational emissions of new buildings towards zero [4]. With a reduction in operational emissions, the relative contribution that the embodied emissions of a building make to its total emissions becomes all the more significant. *Embodied emissions* is a term that encompasses all processes related to the construction and maintenance of a building, including the production of building materials, transportation of materials to the construction site, replacement of materials throughout the building's lifetime and end-of-life processes [5].

2.1.1 Life Cycle Assessment

In order to estimate a building's lifecycle impact on climate change, the life cycle assessment (LCA) methodology is normally used, with global warming potential (GWP) in terms of $kgCO_2e$ being the unit of measure [6]. The European standard EN 15978 [3] provides a calculation method for LCA, and describes specific lifecycle stages into which a building's embodied emissions can be divided. A full life cycle assessment contains numerous stages – as such, only a selection will be described here:

- Stages A1-A3 represent the emissions for material production from cradle-to-gate, meaning from resource extraction (cradle) to the factory gate (i.e. before it is transported to the consumer) [7].
- A4 represents the transportation of the materials from the factory to the building site
- B4 represents the replacement of materials throughout a building's lifetime. In a paper by Resch *et al.* [2], this stage is further divided into two sub-stages:
    - B4m is production of replacement materials
    - B4t is transportation of replacement materials

2.1.2 Environmental Product Declaration

In order to get information about the environmental impact of individual building parts and materials, Environmental Product Declarations (EPDs) are used. An EPD is a short document that summarises the environmental profile of a component, product or service in a standardised and objective manner [8]. An EPD consists of quantified environmental information on the lifecycle of a product, thus allowing for comparisons between products that perform the same function [9].

2.2 Building LCA Database

To conduct a useful assessment of a building's embodied emissions, it is important that its emission results are reported with a high resolution and that there is sufficient information on the study design and parameter values. This information can help identify which factors in the building affect the GWP impact, whether it be design and construction choices or the study design itself. With enough details, one can also use the results for comparisons and statistical applications across different buildings. Unfortunately, many LCA studies of buildings provide lacking or inadequate documentation, with study results being mostly reported with low resolution, and without necessary details about system boundaries, calculation methods or other information [10].

In an attempt to mitigate these challenges, Resch and Andresen [4] developed the building LCA database (bLCAd) tool, a relational MySQL database designed to store results from existing, as well as calculate new, building LCAs. The bLCAd tool systematises embodied emission assessments of buildings by organising buildings as a hierarchical set of building elements, themselves consisting of specific materials, according to the Norwegian standard NS 3451 [11] – the hierarchical structure can be seen in Figure 2.1. This allows for a high-resolution breakdown of a building's embodied emissions. The emissions are further separated into distinct lifecycle stages according to the European standard EN 15978 [3]. By storing building LCAs using this approach, the tool is able to produce consistent, systematic data, which can help facilitate statistical analyses and generation of reliable embodied emissions figures [4].

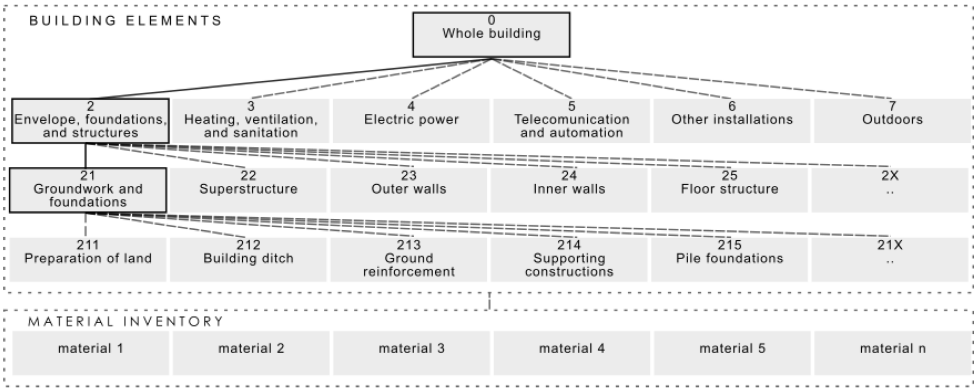


Figure 2.1: The hierarchical structure of building elements in the bLCAd tool, and the associated material inventory. The outlined building elements are expanded to show their sub-elements, and the inventory items are associated with specific building elements. From Resch and Andresen [4, p. 5].

The bLCAd tool currently contains data from 20 different building projects – six of these are from FME ZEN and ZEB (see Section 2.3), while 14 are from various other sources. Table 2.1 shows an overview of all the buildings currently included in the bLCAd tool.

2.3 FME ZEN

The Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) [12] develops solutions for future buildings and neighbourhoods with no GHG emissions, with the aim of contributing to a low carbon society. A variety of stakeholders, including researchers, municipalities, industry and governmental organisations, collaborate in order to plan, develop and run neighbourhoods with zero emissions. A neighbourhood, in the context of ZEN, is defined as a group of interconnected buildings with associated infrastructure, located within a confined geographical area [13]. FME ZEN currently develops nine test areas, or pilot projects, which are spread all over Norway. Two buildings from the Ydalir pilot project in Elverum are part of the bLCAd tool's dataset.

2.3.1 ZEB

FME ZEN is the successor of the Research Centre on Zero Emission Buildings (ZEB) [14]. Similarly to the ZEN definition, a zero emission building is defined as a building that produces enough renewable energy to compensate for the building's

Table 2.1: Buildings currently included in the bLCAd tool

Name	**Typology**	**Construction**	**Location**	**HFA (m^2)**	**Study year**
Papirbredden II	Office	Concrete	Drammen, Norway	8536	2012
ZEB SFH Concept	Residential	Concrete	n/a, Norway	160	2013
ZEB Office Concept	Office	Concrete	Oslo, Norway	1980	2013
ZEB Living Lab	Residential	Timber	Trondheim, Norway	102	2014
ZEB Multikomfort	Residential	Timber	Larvik, Norway	202	2014
A14 Bjørvika	Office	Concrete	Oslo, Norway	4291	2014
Råstølen sykehjem*	Nursing home	Timber/Concrete	Bergen, Norway	8076	2014
NTNU Gjøvik	University	Concrete	Gjøvik, Norway	5052	2016
Østensjø skole	School	Concrete	Oslo, Norway	3629	2017
Prinsdal skole	School	Timber	Oslo, Norway	1215	2017
Powerhouse Telemark	Office	Concrete	Porsgrunn, Norway	7908	2017
Flesberg skole	School	Concrete	Flesberg, Norway	6664	2018
Flesberg skole sv.hall.	Swimming hall	Concrete	Flesberg, Norway	2344	2018
Eufemia B7 Vestbygg	Apartment block	Concrete	Oslo, Norway	8330	2018
Ydalir kindegarten	Kindergarten	Timber	Elverum, Norway	2140	2019
Ydalir school	School	Timber	Elverum, Norway	6474	2019
Eufemia B7 Sørbygg	Apartment block	Concrete	Oslo, Norway	5616	2019

*four alternative designs

greenhouse gas emissions over its life span. Four buildings in the bLCAd tool's dataset are from ZEB – the buildings consist of a mix of both residential and office type buildings.

2.4 Web Applications

A web application, according to Sturm *et al.* [15], is a software program that is stored on a remote server and uses web technologies (e.g., JavaScript, HTML, CSS) and web browsers to deliver one or more functions for the end user over a network through a browser client. Many modern web applications are so-called single page applications (SPAs) – applications that consist of only one HTML web page, whose content gets dynamically updated using JavaScript. One of the fundamental building blocks of an SPA is AJAX (Asynchronous JavaScript and XML), a technique that makes it possible to dynamically and asynchronously load resources from a remote server without blocking the user interface. By using AJAX, an SPA never has to be refreshed or reloaded, and the user interface remains responsive even while data is read from or sent to a web server. This is in contrast with traditional web pages, which require a full reload when a user interaction triggers any form of fetching of data from a web server [16].

One of the main benefits of web applications is that they are accessible from any type of device or operating system that has a web browser, with no installation required – a web application is platform agnostic [16]. Development and support costs are therefore reduced, as the need to build software compatible with specific types of computers or specific operating systems is eliminated. There is also no need to routinely upgrade the software in order to maintain compatibility with operating system updates [15].

There are a number of unique aspects related to web application development which bring inherent challenges when it comes to building secure applications. Improper coding can introduce a host of security vulnerabilities, which can make a web application susceptible to attacks like SQL injection and cross-site scripting (XSS) [17]. SQL injection is the placement of malicious code into an SQL query via a field or input on a web page, which is then accepted by the web application and sent to the backend database. This can allow an attacker to view, change and delete contents of the database. XSS is another type of injection, in which an attacker sends malicious scripts to a user's browser for execution [18].

Web applications have become more sophisticated and powerful over the years, and this has made the line between desktop applications and web applications more blurred. While taking precautions to avoid the aforementioned security risks, one can quickly develop and publish good looking and accessible web applications, using the help from the numerous frameworks, libraries and cloud platforms that are available [15][19].

2.5 Interactive Learning

One of the goals of this project is to measure the effect that a web application for exploring systematised building LCAs can have on its users' awareness of sustainability in buildings. According Deniz [20], environmental awareness can be increased through education, or learning. As such, some theory must be provided on how one's learning can be augmented with the use of an interactive system such as a web application.

According to Barker [21, p. 27], interactive learning based upon the use of computer-based technologies is "rapidly becoming an important mechanism of knowledge and skill transfer within many different areas of human activity". He states that interactive learning is a necessary and fundamental technique for knowledge acquisition and the development of both cognitive and physical skills. In a study about the interactivity effect in multimedia learning by Evans and Gibbons [22], the authors conclude that interactive systems can facilitate deep learning, or understanding, by actively engaging the learner who is using the system. In another study by Sims [23], it is stated that in order to assure the success of functional and effective instructional applications, one must focus on three types of design – instructional design, graphic design, and communication design. By keeping these forms of design in mind, one can implement interactions that do a better job at motivating and engaging the learner.

2.6 Related Projects

Through the literature that was acquired, a number of projects related to FME ZEN and visualisation of building LCAs were discovered, both of which are relevant themes for this project. The following subsections cover some of these projects.

2.6.1 ZEB Tool

A method for calculating the embodied emissions of materials in buildings, later known as the *ZEB tool*, was initially developed by Wiberg *et al.* [24] in the period from 2010 to 2015. The ZEB tool has been further developed by a number of contributors since then, including students from the Sustainable Architecture master-programme at the Norwegian University of Science and Technology (NTNU), as well as other ZEB researchers.

The ZEB tool is a Microsoft Excel-based spreadsheet, and one of its key features is the organisation of building components (or building elements) as separate linked sheets using specific codes according to Norwegian standard NS 3451 [11]. The ZEB tool was used to calculate the emission data of the six ZEN/ZEB related buildings present in the bLCAd tool's dataset.

2.6.2 ZENVR

As part of their master's thesis, Løvhaug and Mathisen [25] developed a virtual reality application for visualising key performance indicators (KPIs) in ZENs. The virtual reality application, called ZENVR, connects to the bLCAd tool and uses it as a data source for the KPIs. Using ZENVR, one can explore 3D models of a set of predetermined buildings in different scales in a virtual reality environment. Emission data and other KPIs can be visualised in different formats, including more traditional formats such as numbers, colours and columns, but also with representations of the emissions in the form of 3D models of planes and cars. The goal of ZENVR is to communicate and contextualise ZEN KPIs to a diverse set of stakeholders, in order to improve their engagement and participation in ZEN projects.

Through evaluations, Løvhaug and Mathisen [25] conclude that professionals with a background in architecture prefer traditional visualisation approaches, such as columns, colours and numbers, when accessing KPI related data.

2.6.3 Visual LCA in ZENs

For their master's thesis, Slåke and Auklend [26] developed a proof of concept dashboard that connects to the ZEB tool (see Section 2.6.1) and uses the material inventory from the ZEB Living Lab to create various neighbourhood configurations using a parametric script. Using the dashboard, one can control and change the configurations, material choices and material quantities in the neighbourhood, and receive visual representations of the GHG emissions tied to it. The visual representations consist of interactive graphs and 3D models, in addition to an interactive map that shows the transport routes of the materials used.

In their thesis, Slåke and Auklend [26] emphasise the importance of making data related to the environmental impact of building materials accessible and understandable through transparent and interactive visualisations, stating that untrained architects and planners can feel alienated by the sheer amount of data available. As such, they strongly recommend including interactive functionality when designing dashboards for displaying large and complicated datasets.

2.7 Summary

The theory reviewed in this chapter has provided insight into how the LCA methodology is used to calculate a building's embodied emissions, and how the bLCAd tool systematically stores and organises LCA studies to facilitate statistical analyses and generation of reliable embodied emissions figures. Additionally, FME ZEN and ZEB are presented and related to the bLCAd tool's dataset. Furthermore,the benefits and challenges associated with web applications are described, and insight is provided into how a web application as an interactive system can be used to augment a user's learning and knowledge acquisition. Finally, the related projects that are presented describe previous attempts at visualising data present in the bLCAd tool through interactive systems.

As of now, the only interactive system that directly connects to the bLCAd tool is the virtual reality application ZENVR, by Løvhaug and Mathisen [25]. While it manages to make data from LCAs of buildings visually accessible, the fact that one must have access to dedicated virtual reality equipment in order to use it is a hindrance when it comes to the overall accessibility of the application. Furthermore, ZENVR only contains a small subset of the buildings available in the bLCAd tool, and requires developers to manually import 3D models of other buildings in order to be scalable.

One can therefore conclude that there is currently no way to access all of the systematised LCAs found in the bLCAd tool in an interactive manner. This indicates the existence of a research gap, which the first research question of this thesis aims to address:

RQ1 *How can systematised life cycle assessments of buildings be made accessible through a web application?*

Similarly, while it is shown that interactive systems can increase learning, and that learning can increase awareness, there are currently no studies that show what effect an interactive application dedicated to exploring systematised LCAs of buildings can have on its users' awareness of sustainability in buildings. This research gap is addressed by the second research question:

RQ2 *What effect would a web application for exploring systematised life cycle assessments of buildings have on its users' awareness of sustainability in buildings?*

Chapter 3

Research Method

This chapter addresses the various research methods, theories, and models that were used throughout this project.

3.1 Design Science Research

Design science research is a research paradigm with the end-goal of contributing new knowledge to the scientific field by means of creating innovative artifacts, which serve the purpose of providing answers or solutions related to one or several human problems. The fundamental principle of design science research, according to Hevner, is that “knowledge and understanding of a design problem and its solution are acquired in the building and application of an artifact” [27, p. 5].

3.1.1 Three Cycle View

Design science research can be seen as the execution of three closely connected activity cycles, as seen in Figure 3.1. Hevner claims that these cycles must be present and clearly identifiable in a design science research project [28].

Relevance Cycle

The *Relevance Cycle* is the initiator of design science research, and it is in this cycle that the application context is defined. The context includes the requirements for the research, such as the opportunities or problems that the research aims to solve, as well as acceptance criteria for the concluding evaluation of the research results. Questions such as "Does the design artifact improve the environment?" and "How can this improvement be measured?" should be in focus during this cycle. The result from the design science research (design cycle) must continuously be returned into the environment in order to ascertain its continued relevance, by means of field testing and evaluation of the result in the application context. Depending on the results of the field testing, one can determine whether additional iterations of the relevance cycle are required for a given design science research project.

Rigor Cycle

The *Rigor Cycle* connects past knowledge and research to the design science activities. The knowledge base consists of established scientific theories and engineering methods, as well as the experiences and expertise that determine the state of the art in the application domain. Existing artifacts, products and processes in the application domain are also an integral part of this knowledge base. The aim of the rigor cycle is to make sure that the designs that are produced by the research are actual research contributions, and not only routine designs.

Design Cycle

The *Design Cycle* is considered to be the heart of design science research. In this cycle, one iterates quickly between the construction of an artifact, the evaluation of said artifact, and the ensuing feedback to refine and improve the design further. According to Simon [29], the nature of this cycle is to generate design alternatives and to evaluate the alternatives against requirements until a satisfactory design is achieved. The requirements come from the aforementioned relevance cycle, and the design and evaluation theories and methods come from the rigor cycle. Thus, one can see how the three cycles are closely connected and dependent on each other in the process of design science research.

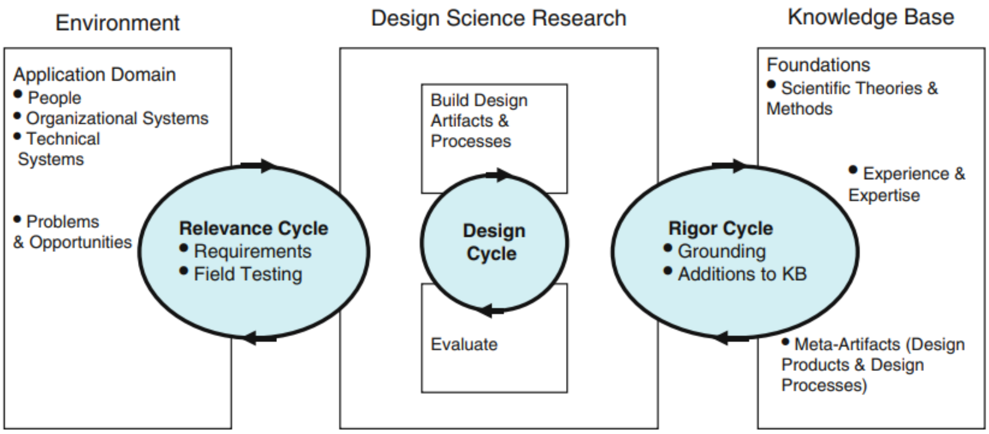


Figure 3.1: Hevner's Design science research cycles, from Hevner and Chatterjee [27, p. 16]

3.1.2 Checklist

In an MIS Quarterly paper by Hevner *et al.* [30], seven guidelines for conducting top quality design science research are presented – a summarised version of them can be found in Table 3.1. The aim of these guidelines is to help give researchers, reviewers, editors and readers an understanding of the requirements for effective design science research.

In order to more easily assess progress on design science research projects, Hevner has compiled a set of questions, based on the seven guidelines, that serve as a useful checklist to ensure that the work done addresses the key aspects of design science research [27]. Table 3.2 shows the questions from the checklist, along with answers that are applicable for this project. Figure 3.2 shows the relationship of the checklist questions with the three design science research cycles by mapping each question to the appropriate cycle.

Table 3.1: Seven guidelines for design science research, from Hevner *et al.* [30, p. 83]

Guideline		Description
1.	Design as an Artifact	Design science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation
2.	Problem relevance	The objective of design science research is to develop technology-based solutions to important and relevant business problems
3.	Design evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods
4.	Research contributions	Effective design science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies
5.	Research rigor	Design science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact
6.	Design as a search process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment
7.	Communication of research	Design science research must be presented effectively to both technology-oriented and management-oriented audiences

3.2 Interviews

Throughout the duration of the project, interviews were used as a research method for both gathering preliminary data, and for evaluating the application developed in conjunction with the project. According to Brinkmann and Kvale [35], qualitative interviews are a "key venue" for discovering and understanding a subject's point of view and experiences. It's a powerful tool for producing knowledge about a particular topic, and it lets the subject describe their experiences and opinions

Table 3.2: Checklist for design science research by Hevner and Chatterjee [27, p. 20], applied to this project

	Questions	Answers
1.	What are the research questions (design requirements)?	The research questions are described in Section 1.4.
2.	What is the artifact? How is the artifact represented?	The artifact is ExploreLCA, a web application for exploring and visualising systematised LCAs of buildings.
3.	What design processes (search heuristics) will be used to build the artifact?	The artifact will be built by studying existing examples of similar artifacts, and by researching the capabilities of the bLCAd tool, as well as existing examples of its usage.
4.	How are the artifact and the design processes grounded by the knowledge base? What, if any, theories support the artifact design and the design process?	The design processes are grounded by the following theories: • Technology Acceptance Model [31] • Nielsen's ten usability heuristics [32] • System Usability Scale [33] • Grounded Theory Method [34]
5.	What evaluations are performed during the internal design cycles? What design improvements are identified during each design cycle?	The evaluations in the internal design cycles consist of biweekly demos during unstructured expert interviews. The design improvements that are identified include additions and modifications to functionality and the interface.
6.	How is the artifact introduced into the application environment and how is it field tested? What metrics are used to demonstrate artifact utility and improvement over previous artifacts?	The artifact is field tested by means of usability testing, a questionnaire and interviews. The metrics that demonstrate the artifact's utility are *perceived ease of use* and *perceived usefulness*, along with the effect it has on one's awareness of sustainability in buildings.
7.	What new knowledge is added to the knowledge base and in what form (e.g., peer-reviewed literature, meta-artifacts, new theory, new method)?	This thesis is the main contribution to the knowledge base, along with the source code for the developed web application.
8.	Have the research questions been satisfactorily addressed?	Yes, as described in Chapter 7.

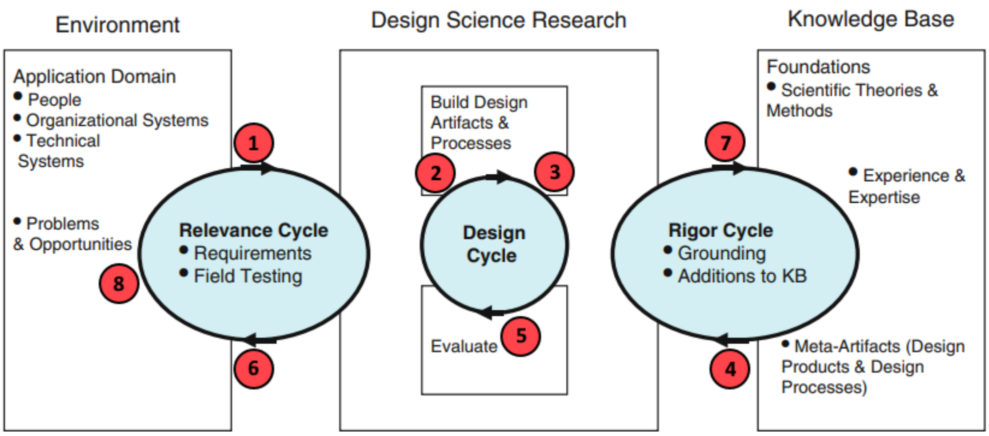


Figure 3.2: Checklist questions from Table 3.2 mapped to the three design research cycles

in their own words.

3.2.1 Supervisor Meetings

Meetings with my supervisor and two co-supervisors were held every other week in the first few months of the project period. One of the co-supervisors was Christofer Skaar, who is a key researcher at FME ZEN. The other co-supervisor was Eirik Resch, who is a researcher at the Department of Architecture and Technology at NTNU, and the creator of the bLCAd tool. During these meetings, they provided ideas and requirements for what they wanted to see from the project.

They idea of creating a web-based user interface was proposed, with the requirement that it should be able to connect to at least one existing tool or application related to building LCAs, such as SimaPro[1], openLCA[2], or the bLCAd tool. Another idea that was proposed was to create a tool that enabled interoperability across different LCA tools, to make communication and data transferal between different systems more seamless. Because the creator of the bLCAd tool was involved as a co-supervisor, it was agreed upon that the initial focus should be on developing a web interface that would only connect to the bLCAd tool to begin with. As the project progressed, the focus eventually shifted away from supporting interoperability across multiple tools, and creating a web application for accessing data from the bLCAd tool became the main priority.

Unstructured Expert Interviews

The biweekly supervisor meetings were conducted in a way that can be likened to unstructured interviews. An unstructured interview is a type of interview in which the person being interviewed is both the source of questions and the source

[1] SimaPro: `https://simapro.com/`
[2] openLCA: `https://www.openlca.org/`

of answers. The interviewer does not know the form of the information they seek in advance, and the questions are therefore often open-ended. This lets the interviewer draw out as much information as possible on a broadly defined topic from the interviewee [36]. Zhang and Wildemuth [37] note that unstructured interviews can be especially useful for studies that deal with information system design and implementation.

The unstructured interviews can also be seen as expert interviews. In this research project, an expert is defined as an individual with an education or profession relevant to the field of interest. As such, both of the aforementioned co-supervisors can be seen as experts in the context of this project. According to Bogner *et al.* [38], "expert interviews can serve to establish an initial orientation in a field that is either substantively new or poorly defined, as a way of helping the researcher to develop a clearer idea of the problem". The first few interviews were focused on gathering insight and knowledge about the field of sustainable buildings and neighbourhoods – this helped provide a better understanding of what kind of research contribution could be made with this project. As the research scope narrowed down and the focus of the project turned to the development of ExploreLCA, the biweekly expert interviews became more structured in nature. Both open-ended and specific questions, such as "what functionality do you think is missing?" and "what should the default option be for this dropdown?", were asked about design choices concerning ExploreLCA.

By having biweekly interviews, the application, or artifact, was continuously evaluated against the requirements set in the relevance cycle of design science research – this presented opportunities for quickly identifying design improvements, and was one of the main evaluation methods in this project's design cycles. The interviews were also a way to ascertain the artifact's continued relevance in the application domain, as per the relevance cycle of design science research.

3.3 Technology Acceptance Model

The Technology Acceptance Model (TAM), originally presented by Davis [31], is a popular model for predicting the acceptance and use of information systems and technologies. TAM presents two primary variables that influence a user's intention to adopt and use new technology: *perceived usefulness* and *perceived ease of use*. Perceived usefulness is defined by Davis [39] as "the degree to which a person believes that using a particular system would enhance his or her job performance". Perceived ease of use, on the other hand, is defined as "the degree to which a person believes that using a particular system would be free of effort".

In order to determine if the application developed in conjunction with this project had the potential to be adopted and used by actual users, evaluations were performed to specifically measure perceived usefulness and perceived ease of use. Both of these aspects were evaluated using methods such as heuristic evaluation (Section 3.4), interviews (Section 3.2), usability testing (Section 3.5) and questionnaires (Section 5.4). *Behavioural intention to use* was also directly evaluated through interviews and questionnaires, to see if it correlated with the results from the evaluations of the other two variables.

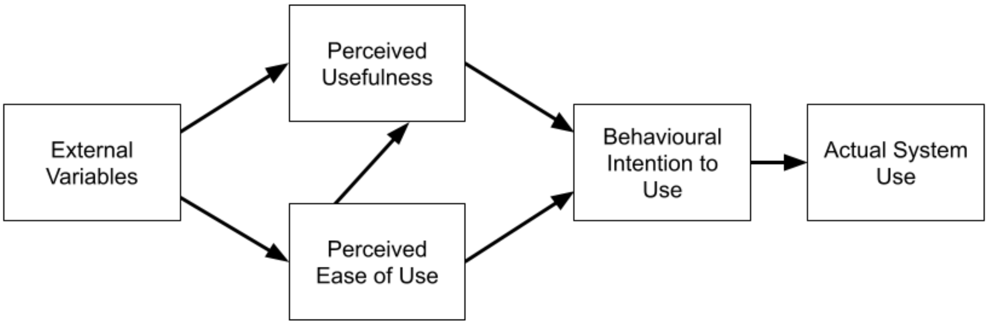


Figure 3.3: Technology Acceptance Model, from Venkatesh and Davis [40, p. 453]

3.4 Heuristic Evaluation

Jakob Nielsen's ten usability heuristics [32] are general principles that cover the most important aspects of designing a good user interface. These heuristics can be used for evaluating a user interface design, and can help identify potential usability issues with it [41]. The ten heuristics are presented in Table 3.3.

For every iteration of the design cycle, the application was evaluated against the usability heuristics. This was to ensure that the design choices that were made were grounded in scientific theory.

3.5 Usability Testing

Usability testing is a popular research methodology in the domain of user experience and interface design. With the help of usability testing, one can identify problems in the design of the interface, uncover opportunities to improve and learn about the target users' behaviour and preferences [42].

3.5.1 Test Users

According to Nielsen [43], test users should be as representative as possible of the intended users of the system. It is especially important to not choose test users from outlier groups if only a small number of test users are to participate in the usability testing. On the other hand, if a larger number of test users are to participate in usability testing, they should be selected from several different subpopulations to cover the main different categories of expected users.

Table 3.3: Nielsen's ten usability heuristics, from Nielsen [32]

Heuristic		Description
#1	Visibility of system status	The design should always keep users informed about what is going on, through appropriate feedback within a reasonable amount of time.
#2	Match between system and the real world	The design should speak the users' language. Use words, phrases, and concepts familiar to the user, rather than internal jargon. Follow real-world conventions, making information appear in a natural and logical order.
#3	User control and freedom	Users often perform actions by mistake. They need a clearly marked "emergency exit" to leave the unwanted action without having to go through an extended process.
#4	Consistency and standards	Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform and industry conventions.
#5	Error prevention	Good error messages are important, but the best designs carefully prevent problems from occurring in the first place. Either eliminate error-prone conditions, or check for them and present users with a confirmation option before they commit to the action.
#6	Recognition rather than recall	Minimize the user's memory load by making elements, actions, and options visible. The user should not have to remember information from one part of the interface to another.
#7	Flexibility and efficiency of use	Shortcuts – hidden from novice users – may speed up the interaction for the expert user such that the design can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.
#8	Aesthetic and minimalist design	Interfaces should not contain information which is irrelevant or rarely needed. Every extra unit of information in an interface competes with the relevant units of information and diminishes their relative visibility.
#9	Help users recognize, diagnose, and recover from errors	Error messages should be expressed in plain language (no error codes), precisely indicate the problem, and constructively suggest a solution.
#10	Help and documentation	It's best if the system doesn't need any additional explanation. However, it may be necessary to provide documentation to help users understand how to complete their tasks.

3.5.2 Test Tasks

Similarly, test tasks should be chosen to be as representative as possible of the scenarios in which the application will be put to use in the field. The tasks should also take care to cover the most significant aspects of the user interface. A test task should be small enough that it can be completed in a reasonable amount of time, but not so small that it becomes trivial. Finally, test tasks should specify a precise result or goal that the user has to achieve, i.e. not loosely defined instructions such as "play around with this setting" [43].

3.5.3 Thinking Aloud

Thinking aloud is a method that involves having a user test a system while continuously thinking aloud [44]. When test users verbalise their thoughts, they give us the opportunity to better understand their view of the application being tested. This helps us with identifying major misconceptions that the user might have – since the thinking-aloud method shows how the user interprets each individual element of the interface, we can more easily pinpoint what parts of the system cause the most problems. According to Nielsen [43], "thinking aloud may be the single most valuable usability engineering method".

3.6 System Usability Scale

As shown by the Technology Acceptance Model in Figure 3.3, perceived ease of use, or usability, is one of the main factors for user adoption of new technology. In order to quantify the perceived usability of ExploreLCA, the System Usability Scale (SUS) was used.

SUS [33] is a ten-item Likert scale that gives a general view of an individual's subjective impression of a system's usability. Each item in the scale has five response options, ranging from *Strongly agree* to *Strongly disagree*. Using the responses, one can calculate a SUS score which represents the overall usability of the system being evaluated. The score is calculated by summing the score contributions from each item – the score contribution for the odd-numbered items is the scale position minus 1, while for the even-numbered items it's 5 minus the scale position. The sum of the scores is then multiplied with 2.5 so that the score is a number out of 100.

A SUS score can be hard to interpret by itself, and it should therefore be measured by comparing it to a standard, such as an industry average [45]. Using data from over "10,000 responses and hundreds of products", Sauro [46] has developed a set of metrics that can help with interpreting a SUS score. After calculating a SUS score, one can see what adjective and grade letter it corresponds to using Figure 3.4. Furthermore, Sauro [47] specifies that the average SUS score is 68, meaning that anything above 68 would be considered above average, while anything below 68 would be considered below average.

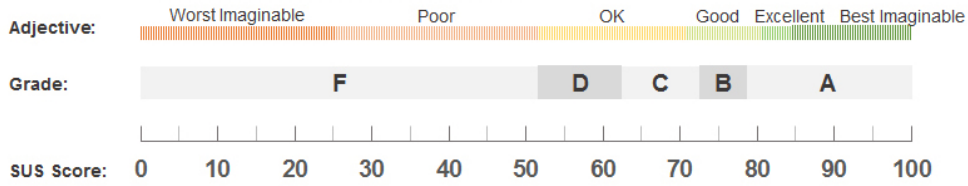


Figure 3.4: SUS scores with corresponding adjectives and grades, from Sauro [46]

3.7 Grounded Theory Method

In order to systematically analyse qualitative data derived from evaluations, three coding techniques from the grounded theory method were used: open coding, axial coding and selective coding [34].

3.7.1 Open Coding

The initial process of grounded theory is often the technique known as open coding, in which raw data is analysed, broken up into discrete parts and labeled with a code. The codes act as conceptual labels, so that conceptually similar pieces of data are grouped together to form categories and sub-categories. In order to create meaningful codes, the different pieces of data are continuously compared and contrasted with each other so that one might find similarities and differences between them.

The coding process involves being able to think abstractly - labels shouldn't necessarily just be phrases taken from the raw data. According to Corbin and Strauss [48], "coding requires searching for the right word or two that best describe conceptually what the researcher believes is indicated by the data".

3.7.2 Axial Coding

Axial coding is the process of drawing connections between codes generated during open coding. Codes and their underlying data are analysed and grouped into categories. A category can be be directly based on an existing code, or be more abstract in nature so that it encompasses a variety of different codes. The relationships between categories and their sub-categories are continuously tested against the underlying data, to ensure that any new piece of data or code is assigned to an adequate category or sub-category.

3.7.3 Selective Coding

Selective coding is normally the last step in grounded theory. In this process, all code categories are unified around a core category. This core category can emerge from one of the categories generated in the axial coding stage, or it can be a more abstract term needed to encompass all the different codes and categories. The point of selective coding is to identify the main analytic idea presented in the research. This in turn can be used to define one unified theory about the research.

Chapter 4

Implementation of ExploreLCA

This chapter presents ExploreLCA, the web application that was developed in conjunction with this thesis. ExploreLCA lets users explore and visualise data from all of the LCA studies found in the bLCAd tool by Resch and Andresen [4]. All aspects of the application are reviewed in detail, including the design choices made, the tools and libraries used for building it, the application architecture, and an overview of its functionality and features.

The source code of ExploreLCA is available on GitHub, along with a README file with instructions on how to set up and run the project on your own computer. The Git repository can be found at `https://github.com/ericvel/explore-lca`.

Finally, a short user guide for ExploreLCA can be found in Appendix E.

4.1 Design Choices

The design choices for ExploreLCA were influenced by several factors: the unstructured expert interviews with my co-supervisors helped decide the initial direction for the application's functionality, as described in Section 3.2.1. At the same time, Nielsen's ten usability heuristics [32] were used to make design choices concerning the application's usability. Table 4.1a and Table 4.1b show how each of Nielsen's heuristics were taken into consideration when making design choices for the usability of ExploreLCA. Finally, the results from the evaluations helped shape design choices for both the functionality and the usability of the application, as presented in Chapter 6.

4.2 Tools and Libraries

A number of tools, libraries and packages were used when developing ExploreLCA. The following subsections cover each of them briefly.

(a) Usability heuristics #1 to #5

Heuristic		**Application in ExploreLCA**
#1	Visibility of system status	• When a view, table or chart is waiting to receive data to display, loading indicators, such as spinners and skeleton placeholders, are displayed to the user. • Every interactable element provides visual feedback when interacted with, both for hover and click events.
#2	Match between system and the real world	• Terminology used throughout the application is plain and straightforward. • Architecture related terms are based on existing literature.
#3	User control and freedom	• The building element navigation has a breadcrumb trail, in addition to back and forward buttons, so the user can easily undo one or more unintended selections. • The Edit material dialog contains a cancel button, in case the user misclicks, or changes their mind.
#4	Consistency and standards	• Orange is used to depict all elements related to Edit mode. This includes the Edit mode switch, edited material fields in both table and chart display mode, as well as the total building emission labels when a material has been edited. • The help button is placed in the top-right of the main view, to follow Material Design and industry conventions.
#5	Error prevention	• It's only possible to edit materials when grouping them by product. To stop the user from editing in one of the other groupings, the "Group by" dropdown is restricted to the *Product* option as a helpful constraint.

Table 4.1: Nielsen's ten usability heuristics [32] and how they've been applied in the design of ExploreLCA.

(b) Usability heuristics #6 to #10

Heuristic		**Application in ExploreLCA**
#6	Recognition rather than recall	• In order to minimise the user's memory load, all of the main features of the application are visible at all times. Labels provide context and help make every interactable element easily recognisable.
#7	Flexibility and efficiency of use	• The vertical divider that splits the application into two views (building overview table and details view) can be dragged left or right to adjust the width of each view, allowing the user to customise the layout according to their preferences.
#8	Aesthetic and minimalist design	• Since the application is focused on delivering a limited set of features, clutter is reduced and a minimalist design is achieved. • By almost exclusively using components from the Material-UI library, the application achieves a cohesive aesthetic.
#9	Help users recognize, diagnose, and recover from errors	• If a user attempts to log in with either a wrong email address or a wrong password, they are presented with an appropriate error message. • If the application for some reason cannot reach the building LCA database, a red error alert is displayed at the bottom of the screen to let them know. The alert serves the purpose of informing them that the error is beyond their control.
#10	Help and documentation	• All interactable elements without a text label display a tooltip when hovered. • A documentation dialog can be accessed by clicking the Help button. The documentation includes a short guide of how to use the main features of the application, as well as a list of terminology for certain architecture related terms.

Table 4.1: *Continued*

4.2.1 React

React[1] was used as the base for building ExploreLCA. React is an open-source JavaScript library that allows you to build component-based user interfaces. Each React component maintains its own "state", i.e. property values that belong to the component, and the user interface dynamically updates itself to match this state whenever it is changed.

4.2.2 Material-UI

Instead of building React components from scratch, the Material-UI[2] component library was utilised. Material-UI is a UI framework based on Material Design[3], and includes many React components that, when put together, can create more aesthetically pleasing and accessible applications.

4.2.3 DevExtreme

A set of responsive and customisable UI components from DevExtreme[4] and DevExtreme Reactive[5] were used to create the charts and tables present throughout the application – specifically React Charts and React Grid.

4.2.4 Redux

In order to more easily manage the React state in ExploreLCA, the JavaScript library Redux[6] was implemented. Redux is a so-called *predictable state container* that centralises and manages an application's state and logic. By using Redux, the state of the application can be accessed by any component that needs it from anywhere in the code. This makes it easier for different components in a React application to communicate with one another.

4.2.5 Firebase

Firebase[7] is an application development platform by Google that offers a variety of useful services and tools that integrate well with both mobile and web applications. ExploreLCA uses Firebase Authentication for managing and authenticating its users, and Cloud Firestore as a NoSQL database for storing data related to edited building materials. Firebase Authentication supports many different authentication methods, including passwords, phone numbers and popular federated

[1] React: `https://reactjs.org/`
[2] Material-UI: `https://material-ui.com/`
[3] Material Design: `https://material.io/`
[4] DevExtreme: `https://js.devexpress.com/`
[5] DevExtreme Reactive: `https://devexpress.github.io/devextreme-reactive/`
[6] Redux: `https://redux.js.org/`
[7] Firebase: `https://firebase.google.com/`

identity providers like Google, Facebook and Twitter, making it a flexible alternative. Cloud Firestore, on the other hand, allows you to store and structure data with varying amounts of complexity in a logical and flexible way.

4.3 Application Architecture

ExploreLCA relies on several sub-modules in order to work, each with its own function. These modules consist of three different Firebase services, in addition to a MySQL instance hosted on Google Cloud Platform. The following subsections cover the Cloud Function and Cloud SQL modules in greater detail – Firebase Authentication and Cloud Firestore are omitted, as they are already covered in Section 4.2.5. A diagram of the application architecture can be seen in Figure 4.1, in which the relationship between the different modules is presented.

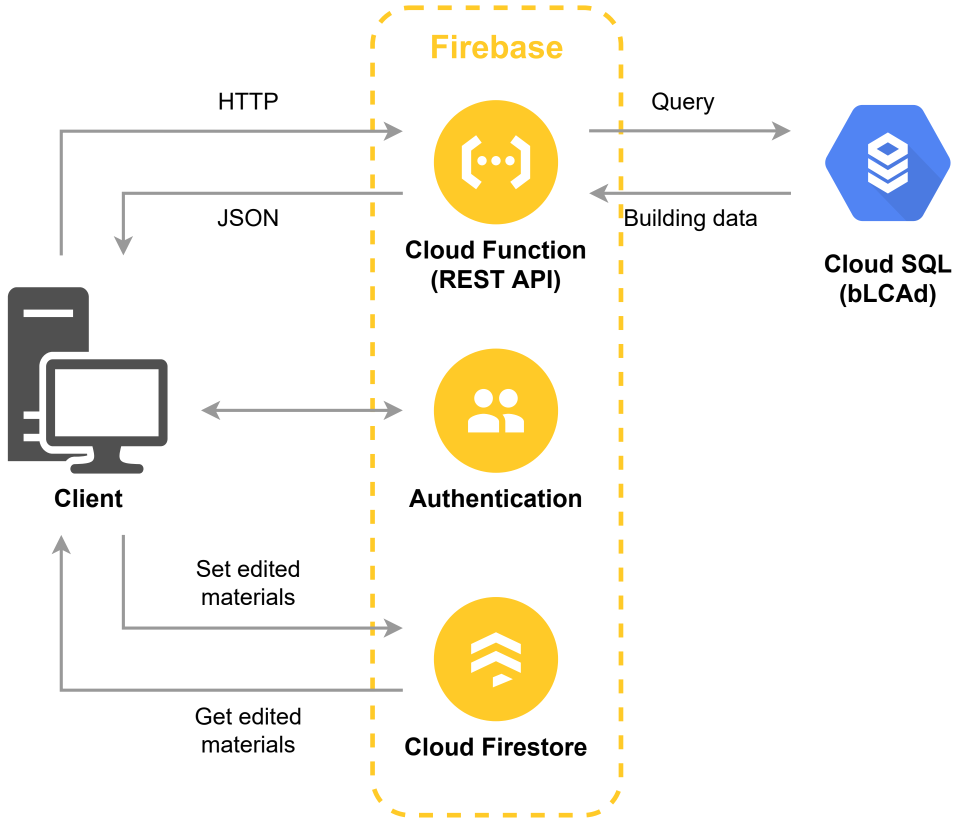


Figure 4.1: Application architecture of ExploreLCA

4.3.1 Cloud SQL

In order for ExploreLCA to be able to access the bLCAd tool from anywhere, the database had to be hosted from a remotely available location. Since ExploreLCA already uses services from the Google ecosystem in the form of Firebase, Google Cloud Platform[8] seemed like a natural choice. Cloud SQL[9] is a fully managed relational database service available through Google Cloud Platform, and supports hosting MySQL databases, making it a great fit for hosting the bLCAd tool. The database accepts SQL queries, such as "SELECT * FROM buildings", and returns data that matches the query – the previous example would return all the rows from the "buildings" table.

4.3.2 Cloud Functions

A Cloud Function hosted on Firebase is used as a REST API, or Representational State Transfer Application Programming Interface, and serves the purpose of transferring data between the client and the Cloud SQL database. Cloud Functions is a serverless framework that lets you run backend code in response to events triggered by external actions, such as HTTP requests.

The Cloud Function used in ExploreLCA is built using Node.js[10] and Express.js[11] – Node.js is an open-source JavaScript runtime environment and is often used for building backend services, while Express.js is a small web framework for Node.js that simplifies building APIs thanks to a variety of included utility methods and middleware.

The Cloud Function is triggered by HTTP GET requests, and uses the information from the requests to create SQL queries for the Cloud SQL database. The Cloud SQL database then returns matching data to the Cloud Function, which in turn sends it as a response to the client in JSON format.

Three types of queries are currently used in ExploreLCA:

- Get all buildings
- Get building elements of a specified building
- Get material inventory of a specified building

4.4 Components

The following subsections cover each of the main interface components, or features, present in ExploreLCA.

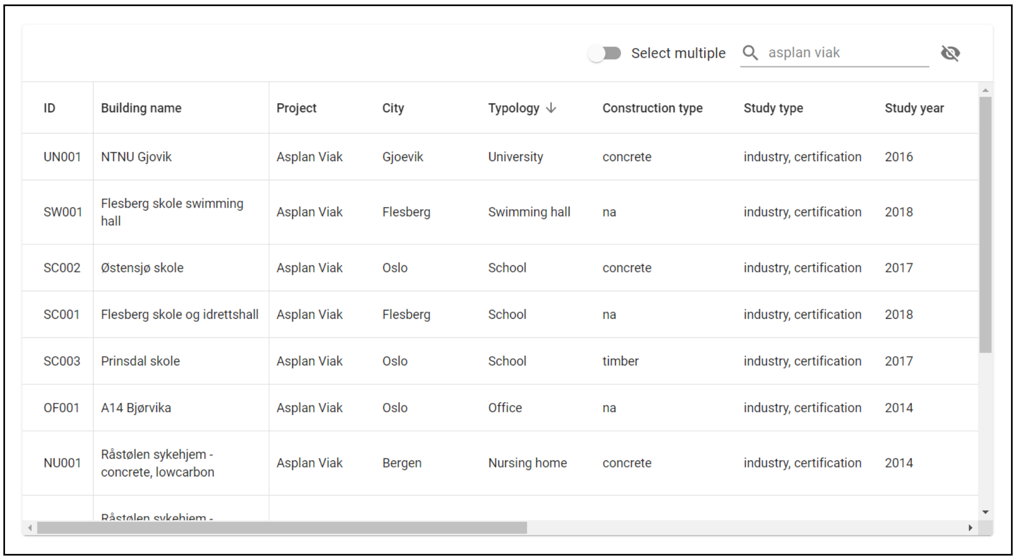
4.4.1 Building Overview Table

The first thing the user is presented with when accessing the application is an interactive table containing all the buildings present in the bLCAd tool. The table has sortable columns, a search field that lets you search for data in any column,

[8]Google Cloud Platform: https://cloud.google.com/
[9]Cloud SQL: https://cloud.google.com/sql
[10]Node.js: https://nodejs.org/en/
[11]Express.js: https://expressjs.com/

and an option that lets you show or hide specific columns – only some of the available columns are shown by default.

The table contains a lot of information on each building, including its typology, geographical location, construction type, floor area, embodied emissions for different lifecycle modules and more. A building can be selected by clicking on its table row – this populates the Building Details View with additional information on the selected building, see Section 4.4.2. The table also contains a switch that, when activated, allows the user to select multiple buildings that they want to compare, see Section 4.4.5.


Select multiple asplan viak

ID	Building name	Project	City	Typology ↓	Construction type	Study type	Study year
UN001	NTNU Gjovik	Asplan Viak	Gjoevik	University	concrete	industry, certification	2016
SW001	Flesberg skole swimming hall	Asplan Viak	Flesberg	Swimming hall	na	industry, certification	2018
SC002	Østensjø skole	Asplan Viak	Oslo	School	concrete	industry, certification	2017
SC001	Flesberg skole og idrettshall	Asplan Viak	Flesberg	School	na	industry, certification	2018
SC003	Prinsdal skole	Asplan Viak	Oslo	School	timber	industry, certification	2017
OF001	A14 Bjørvika	Asplan Viak	Oslo	Office	na	industry, certification	2014
NU001	Råstølen sykehjem - concrete, lowcarbon	Asplan Viak	Bergen	Nursing home	concrete	industry, certification	2014
	Råstølen sykehjem -						

Figure 4.2: Building Overview Table, showing results for the search query "*asplan viak*" sorted by typology in descending order

4.4.2 Details View

The details view shows additional details about a selected building, and consists of three sub-components:

- **General info**
  Displays a selection of key information about the building.
- **Embodied emissions chart**
  Shows the total embodied emissions of the building as a bar chart, with each bar representing an LCA module. If the user hovers their cursor above a bar, the exact value of the LCA module is shown in a tooltip. By clicking on the settings wheel, the user can toggle the metric settings for the chart – *per* m^2 is activated by default.
- **Material view**
  See Section 4.4.3.

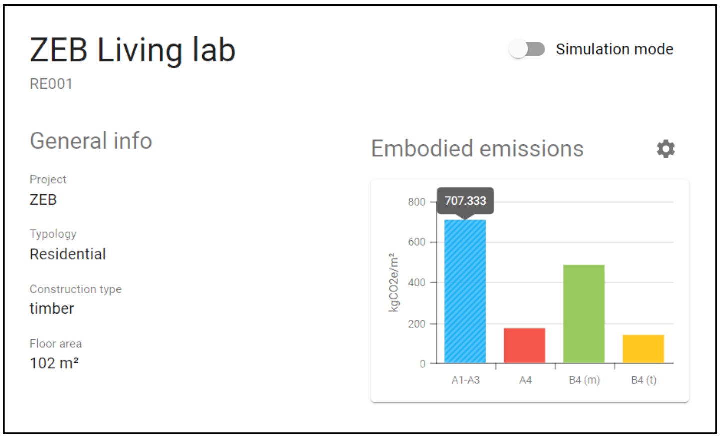


Figure 4.3: Details View (excluding Material View), with cursor hovering over chart to show exact value of the A4 module

4.4.3 Material View

The material view is the main sub-component of the details view, and contains detailed information about the materials and building elements that a building consists of, presented in an interactive and customisable format. The user can browse through materials by grouping them in one of three different ways using a drop-down menu, and the data can be displayed in either a table or a bar chart format using radio buttons. Similarly to the building overview table mentioned in Section 4.4.1, the material tables also include sortable columns, a search field that lets you search for data in any column, and an option that lets you show or hide specific columns. When viewing materials using the chart display mode, they are automatically sorted by their total embodied emissions in descending order.

Group by Product

The default grouping option is *Group by Product*. If there are multiple inventory entries of a specific material product present in a building, they are grouped together and their emissions and quantities are summed. When in table display mode, the user can click on the expand arrow of a material product to see all of its individual inventory entries, including which building element the inventory entries appear in.

When in chart display mode, the material products are simply represented by their embodied emission values, sorted descendingly.

Group by Building Element

All material inventory entries in a building are tied to a specific building element. Building elements are organised in a hierarchical manner, and their emission values are calculated as the sum of their sub-elements' emission values. By grouping

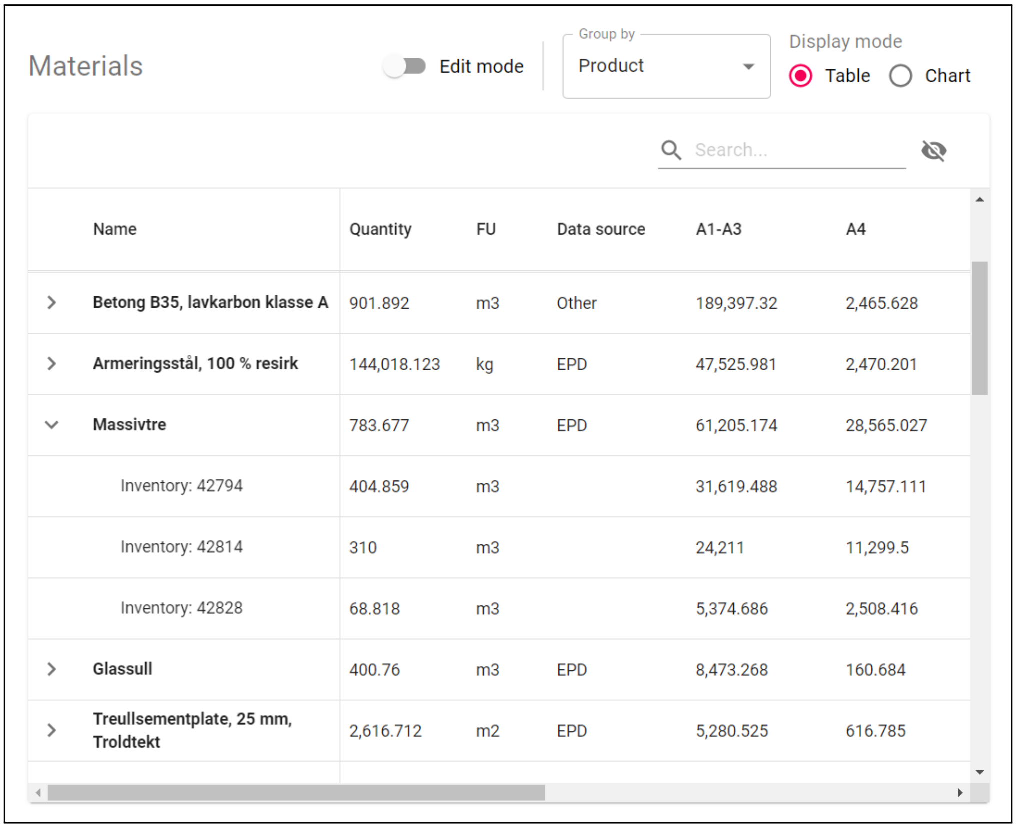


Figure 4.4: Material view, grouped by product and in table display mode. "Massivtre" has been expanded and shows the three inventory entries under it.

materials by building element, the user can browse through different levels of the building element hierarchy and observe the different emission values at each level.

To select a building element and navigate down to its sub-elements, the user can click on the element's row in table display mode, or click on the element's bar in chart display mode. To assist the user in navigating through the elements, back and forward buttons are displayed, along with an interactive breadcrumb trail that displays the currently selected building element and the elements preceding it hierarchically. When the user navigates to a building element's last level, the material inventory entries associated with that element are displayed.

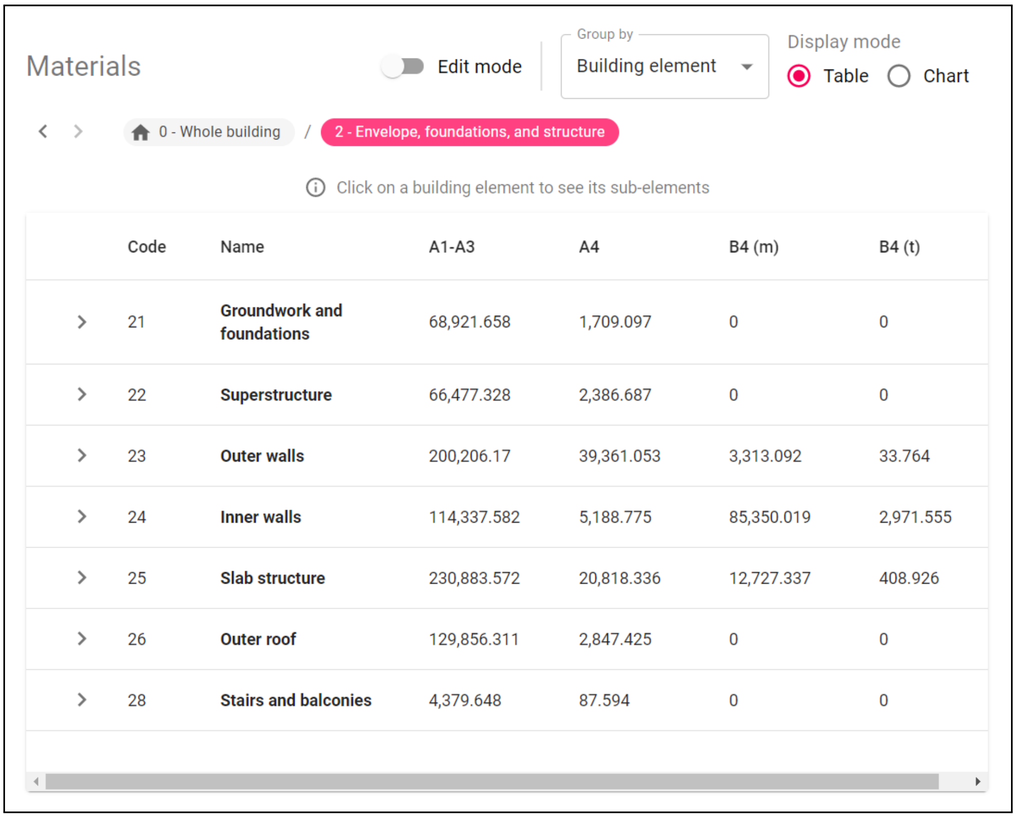


Figure 4.5: Material view, grouped by building element and in table display mode. The user is browsing the sub-elements of the building element "Envelope, foundations and structure".

Group by Category

When grouping by category, material inventory entries are first grouped by product, and then by their material category (e.g. *steel*, *concrete*, *wood*). In table display mode, the user can click on a category row to expand it and see what material products are under it. Chart display mode works similarly – when the user clicks on a bar representing a material category, bars representing the materials under it are displayed.

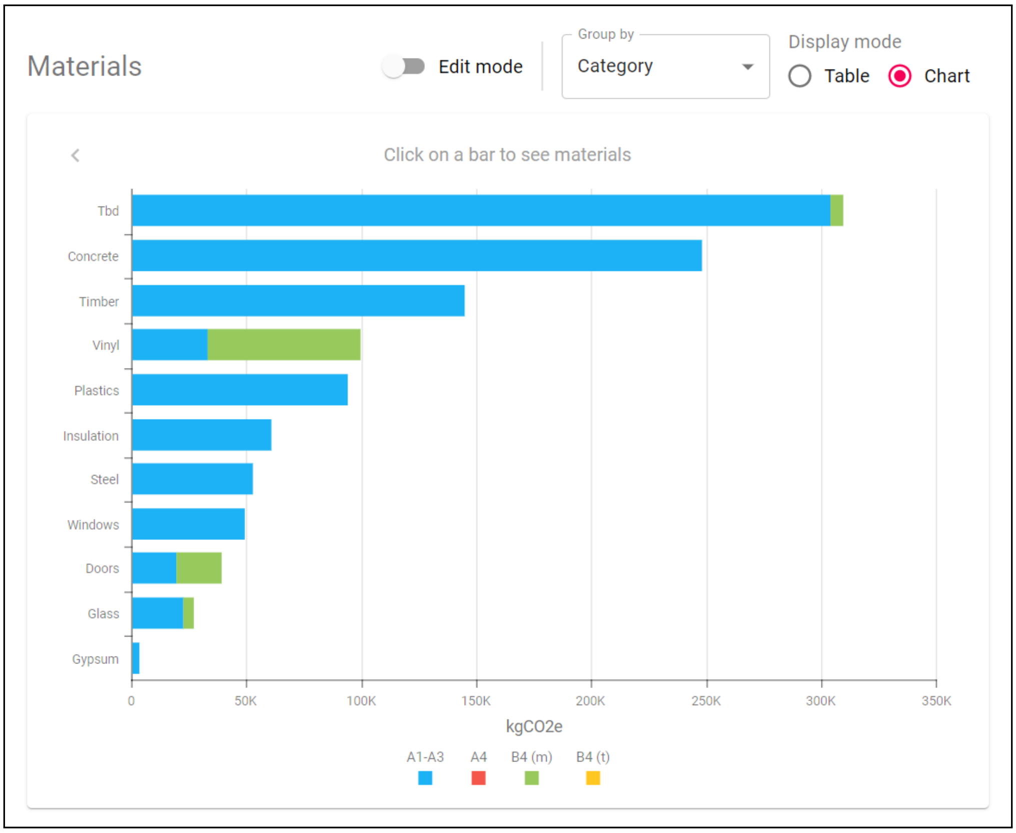
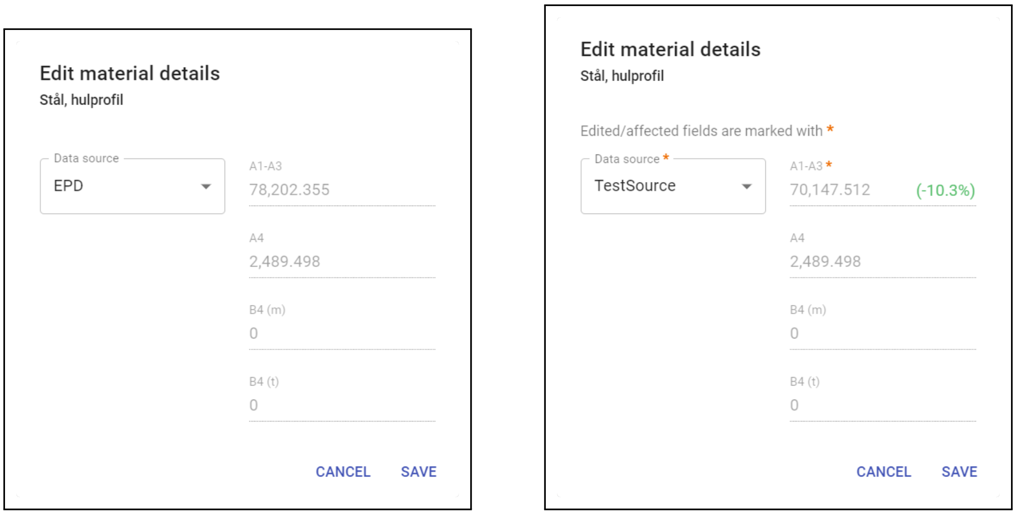


Figure 4.6: Material view, grouped by category and in chart display mode

4.4.4 Edit Mode

Edit mode can be activated by toggling the *Edit mode* switch in the material view. This automatically sets the grouping option to *Group by Product*, and displays an edit button next to each material product row. When the user clicks on a material product's edit button, a dialog for editing the material pops up (see Figure 4.7). The user can edit the source for the material's emission data to see if other data sources produce different emission numbers. By clicking *Save*, the changes in data source and emission data are applied to the material view and details view – affected fields in the product table, product chart and total embodied emissions chart are marked in a bold, orange font.

Material modifications saved in Edit mode don't actually affect the original data in the bLCAd tool, as they are stored separately from each other. When the user deactivates Edit mode by re-toggling the switch, all the original data is loaded back into the material view and details view.



(a) Default data source is selected

(b) Data source is changed to "TestSource"

Figure 4.7: Edit material dialog. By changing the data source from "EPD" to "Test-Source", one can observe a decrease in emissions of the A1-A3 module.

4.4.5 Compare Buildings View

The user can toggle the *Select multiple* switch in the building overview table to display checkboxes next to each building row. This allows them to select multiple buildings at once, and populates the details view with a bar chart that displays the total embodied emissions of selected buildings. By clicking on the settings wheel, the user can toggle the metric settings for the chart – *per m*^{2} is activated by default.

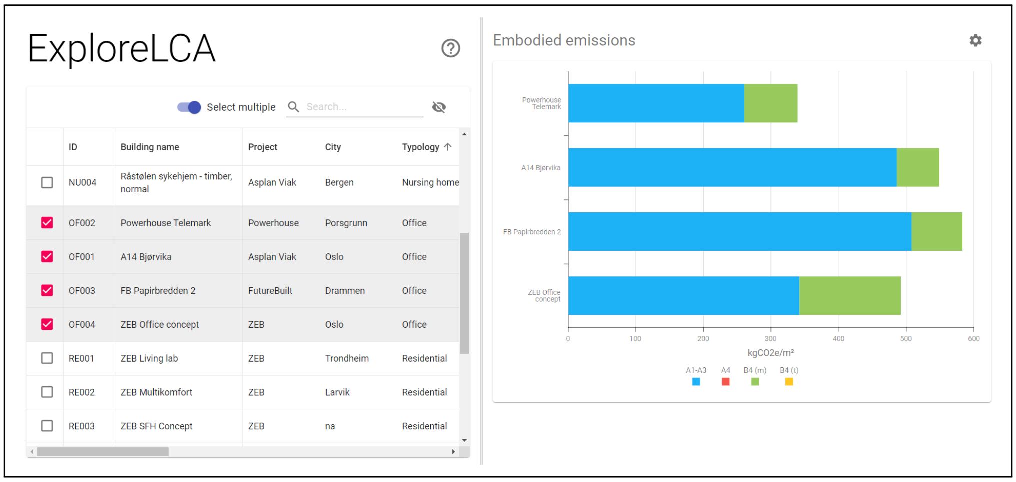


Figure 4.8: Comparison of the total embodied emissions of four office buildings

4.4.6 Other Features

Sign in Page

To limit unauthorised users' access to potentially confidential building data, a sign in page has been implemented. Currently, the registration of new users is only possible through the Firebase Console.

Figure 4.9: Sign in page

Help Button

A help dialog can be displayed by pressing the *Help* button next to the application title. The dialog contains a simple "How to use" guide, and a list of terminology used throughout the app, with their definitions.

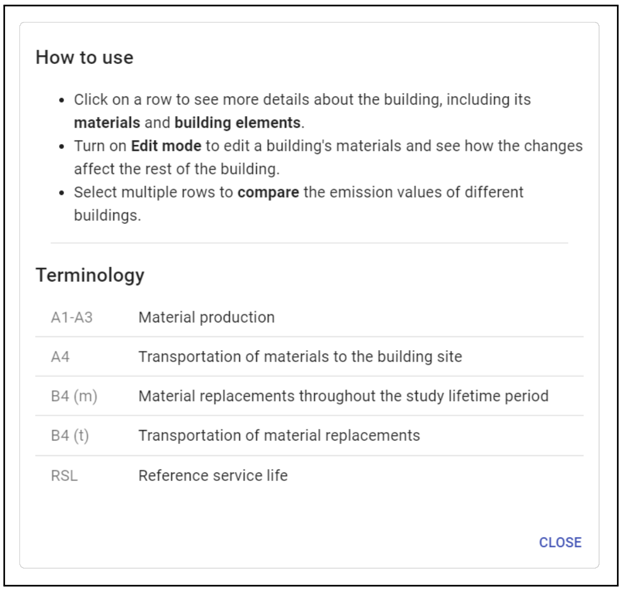


Figure 4.10: Help dialog

Chapter 5

Evaluation of ExploreLCA

This chapter describes the studies that were conducted in order to evaluate ExploreLCA. The participants of each study are presented, and the methods and activities that were used are described in detail.

5.1 Introduction

Two separate studies were conducted to evaluate ExploreLCA – one with an energy and environment advisor from the architectural firm Asplan Viak, and one with students from the Sustainable Architecture masterprogramme at NTNU. There was a period of eight weeks between each study, during which no significant modifications were done to ExploreLCA. Although both studies involved a form of usability testing, a questionnaire, and follow-up discussions, there were some variations in evaluation activities to accommodate for the differences in number of participants.

The following sections describe each of these evaluation studies:

- Section 5.2 describes the evaluation with the energy and environment advisor (expert evaluation)
- Section 5.3 describes the evaluation with the Sustainable Architecture students (student evaluation)

Since the questionnaires presented in each study had many elements in common, they are covered together in Section 5.4.

5.2 Expert Evaluation

The first study was conducted with one participant: Émilie Chartrand, an energy and environment advisor from Asplan Viak. The study consisted of a usability test session (as described in Section 3.5), a questionnaire (as described in Section 5.4) and a semi-structured interview.

5.2.1 Usability Testing

The usability test session consisted of a short presentation of the project, followed by 20 minutes of testing the application. The participant was presented with one test task at a time, and they were asked to continuously think aloud as they attempted to complete the tasks. After the participant had completed the tasks, a short discussion was held to gather initial feedback. The test tasks chosen for the usability testing can be found in Appendix B.

5.2.2 Semi-structured Interview

A semi-structured interview was held with the participant after they had concluded a round of usability testing. According to Seaman [36], semi-structured interviews consist of a mix between open-ended and specific questions. This allows the interviewer to bring forth both expected pieces of information, but also unforeseen types of information.

The questions asked during the interview were focused on the interviewee's thoughts and opinions about the current state of the application, as well as what ideas or wishes they had for future improvements and additions to its functionality. As suggested by Seaman [36], the questions asked were both open-ended and specific, e.g. "what other uses do you think this kind of application could have?" and "do you see any value in visualising emissions as a chart?".

5.3 Student Evaluation

The second study had 33 total participants, all students from the Sustainable Architecture masterprogramme at NTNU. The study consisted of two separate usability test sessions – the first session had 14 participants, and the second session had 19 participants. After each test session, participants were asked to fill out the questionnaire presented in Section 5.4.

5.3.1 Group Usability Testing

In order to take advantage of many participants being gathered in one place, and because of limited time resources, a methodology called group usability testing was used.

Downey [49] defines group usability testing as "a group of users individually, but simultaneously, performing a set of tasks with one or more testers observing and interacting with participants". The actual testing approach that was used differed slightly from this definition, as some participants shared one computer to complete the test tasks in a collaborative manner. Participants were also encouraged to communicate and discuss amongst each other, even when using separate computers. The intent behind this was to make the test sessions more engaging, as well as to take advantage of the benefits of cooperative learning [50]. Because one could not guarantee that all participants would complete all test tasks in the same amount of time, they were not presented one at a time – instead, every participant received a list of all the tasks simultaneously. There was also a risk of participants getting stuck with a task and not being able to receive one-on-one assistance. In order to mitigate this, the tasks were simply presented as examples, or as an inspiration, of what they could attempt to do during the test session.

The test sessions lasted for 20 minutes, after which a short, focused discussion was held to gather initial feedback. The test tasks were the same as the ones presented in the expert evaluation (see Section 5.2), and can be found in Appendix B.

5.3.2 Coding of Qualitative Data

In order to systematically analyse qualitative data derived from the test sessions and questionnaires in which the students participated, the data was taken through a coding process according to the grounded theory method – as described in Section 3.7. As a result of this coding process, the data was broken up into discrete parts and labelled with codes. These codes were then combined to form a number of subcategories, which themselves combined to form three main categories:

- Useful aspects of ExploreLCA
- Challenging aspects of ExploreLCA
- Missing features in ExploreLCA

The complete results of the coding process are presented as spider diagrams in Appendix D.

5.4 Questionnaire

Along with the previously described evaluation activities, a questionnaire was used to gather feedback from participants in both studies. There are a number of benefits in using questionnaires as a research method – one of them is it being easy to gather information from many respondents in a short amount of time [51]. The questionnaire used in this project can be found in Appendix C.

5.4.1 Likert Scale

Most questions in the questionnaire were Likert scales. Likert scales are commonly used to measure attitude, by providing a range of responses to a given question or statement [52]. According to Uebersax [53], a true Likert scale is defined by a set of specific characteristics:

1. The scale contains several items
2. Response levels are arranged horizontally
3. Response levels are anchored with consecutive integers

4. Response levels are also anchored with verbal labels which connote more-or-less evenly-spaced gradations
5. Verbal labels are bivalent and symmetrical about a neutral middle
6. The scale always measures attitude in terms of level of agreement/disagreement to a target statement

The Likert scales in this questionnaire adhered to all of these criteria, except for criterion 3; *Response levels are anchored with consecutive integers*. Although this means the questions were only what one would call "Likert-type" scales, they will still be referred to as Likert scales for simplicity's sake.

According to Jamieson [52], the data produced by Likert scales should normally be considered as ordinal. Ordinal data is, according to Allen and Seaman [54, p. 64], "data in which an ordering or ranking of responses is possible but no measure of distance is possible". Not all respondents might have the same perception of the emotional distance between the response options, and there is often hesitancy tied to expressing a strong opinion, which in turn can make responses gravitate towards the neutral middle response [55]. As such, in order to find the central tendency in a set of Likert responses, one should calculate the median instead of the mean – this was the chosen method for this questionnaire. In addition, the interquartile range (IQR) was calculated in order to quantify the spread of the responses. A small IQR indicates a consensus among the respondents, while a larger IQR indicates that the respondents' opinions are more polarised.

5.4.2 Content

The questionnaire presented to the energy and environment advisor (expert respondent) consisted of two sections:

1. Usability of the application
2. Usefulness of the application

The questionnaire presented to the Sustainable Architecture students (student respondents) consisted of four sections – these included the two previous sections, in addition to two new sections:

1. Demographic information
2. Usability of the application
3. Usefulness of the application
4. Awareness of sustainability and LCA

The *Usefulness* section in the student respondents' questionnaire also contained three additional open-ended questions. The following subsections are structured after the sections present in the student respondents' questionnaire, and as such also include the sections from the expert respondent's questionnaire.

Demographic Information

The demographic information section contained questions about respondents' former work experience as architects, and about their familiarity with the LCA methodology and LCA related applications. Questions about demographic information were kept to a minimum, so as to avoid making the questionnaire seem as being intrusive by the respondents [56].

Usability of the Application

In order to quantify the respondents' perceived usability of ExploreLCA, the System Usability Scale (SUS) was used – as described in Section 3.6. After finding the individual SUS scores of all the respondents, their mean and median were calculated in order to find the central tendency.

The mean SUS score for the two studies was then translated to an adjective and a grade letter, according to Figure 3.4. Finally, it was compared to the average SUS score, which is 68 [47], in order to determine if the usability of ExploreLCA can be considered to be above, or below, average.

An additional question about the respondents' overall impression of the application's user friendliness was also included in this section. This was a seven-point adjective-anchored Likert scale whose response options reflected the adjectives present in Figure 3.4. The adjective rating scale was originally presented by Bangor *et al.* [57], where it was argued that the addition of the adjective rating scale to the SUS may assist practitioners with interpreting individual SUS scores and help them with explaining the results to non-human factors professionals. Since an adjective associated with this questionnaire's SUS score can already be worked out using the corresponding scale in Figure 3.4, this additional question served as a way to validate that adjective score.

According to Bangor *et al.* [57], psychometric theory suggests that multiple-item measures tends to yield more reliable results than single-item measures. This is supported by Oshagbemi [58, p. 388], who after comparing different ways of measuring job satisfaction, concludes that "the results from the single-item measure tend to paint a rosier picture of job satisfaction than the impression conveyed from the multiple-item measure would justify". This was the main reason for using the full SUS to measure usability, instead of settling for a single question asking about the overall user friendliness.

Usefulness of the Application

In an MIS Quarterly paper by Davis [39], he presents a scale for measuring the perceived usefulness of a system. The items in this scale can all be divided into three main clusters, or categories: the first relates to job effectiveness, the second to productivity and time savings, and the third to the importance of the system to one's job. For this questionnaire, one item was selected from each of the three clusters – the idea was to keep the question short and concise, while still measuring all aspects related to the application's usefulness.

A fourth item was added to the question asking if the respondents could see themselves using the application in the future. The purpose of this item was to get insight into the respondents' *intent to use the system*, which is one of the variables present in the Technology Acceptance Model [31]. Each item in this question also had five response options, ranging from *Strongly agree* to *Strongly disagree*, making it a Likert scale.

Finally, three open-ended questions were asked regarding what specific aspects or features the respondents thought were most useful, most challenging, or missing from the application.

Awareness of Sustainability and LCA

The final section of the questionnaire contained questions about the effect the application had on the respondents' awareness and understanding of the LCA methodology, as well as on their general awareness of sustainability in buildings. The questions were arranged as items in a Likert scale with five response options, ranging from *Strongly agree* to *Strongly disagree*.

Chapter 6

Results

This chapter presents the results from the evaluations that were conducted during this project. The results are separated into three distinct parts: results from the expert evaluation, results from the student evaluation, and results from the questionnaire.

6.1 Expert Evaluation

The expert evaluation had one participant: an energy and environment advisor from Asplan Viak (N=1). Three types of information were gathered from the participant, as presented by the following subsections.

6.1.1 First Impressions

When asked for first impressions after having completed their test session, the interviewee described both the features they had liked, as well as the features that they thought were challenging to use or understand. Among the things that they liked, they mentioned the "select multiple buildings" switch, which hides and shows checkboxes next to each building, describing it as intuitive. They also said that the "display mode" and "group by" features were easy to understand. They appreciated being able to see which materials contributed the most to a building's total emissions using the chart display mode, and were impressed by the transparency and level of detail of the different buildings' material usage.

As for the things they thought were challenging, they mentioned that it was hard to find the settings for changing the emission metric of the charts - they initially avoided the Settings button as they thought it was meant for adjusting things such as preferences or account settings. They also mentioned that it was impractical to have to uncheck the "select multiple buildings" switch to see the details of a single selected building. The interviewee also thought it was hard to figure out how to edit a material, and suggested renaming Simulation mode (the previous name for Edit mode) to "Edit" or something similar.

Finally, they mentioned that they normally use Microsoft Excel when working with data related to LCAs of buildings, and compared that to using the application: "We're so used to only working with Excel that having something interactive like [ExploreLCA] is really, really cool". Overall, they found the application to be great.

6.1.2 Uses for the Application

The interviewee was asked about what uses they saw for the application in their daily work tasks. The first usage scenario they thought of was using it to compare their own projects to other projects with a similar emission level or typology – it could be useful to see what type of materials were used in the other projects, and it could serve as an inspiration in the early phases of project planning. They also mentioned that they could see themselves using the application as a complementary data source for projects where the reference building that they're given is lacking documentation.

When asked about their thoughts on using Simulation mode, they said they could also see it as being especially useful in the early phases of a project, when they need estimates or preliminary results based on more generic emission values. They went on to say: "Different EPDs, or data sources, can sometimes have big differences in emission numbers for a certain material, so it's nice to be able to select from multiple EPDs in order to find the one that is the most relevant to your project". Despite this, they pointed out that Simulation mode would only be useful to some extent, and that they would mainly use the application for comparing projects. They then suggested that: "[Simulation mode] would be more useful if you could change entire material types, for example from concrete to wood".

Finally, the interviewee was asked about how they imagined that one should be able import their own data into the application. They answered that since many other LCA tools, such as OneClickLCA and an internal tool they use at Asplan Viak, let you export their data as Excel spreadsheets, the application should be able to import data from a spreadsheet. They added that there should be some clear rules or instructions on how to format such a spreadsheet to make it compatible with the application.

6.1.3 Missing Features

The interviewee was then asked about whether there were any features they missed in the application, both functionality and interface-wise. The first thing they mentioned was displaying building element codes when grouping materials by building element, as people who have worked with them for a long time might recognise codes more easily than the actual element names. They also would have liked the application to have support for other LCA modules and stages, and not just stages A-B. They mentioned that it would be nice to be able to make each screen section bigger, and suggested either having the sections resize automatically when selecting a building, or having a draggable divider in the middle so the user could manually resize each section as they wanted. Finally, they thought it could be useful to include a picture of a selected building in its details view so that the user could get an idea of how it looks in real life. Alternatively, they suggested that an external link to a building project's website could be shown instead.

6.2 Student Evaluation

The student evaluation had 33 participants, all students from the Sustainable Architecture masterprogramme at NTNU (N=33). Data gathered from these participants was analysed and divided into subcategories, which were then combined into main categories. The following sections are structured according to these categories.

6.2.1 Useful Aspects of ExploreLCA

The first category describes which aspects of the application test users deemed as most useful. Some aspects were mentioned more often than others, while some were only mentioned by as few as one test user.

Material Grouping Options

Most test users considered the material grouping options to be the most useful aspect of the application. Some test users mentioned specific grouping options when describing what they found most useful, e.g. group by building element or group by product, while others found the material grouping options as a whole to be a useful feature. A few test users specified that it was a nice way to find specific emission data, while others appreciated that it allowed them to categorise and filter material information.

Visualisation of Data

Many test users mentioned visualisation of data as one of the application's most useful features. They liked being able to compare building and material emissions using charts, as well as seeing the difference between the different LCA modules with colours. They also said that it was easy to switch between the table and chart display mode.

Comparison of Data

Another generally popular aspect was comparison of data. Feedback in this category included both comparison of total building emissions and comparison of materials. Although comparison of buildings was mentioned more often than that of materials, both were still prominent responses - this ties in with some of the points related to visualisation of data.

Edit Mode

Many users saw Edit mode as the most useful feature. Being able to change a material's data source was an important feature to them, and they saw potential in being able to freely manage EPDs related to materials in a building project. Some test users also mentioned that they liked the visual feedback shown after editing a material, i.e. different colours for edited fields and a percentage of emission change.

Table View

Table view was not among the most popular aspects of the application, but a few test users mentioned that they liked being able to see more details about materials than what the chart view offered. Another test user mentioned the general building overview table as one of the most useful aspects, since they could easily gain insight into many projects at once.

User-friendliness

Almost all of the test users mentioned the user-friendliness of the application in one way or another; many test users described the interface as being simple and easy to use, while some also said that they appreciated the flexibility in data retrieval that the application offered. Two test users also specifically said that they found it easy to complete the test tasks presented to them.

6.2.2 Challenging Aspects of ExploreLCA

The second category describes which aspects of the application test users deemed as most challenging. Each of the challenging aspects presented were mentioned by a more or less equal amount of test users.

Lacking Documentation

Some users said that they found it challenging to not have an overview of all the functionality available in the application. They also mentioned that they needed some time to understand the logical way in which the app was built.

Lack of Clarity

Similarly to the challenges related to lacking documentation, some users found the general lack of clarity present in some parts of the application to be challenging. The material inventory IDs that appear when a material product is expanded didn't make sense to some users, while some other users thought the connection between emissions of individual materials and the emissions of the whole building weren't clear enough. Additionally, one user thought the application didn't make it clear that you couldn't add your own data to it, such as new buildings or materials.

Edit Mode

A handful of users experienced some aspects of the Edit mode as challenging. They needed some time to understand how to edit a material, as well as how to specifically change a material's data source. Some users also thought that it wasn't clear enough if an edited material had affected the total building emissions or not, which ties in to the challenges related to lack of clarity.

Interface Interaction

Some users found it challenging to interact with a some aspects of the interface. Two users mentioned the horizontal scroll bars present in the tables of the application; one found it hard to scroll horizontally in order to see data that was out of view, while the other wasn't even aware that horizontal scrolling was possible. One final user found the vertical screen divider to be impractical on smaller screens, because they couldn't drag it very far to the side and as such couldn't see much of the details view.

Language

A few test users found the language used in the application to be a challenge. They couldn't understand some of the Norwegian material names, and found it confusing that there was a mix of English and Norwegian material names.

6.2.3 Missing Features in ExploreLCA

The final category presents which missing features test users wanted to see in the application. These include additions or changes to either the application's functionality, interface or both.

Add own Data

The ability to add your own data was the feature that most test users missed by far. This included being able to create and add new building projects to the list of buildings, as well as being able to add and edit data, such as materials, in existing buildings. Some users also wanted to manually edit emission data of materials in case no data sources had relevant emission numbers available.

Synchronise with External Resources

Another missing feature that was mentioned by many test users was having the application synchronise with external resources. Most of the test users requesting this feature wanted to be able to connect to EPDs and import data from them, either manually or automatically. One test user missed being able to update materials present in a building with newer versions as they come into the market, to see how that would affect the building.

Better Building Comparison

Some test users missed a few features related to building comparison, the most mentioned one being the option to compare details and materials of multiple buildings with one another, instead of just total emissions. One test user also mentioned that they would like to be able to filter the building table by different columns, e.g. by a specific typology. In addition to this, they said they wanted a "select all" button so that one could easily select all buildings after filtering them.

Expanded Dataset

One user mentioned that they wanted to have access to an even larger database of building projects. A few other users additionally mentioned that they would like to see data from a full life cycle assessment, i.e. data from stages A-D, and not just from stage A-B.

Interface Enhancements

The interface enhancements category contains three types of features that some test users missed; one test user missed being able to resize the height of tables and charts in the details view, while another test user wanted a fullscreen option for the details view after selecting a building. One test user recommended colouring building element levels differently from each other in the breadcrumb trail, to more easily see how deep in the building element hierarchy they are.

Export Data

A couple of test users missed being able to export data. This included exporting tables and charts as image or PDF files, as well as having the option to print them directly from the application.

Other Features

The final category includes several different types of missing features. One user missed being able to search for any building element in a building, using either its code or its name. Another user missed the option to select a "per inhabitant" emission metric along with "per m^2" and "per year", because they thought it might be a more relevant metric for certain situations. Two test users said they would like materials to include an external link to the EPDs that they have their data from, and two other users missed some form of translation functionality for foreign material names.

6.3 Questionnaire

Responses from a total of 28 respondents were collected for the questionnaire – the respondents consisted of an energy and environment advisor from Asplan Viak (expert respondent), and 27 students from the Sustainable Architecture master-programme at NTNU (student respondents).

6.3.1 Demographics

Table 6.1 shows demographic information relating to the student respondents' experience in the field of architecture and familiarity with the LCA methodology, divided into three characteristics. Each characteristic is based on a question from the questionnaire, and has its own set of answer options. Each answer option is displayed along with the number of respondents that chose it.

Out of 27 respondents, 24 (89.9%) answered that they had former work experience as an architect – these respondents received a follow-up question asking about how many years or months of experience they had. The answers to the follow-up question ranged from "one month" to "13 years", with a median of 24 months (or two years).

The majority of respondents stated that they were somewhat familiar with the LCA methodology, while a smaller majority said answered that they were slightly familiar with other LCA related applications.

Table 6.1: Demographic characteristics of questionnaire respondents (N = 27)

Characteristic	**Options**	**N**
Former work experience as an architect	Yes	24
	No	3
Familiarity with the LCA methodology	Very Familiar	5
	Somewhat Familiar	20
	Slightly Familiar	2
	Not at All Familiar	0
Familiarity with other LCA related applications	Very Familiar	1
	Somewhat Familiar	9
	Slightly Familiar	13
	Not at All Familiar	4

6.3.2 Usability

The *Usability* section of the questionnaire consisted of a System Usability Scale (SUS) and a question asking for an overall rating of the application's user friendliness. This section was presented to both the expert respondent (N=1) and the student respondents (N=27).

The mean SUS score for the 28 respondents was 76.9, and the median was 77.5. The adjective and grade letter associated with these scores are "Good" and B, respectively. Since the average SUS score is 68, the SUS score from this evaluation is considered as above average. Table 6.2 shows the median of all SUS scores, represented by an adjective, along with the median of all responses for the overall rating of the application's user friendliness. The responses for the overall rating ranged from 4 (Fair) to 7 (Best imaginable), with a median of 6 (Excellent). 14 out of the 28 respondents gave an overall rating that was different from the adjective associated with their SUS score. Out of these 14 respondents, ten gave a higher overall rating, while four gave a lower overall rating.

Table 6.2: Results from *Usability* section of questionnaire (N = 28)

Item	Median	IQR
SUS score (represented by adjective)	5 (Good)	1
Overall rating of user friendliness	6 (Excellent)	1

Since scores for individual items in a SUS are not meaningful on their own [33], they are not presented here.

6.3.3 Usefulness

The *Usefulness* section of the questionnaire contained a Likert scale with four items related to the respondents' perceived usefulness of the application. Table 6.3a and Figure 6.1 show frequencies for levels of agreement tied to each item, with 1 representing "strongly disagree" and 5 representing "strongly agree". Table 6.3b shows the median and the interquartile range (IQR) of the responses to the same four items. This section was presented to both the expert respondent (N=1) and the student respondents (N=27), with the exception of Q4 which was only presented to the student respondents.

There was a similar general tendency for each of the four items on the scale; the responses all gravitated towards 4 (Agree), with little to no variability in opinions. Although the majority of the respondents said they agreed, 39.3% of the respondents had a neutral level of agreement towards thinking that the application could support critical aspects of their jobs (Q3). There were also two respondents that disagreed that the application could improve their job performance (Q1). Finally, 23 out 26 student respondents either agreed or strongly agreed that they could see themselves using the application in the future (Q4).

6.3.4 Awareness of Sustainability and LCA

The *Awareness of Sustainability and LCA* section of the questionnaire contained a Likert scale, with three items related to the effect the application had on the respondent's awareness and understanding of sustainability and the LCA methodology. Table 6.4a and Figure 6.2 show frequencies for levels of agreement tied

(a) Frequencies for levels of agreement for each item (1 = strongly disagree, 5 = strongly agree)

Item		1	2	3	4	5
Q1	ExploreLCA could improve my job performance.	0	2 (7.1%)	6 (21.4%)	17 (60.1%)	3 (10.7%)
Q2	ExploreLCA could enable me to accomplish tasks more quickly.	0	0	5 (17.9%)	16 (57.1%)	7 (25.0%)
Q3	ExploreLCA could support critical aspects of my job.	0	0	11 (39.3%)	15 (53.6%)	2 (7.1%)
Q4	I can see myself using ExploreLCA in the future.	0	0	3 (11.5%)	16 (61.5%)	7 (26.9%)

(b) Median and IQR for each item

Item		Median	IQR
Q1	ExploreLCA could improve my job performance.	4 (Agree)	1
Q2	ExploreLCA could enable me to accomplish tasks more quickly.	4 (Agree)	0.25
Q3	ExploreLCA could support critical aspects of my job.	4 (Agree)	1
Q4	I can see myself using ExploreLCA in the future.	4 (Agree)	0.75

Table 6.3: Results from *Usefulness* section of questionnaire (N = 28)

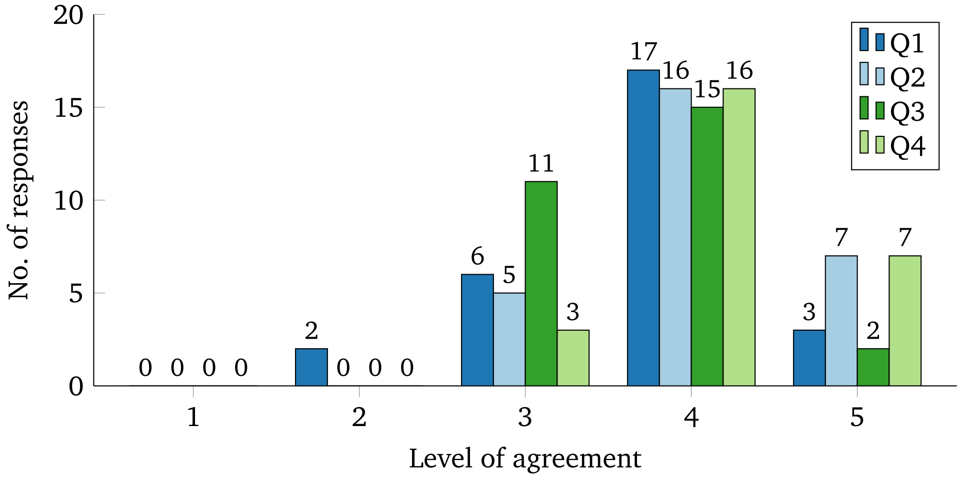


Figure 6.1: No. of responses per level of agreement for items Q1–Q4, as seen in Table 6.3a (1 = strongly disagree, 5 = strongly agree)

to each item, with 1 representing "strongly disagree" and 5 representing "strongly agree". Table 6.4b shows the median and the interquartile range (IQR) of the responses to the same three items. This section was only presented to the student respondents (N=27).

Again, most respondents gravitated towards 4 (Agree) for each of the items in the scale, with no significant spread in responses. It is worth noting that not a single respondent strongly agreed with the the idea that the application increased their understanding of the LCA methodology (Q5).

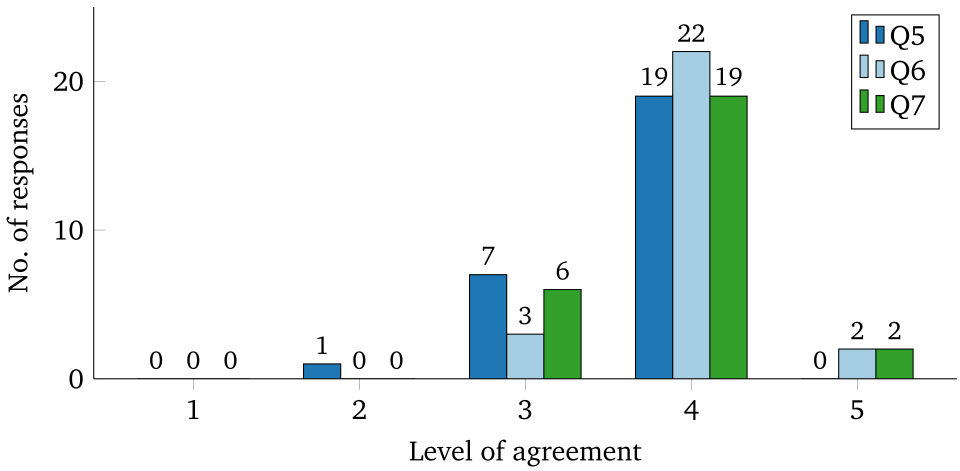


Figure 6.2: No. of responses per level of agreement for items Q5–Q7, as seen in Table 6.4a (1 = strongly disagree, 5 = strongly agree)

(a) Frequencies for levels of agreement for each item (1 = strongly disagree, 5 = strongly agree)

Item		**1**	**2**	**3**	**4**	**5**
Q5	ExploreLCA increased my understanding of the LCA methodology.	0	1 (3.7%)	7 (25.9%)	19 (70.4%)	0
Q6	ExploreLCA increased my awareness of the benefits of systematised LCA results.	0	0	3 (11.1%)	22 (81.5%)	2 (7.4%)
Q7	ExploreLCA increased my awareness of sustainability in buildings.	0	0	6 (22.2%)	19 (70.4%)	2 (7.4%)

(b) Median and IQR for each item

Item		**Median**	**IQR**
Q5	ExploreLCA increased my understanding of the LCA methodology.	4 (Agree)	1
Q6	ExploreLCA increased my awareness of the benefits of systematised LCA results.	4 (Agree)	0
Q7	ExploreLCA increased my awareness of sustainability in buildings.	4 (Agree)	0

Table 6.4: Results from *Awareness of Sustainability and LCA* section of questionnaire (N = 27)

Chapter 7

Discussion

In this chapter, the results presented in chapter Chapter 6 are interpreted and discussed with regard to the research questions of this project. Each section starts by restating a specific research question, after which the question is discussed and answered. Finally, the identified limitations of this study are presented in a separate section.

7.1 Making Systematised LCAs Accessible

RQ1 *How can systematised life cycle assessments of buildings be made accessible through a web application?*

As stated in Chapter 1, *accessible* means both "easy to use", "easy to understand" and "easy to get access to" in the context of the first research question. "Ease of use" was measured by evaluating the usability of ExploreLCA through a questionnaire, an interview and discussions. These evaluation methods all produced results that indicate an overall high level of usability. The main metric that indicates this is the mean SUS score of 76.9 that was calculated from the results of the Usability section of the questionnaire. Since a SUS score of 68 is considered to be average [47], the SUS score of ExploreLCA can be seen as above average. As a complementary measure, the overall rating of the user-friendliness of ExploreLCA was also measured through a single question, resulting in a median of 6, or *Excellent*. In contrast, a SUS score of 76.9 is only equivalent to a rating of 4, or *Good*, indicating that almost half of the respondents gave a higher overall rating than the one associated with their SUS score. This disparity correlates with the findings of Oshagbemi [58], who observed that single-item measures tend to produce a higher score than multiple-item measures.

The high SUS scores and overall ratings were further supported by the qualitative results from the questionnaire and usability test sessions, in which almost all of the test users praised the user-friendliness of ExploreLCA in one way or another. Despite this, the qualitative results also show that some test users found issues with certain aspects of the application's usability, such as challenging interface interaction and lack of clarity. Nonetheless, these test users gave the overall user-friendliness of ExploreLCA a rating of 6, or *Excellent*, indicating that the issues mentioned didn't have a big effect on their overall impression.

Although none of the results directly point to this, the fact that ExploreLCA is a *web application* might have had an impact on making systematised life cycle assessments of buildings accessible, in a practical sense of the word. As Fink and Flatow [16] and Sturm *et al.* [15] state, one of the main benefits of web applications is that they are accessible from any type of device or operating system that has a web browser, with no installation required. Since all computers come with a pre-installed web browser, anyone with a user account can easily and quickly reach ExploreLCA and access the systematised life cycle assessments.

7.1.1 Usage Scenarios

RQ1 (a) *What are the usage scenarios for such an application?*

The clearest examples of usage scenarios were identified using the results from the expert interview with the energy and environment advisor from Asplan Viak. One of the usage scenarios identified is using ExploreLCA to compare one's own building project to other existing projects available in the application. An extension of this usage scenario is using the application as a complementary data source for projects where the reference building that one is given is lacking documentation. Both of these proposed usage scenarios are partly supported by the qualitative results from the questionnaire and usability test sessions, in which the comparison of data within ExploreLCA is pointed out as one of the most useful aspects of the application. Although this doesn't directly imply the existence of a specific usage scenario, it still indicates that users see value in using ExploreLCA as a source for comparing building data.

Another usage scenario identified through the expert interview is using the application's Edit mode in the early phases of a project to experiment with different data sources, or EPDs, in order to find the one that seems most suited to the project in question. This can help with creating good estimates or preliminary results that can then be proposed to a client. This usage scenario is also supported by the qualitative results from the questionnaire and usability test sessions, in which many test users mention Edit mode as being the most useful aspect of ExploreLCA. The qualitative results specifically indicate that users see potential in being able to freely manage EPDs related to materials in a building project.

The missing features presented in the qualitative results indicate that there are additional potential usage scenarios for ExploreLCA, should the missing features be implemented in the future. Among the potential usage scenarios identified, the most prominent one is using ExploreLCA to import one's own building projects into the application, to facilitate making comparisons of one's own project to existing projects. The results from the expert interview indicate a more specific variant of this user scenario: exporting data from other LCA related tools and applications as Excel spreadsheets, and importing those spreadsheets into ExploreLCA.

By combining the results from the Usability and Usefulness sections of the questionnaire, one can get an idea of a user's behavioural intention to use ExploreLCA, as per the Technology Acceptance Model (Section 3.3). While this doesn't indicate a specific usage scenario, it can give an idea of how likely it is that ExploreLCA, as a technology, becomes accepted and used on a general basis. The results from the Usefulness section indicate an overall high level of perceived usefulness, with the majority of respondents agreeing that ExploreLCA could improve their job performance, enable them to accomplish tasks more quickly, and support critical aspects of their job. As mentioned in Section 7.1, results from the Usability section also indicate an overall high level of perceived ease of use. By combining these two metrics, one can deduce that users are likely to accept and use ExploreLCA, should it ever be made available to use. These findings are further supported by the results from the final item of the scale in the Usefulness section, in which 23 out 26 student respondents either agree or strongly agree that they could see themselves using the application in the future.

7.1.2 Included Elements

RQ1 (b) *What elements should be included in such an application?*

The qualitative results from the questionnaire and usability test sessions give insight into which aspects of ExploreLCA test users found *useful*, which aspects they found *challenging*, and what *missing features* they would have liked to see implemented. By combining the results from these three categories, one can get an idea of what elements a web application for accessing systematised life cycle assessments of buildings should include.

The results show that the material grouping options, along with data visualisation features such as the chart display mode, are considered by the test users to be some of the most important elements of ExploreLCA. This correlates with the conclusion presented in the master's thesis by Slåke and Auklend [26], in which the authors emphasise the importance of making data related to the environmental impact of building materials accessible and understandable through transparent and interactive visualisations. By letting users group materials in three distinctly different ways, and by allowing them to display data in both table and chart format, ExploreLCA makes it easy for untrained architects and planners to access and understand data from large and complicated datasets – as recommended by Slåke and Auklend [26].

The results also indicate that some elements that should have been included were either not implemented well enough, or not included at all. These missing elements tie in with Nielsen's ten usability heuristics [32], which describe the most important aspects of designing a good user interface. Firstly, the documentation in ExploreLCA was found to be lacking by some test users – this correlates with

Nielsen's tenth heuristic: *Help and documentation*. According to this heuristic, documentation should be presented in context right at the moment that the user requires it. In ExploreLCA, on the other hand, all the documentation is general, and it is only presented when the user clicks on a designated Help button. Secondly, some test users found certain aspects of ExploreLCA, such as the labelling of material inventory IDs, to be lacking in clarity. This goes against Nielsen's second heuristic – *Match between system and the real world* – which states that the design should be speak the users' language, and that there should be a focus on using words, phrases and concepts familiar to the user. Finally, Nielsen's seventh heuristic – *Flexibility and efficiency of use* – says that an application should provide personalisation by tailoring functionality for individual users, as well as allow for customisation, so users can make selections about how they want the product to work. This correlates with the aforementioned results: some test users wished for a translation feature for foreign material names, indicating a need for personalisation, while some test users missed being able to resize the height of certain elements, indicating a need for customisation.

7.2 Awareness of Sustainability

RQ2 *What effect would a web application for exploring systematised life cycle assessments of buildings have on its users' awareness of sustainability in buildings?*

The most relevant results for measuring the effect that ExploreLCA has on its users' awareness of sustainability in buildings are the ones obtained from the *Awareness of Sustainability and LCA* section of the questionnaire. The section consisted of a three-item scale, with each item being a statement about a specific aspect of sustainability in buildings. The results from each item all indicate that ExploreLCA does a good job at increasing one's awareness of sustainability in buildings. By taking the fact that ExploreLCA is an interactive application into account, these results correlate well with the studies by Barker [21] and Evans and Gibbons [22], in which conclusions are drawn about how learning through interactive systems can lead to a deeper understanding of a particular topic.

In the results from the expert interview, it is mentioned that the interviewee appreciated being able to see which materials contributed the most to a building's total emissions using the chart display mode. This might also support the previously mentioned results from the questionnaire – being able to easily see the exact composition of materials and building elements in a given building, as well as how much each material or building element contributes in terms of total emissions, might enable a learning effect and help increase users' awareness of sustainability in buildings.

7.3 Limitations

As with any research project, this study has its own set of limitations. One of the biggest limitations was the lack of available participants for usability testing. Since the target users of ExploreLCA are individuals that work with concepts such as architecture, LCA, and sustainability, potential participants had to be carefully sourced from relevant organisations. As such, the number of potential participants was small to begin with, and the number of people that actually agreed to participate was even smaller.

The limited number of participants in the usability testing naturally led to a small sample size in the data gathered from the questionnaire. Consequentially, the results from the quantitative sections might not be representative of target users in general – especially since the respondent demographics mostly consisted of students. Despite this, 89.9% of the students had up to several years of prior work experience as architects, indicating that the results might at least be representative of architects as a target user group. Still, evaluating ExploreLCA against a bigger and more varied group of test users would produce more reliable and representative results.

Furthermore, the evaluation of ExploreLCA's effect on users' awareness of sustainability in buildings was not as thorough as it could have been. The only direct measure came from the *Awareness of Sustainability* section in the questionnaire, which consisted of a simple three-item scale that produced a quantitative result. Ideally, a form of qualitative measure should have been included in both the questionnaire and the expert interview, in order to get deeper insight into how exactly the application affected the users' awareness of sustainability, as well as to support the quantitative results. Additionally, the responses from the three-item scale in the questionnaire might have been subject to habituation bias, as they were all worded very similarly to each other. Habituation bias can occur when participants are presented with repetitive and similarly-worded questions, causing them to provide the same answers for those questions.

Chapter 8

Conclusion

In this chapter, the key findings of the project are summarised, and a conclusion is presented. Finally, recommendations for future work on the subject are proposed.

8.1 Conclusion

This thesis has explored how systematised LCAs found in the bLCAd tool can be made accessible through an interactive web application. As a result, a web application called ExploreLCA has been developed, using a number of libraries for web development such as React, Material-UI and Firebase. By having an overall high level of usability and usefulness, and by being accessible through a web browser, ExploreLCA manages to make systematised LCAs found in the bLCAd tool satisfactorily accessible.

A number of usage scenarios for ExploreLCA have also been identified. One usage scenario involves using the application to make comparisons of one's own project with similar existing projects, as a way to get inspiration for material selection in the early phases of project planning. Another usage scenario is using ExploreLCA's Edit mode to change a material's data source to one that is more relevant to one's project, allowing a user to create better estimates or preliminary results to present to a client. A final usage scenario, not currently supported by ExploreLCA, involves importing one's own building projects into the application, so that one may access them in the same way that existing projects are accessed.

Furthermore, the research has identified what elements contribute to making ExploreLCA usable and useful, and as such should be included in the application. One of the most important elements is a dropdown that lets the user switch between different material grouping options, allowing them to browse materials by either product, building element, or category. Another important element is a switch that lets users select the format in which data is displayed – either as a table or as a chart.

Finally, it has been discovered that ExploreLCA can help increase its users' awareness of sustainability in buildings, as it provides a clear way to visualise how much each material and building element contributes in terms of a building's total emissions.

Based on these conclusions, ExploreLCA shows promise as a valuable application for accessing systematised life cycle assessments found in the bLCAd tool. As such, it can be recommended to practitioners who wish to explore systematised life cycle assessments of buildings in an interactive and flexible manner.

8.2 Future Work

Although this project has been completed to a satisfactory degree, there are still some aspects that could be expanded upon in future research. Firstly, ExploreLCA could be improved by expanding and enhancing its existing features, as well as by implementing entirely new types of features. A natural place to start would be to look at the critical feedback from the last round of evaluation (Section 6.2.2 and Section 6.2.3). This feedback indicates possible ways to improve the application, both in terms of functionality and user-friendliness. One of the most obvious features that should be implemented is the ability to add and import your own building data via the application's interface. This could substantially increase the usefulness of the application, as making comparisons between your own data and existing data would be greatly facilitated. Another way to improve ExploreLCA would be to establish an actual connection to different data sources, or EPDs, so that Edit mode can be used for its true purpose, and not only to produce dummy data.

Although one of the research questions addressed the effect that ExploreLCA might have on its users' awareness of sustainability in buildings, this was not the main focus of this project. A recommendation for future research could therefore be to dive deeper into how ExploreLCA can be used to increase knowledge, understanding and awareness of the LCA methodology, and sustainability in buildings in general. By implementing additional visualisation features, for example 3D models of buildings and their materials, one could help users better understand how emissions are distributed across buildings.

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Appendix A

Entity-Relationship Diagram of bLCAd

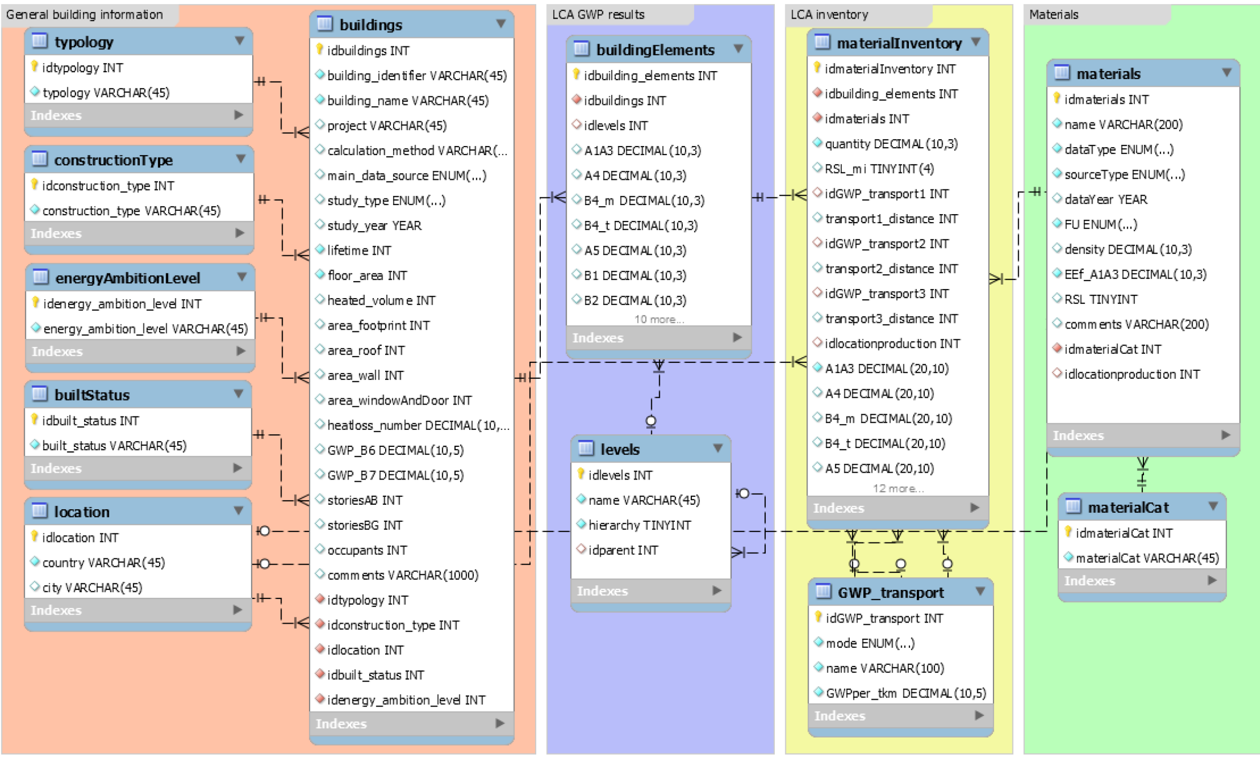


Figure A.1: ERD (Entity-Relationship Diagram) of the bLCAd tool's database

Appendix B

Usability Testing Tasks

Task 1

(a) For the building *Eufemia B7 Sørbygg*, you want to find out what materials the building element *232 - Non-bearing outer wall* consists of

Task 2

(a) For the building *Eufemia B7 Sørbygg*, you want to find the total emission value of the A1-A3 module for materials in the *Steel* category
(b) You want to display the emission values of the individual materials in the *Steel* category in chart form

Task 3

(a) For the building *A14 Bjørvika*, you want to edit the data source of some materials.
Change the data source of the following materials to "TestSource":
- Stålsøyler/stålkjernepeler – S355
- Armeringsstål
- Masonry - Stone

(b) Identify if the changes affected the emission values of the materials
(c) Identify if the changes affected the total emission values of the building

Task 4

(a) You want to compare the total emissions of all buildings with the *Office* typology with one another. Identify the building with the highest total emissions per square metre.
(b) You want to change the metric settings for embodied emissions from "$kgCO_2e/m^2$" to just "$kgCO_2e$" to see if it affects how the buildings compare to each other

Appendix C

Questionnaire

Which group are you in?

Group 01 - Group 12
Other

Do you have any former work experience as an architect?

Yes
No
Unsure

How many years (or months) of experience do you have?

_

Familiarity with LCA

	Not at All Familiar	Slightly Familiar	Somewhat Familiar	Very Familiar
How familiar are you with the LCA methodology?	O	O	O	O
How familiar are you with other LCA related applications?	O	O	O	O

Usability

This section contains ten questions about the usability, or user friendliness, of ExploreLCA.
For each of the following statements, please mark one box that best describes your reactions to ExploreLCA today.

		Strongly dis-agree	Disagree	Neither agree nor dis-agree	Agree	Strongly agree
1.	I think that I would like to use ExploreLCA frequently.	○	○	○	○	○
2.	I found ExploreLCA unnecessarily complex.	○	○	○	○	○
3.	I thought ExploreLCA was easy to use.	○	○	○	○	○
4.	I think that I would need the support of a technical person to be able to use ExploreLCA.	○	○	○	○	○
5.	I found the various functions in ExploreLCA were well integrated.	○	○	○	○	○
6.	I thought there was too much inconsistency in ExploreLCA.	○	○	○	○	○
7.	I would imagine that most people would learn to use ExploreLCA very quickly.	○	○	○	○	○
8.	I found ExploreLCA very cumbersome (awkward) to use.	○	○	○	○	○
9.	I felt very confident using ExploreLCA.	○	○	○	○	○
10.	I needed to learn a lot of things before I could get going with ExploreLCA.	○	○	○	○	○

	Worst imaginable	Awful	Poor	Fair	Good	Excellent	Best imaginable
Overall, I would rate the user friendliness of ExploreLCA as	○	○	○	○	○	○	○

Usefulness

This section contains questions about the usefulness of ExploreLCA.
For each of the following statements, please mark one box that best describes what you think will be applicable for you, as a future architect.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
ExploreLCA could improve my job performance.	○	○	○	○	○
ExploreLCA could enable me to accomplish tasks more quickly.	○	○	○	○	○
ExploreLCA could support critical aspects of my job.	○	○	○	○	○
I can see myself using ExploreLCA in the future.	○	○	○	○	○

What aspect(s) of ExploreLCA did you find to be the most useful during your test session?

–

What aspect(s) of ExploreLCA did you find to be the most challenging during your test session?

–

Are there any missing features that you would like to see in ExploreLCA?

This can be additions or changes to either the app's functionality, interface or both.
–

Understanding of LCA

This final section contains questions about the effect of ExploreLCA on your awareness and understanding of LCA.
For each of the following statements, please mark one box that best describes your reactions to ExploreLCA today.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
ExploreLCA increased my understanding of the LCA methodology.	O	O	O	O	O
ExploreLCA increased my awareness of the benefits of systematised LCA results.	O	O	O	O	O
ExploreLCA increased my awareness of sustainability in buildings.	O	O	O	O	O

Appendix D

Codes and Categories

This appendix shows the results of the coding process performed on the qualitative data gathered through the test sessions and questionnaires in which students participated, presented as spider diagrams. In order to increase readability, the data is separated into three individual diagrams, each of them covering one main category.

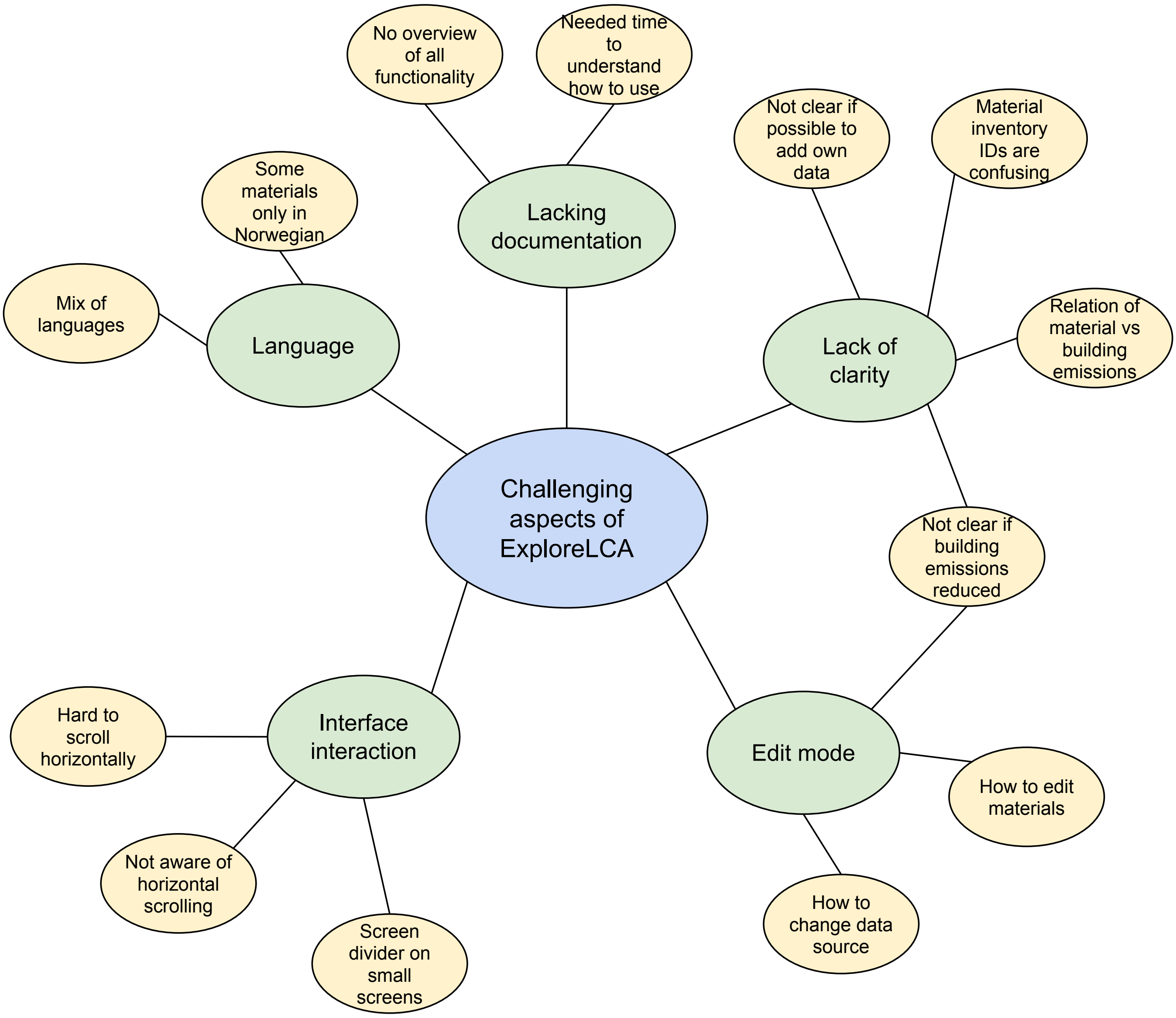
The main categories are:

- Useful aspects of ExploreLCA
- Challenging aspects of ExploreLCA
- Missing features in ExploreLCA

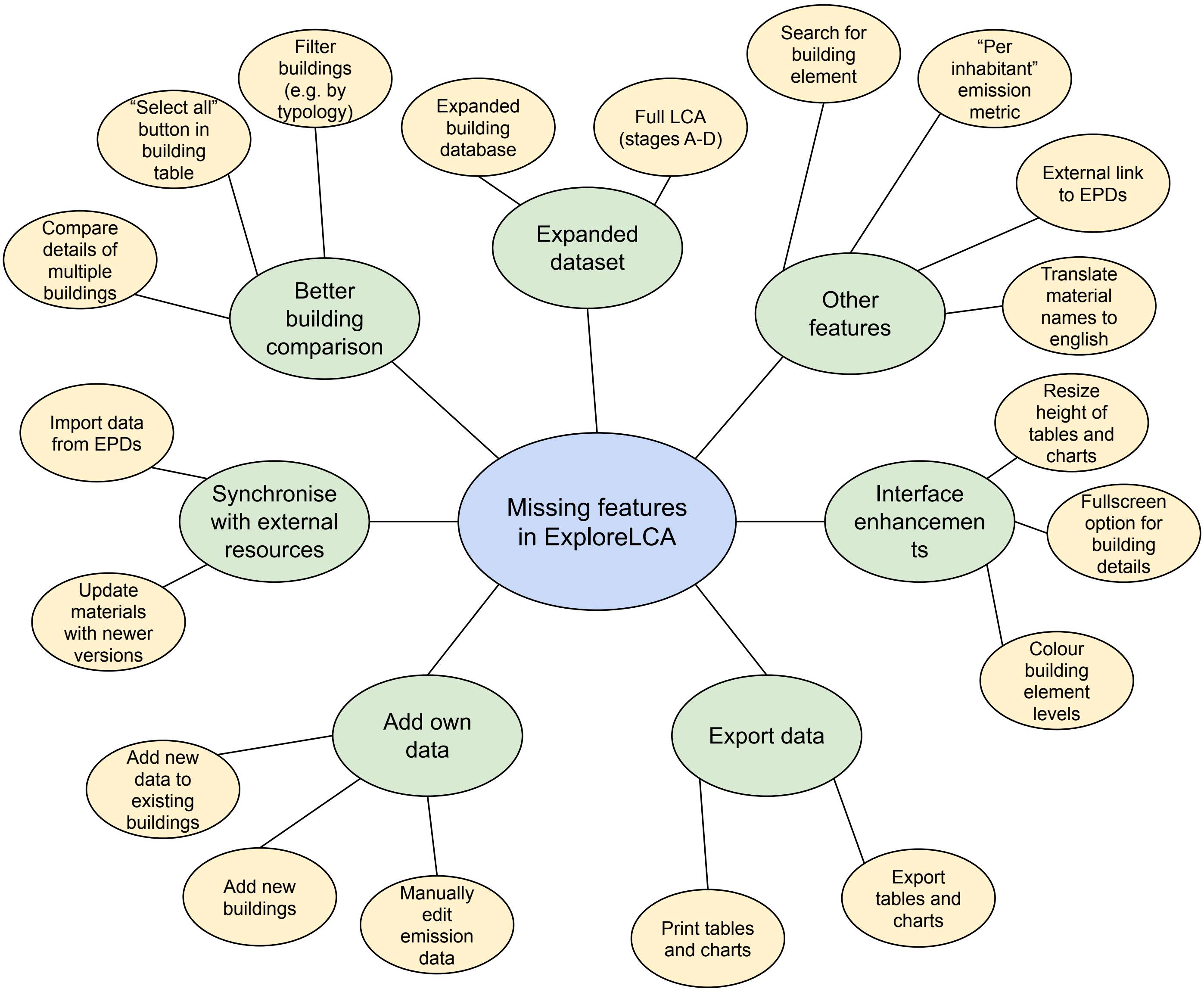
A yellow node represents an individual code, while a green node represents a category. Finally, a blue node represents the main category of that diagram.

Useful Aspects of ExploreLCA

Challenging Aspects of ExploreLCA



Missing Features in ExploreLCA



Appendix E

User Guide for ExploreLCA

This is a short user guide, or manual, for the main features of ExploreLCA.

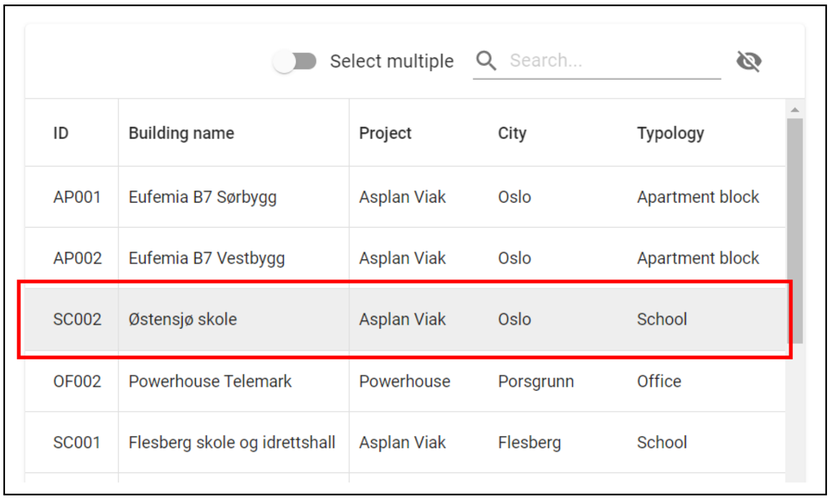
1. Sign in

Enter your username and password, and press the **Sign In** button.

You will be automatically logged out when you close the tab that ExploreLCA is open in.

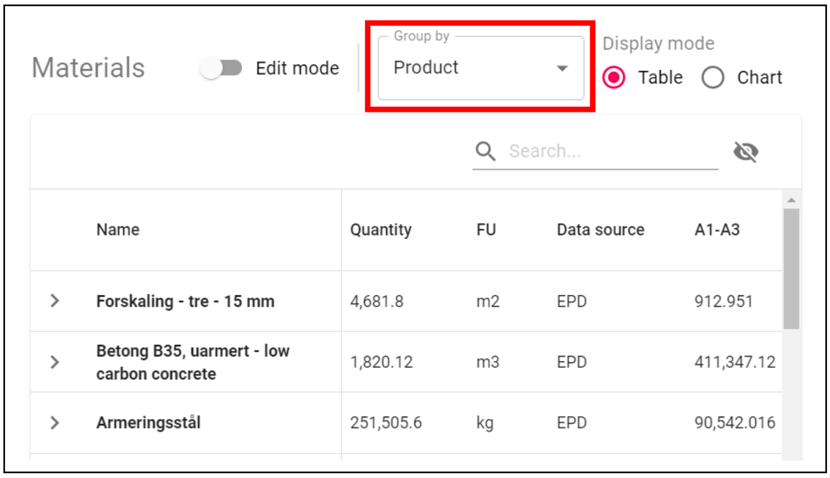
2. Select a Building

Click on a building to select it.
When a building is selected, its details are displayed on the right section of the screen.



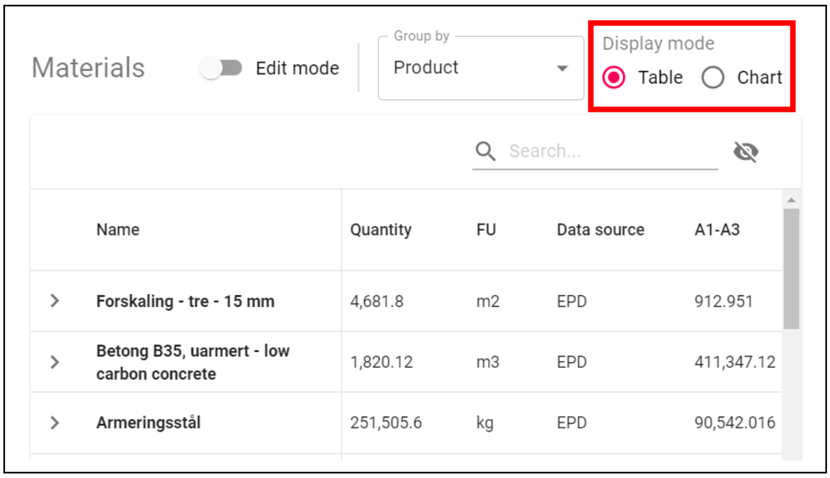
a) Change Material Grouping

To change how the materials are grouped, click on the **Group by** dropdown and select one of the available options.
The available grouping options are "Product", "Building Element" and "Category".



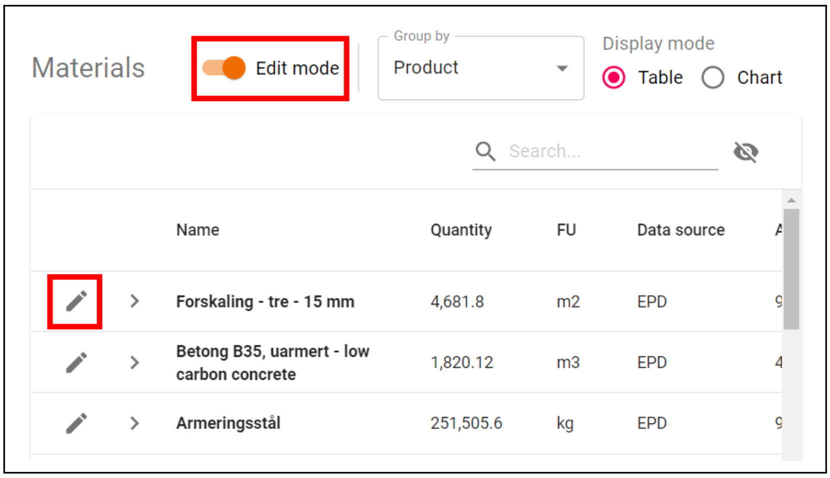
b) Change Material Display Mode

To change the display mode for materials to either "Table" or "Chart", click on the corresponding radio button.

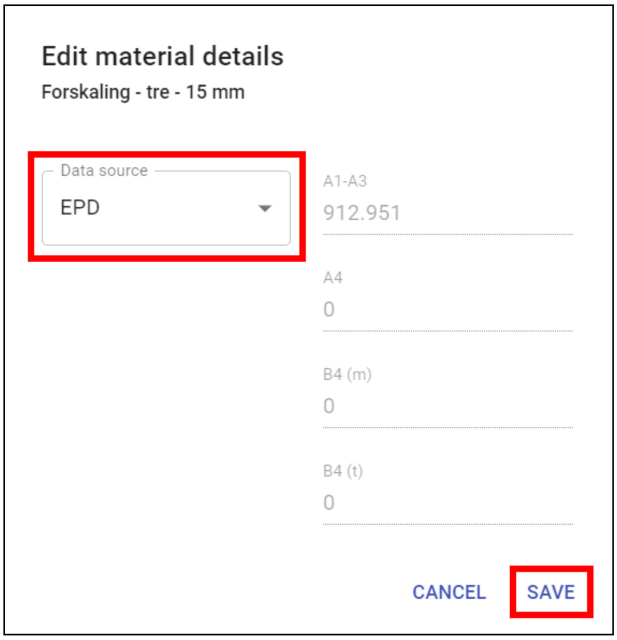


c) Edit Mode

To edit a material, toggle the **Edit mode** switch. Next, click on the **Edit material** button next to the material you want to edit.

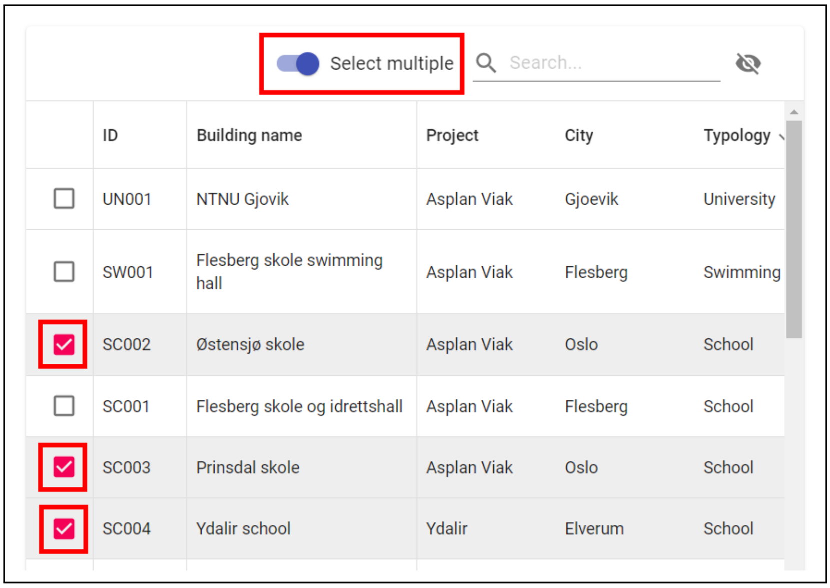


Currently, you can only edit a material's data source.
To do this, click on the **Data source** dropdown in the dialog that appears and select a new data source. To finish editing and close the dialog, click on the **Save** button.



3. Compare Buildings

To compare multiple buildings, toggle the **Select multiple** switch. Next, click on the buildings that you want to compare to select them.
When the buildings are selected, they will appear in the chart on the right section of the screen.



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ExploreLCA – A Web Application for Exploring Systematised Life Cycle Assessments of Buildings

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