# ROTUNDORO. A web-based decision support tool for building refurbishment.

## Insulation material assessment using engineering evaluation method and potential consumer adoption, for owner-occupied Dutch housing refurbishment.

Julia Katharina Kaltenegger – 1337602
Eindhoven University of Technology - Architecture, Building and Planning
Urban Systems and Real Estate (USRE) &
Construction Management Engineering (CME)
Combined Graduation Project 7CZ60M0 – 60 ECTS
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*Julia Katharina Kaltenegger, Master Thesis, October 2021,*
*email: jul.kaltenegger@gmail.com*

*Institute: Eindhoven University of Technology*
*Faculty: Department of the Built Environment*
*Master: Architecture, Building and Planning*
*Master Program: Urban Systems and Real Estate (URSE) &*
*Construction Management and Engineering (CME)*
*Adresse: Den Dolech 2, 5312 AZ Eindhoven*

*Chariman (USRE): Prof.dr. Theo A. Arentze, Graduation Supervision (USRE): Dr. Ioulia V. Ossokina (I.V.Ossokina@tue.nl)*
*Chairman (CME): Prof.dr.ir.B. de Vries, Graduation Supervision (CME): Dr.ir. Pieter Pauwels (p.pauwels@tue.nl)*

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# Abstract

When refurbishing residential buildings, insulation materials play a crucial role in improving housing quality and energy efficiency. Materials however differ in a wide set of criteria. It reaches beyond the thermal properties and addresses environmental, economic, health and safety characteristics. In collective decision-making, it remains difficult to find trade-offs between these criteria. This thesis introduces a web-based tool ROTUNDORO [Latin: circular] that offers an algorithm to assess refurbishing insulation materials, considering engineering evaluation methods and consumer preferences. The tool employs and expands on Building Information Modelling (BIM) practice on the one side and behavioural economic research on the other side. First, the Linked Building Data (LBD) method is used to link material performance to building components and to evaluate them with Life Cycle Assessment (LCA) and cost analysis. Applied to a Dutch terrace house (Rijwoning) as a use case, the tool shows that bio-based materials perform best in environmental concerns, low embodied carbon, high noise and humidity reduction. Fossil- and mineral-based materials are yet market-leading, due to low price and easier application techniques in existing constructions (cavity injection). Following the hard data comparison, the tool simulates the probability of acceptance by the homeowners of various materials used in retrofitting. This simulation is based on consumer research – a stated choice experiment conducted amongst 500 Dutch homeowners, investigating their preferred choices between insulation material packages. Findings reveal that the studied population showed a high willingness to invest in energy refurbishment. Reducing $CO_2$ emissions and noise levels as well as improving comfort are just as important. These criteria vary depending on the chosen material and so does the probability of acceptance. Applied to the Rijwoning case study, results show that the injectable insulation materials are preferred, however are closely followed by materials with low-carbon and high noise-reducing potential. This study contributes to the enhancing of collective decision-making processes. The tool improves the communication between different stakeholders in the effort to reach global climate goals.

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# Preface

This thesis is the result of my time at the TU/e and includes a large and diverse collaboration. Multi- and interdisciplinary working methods and processes are reflected in the overall result of this study as well as in the development activities. For more than one year, (February 2020 until 2021), I had the honour to meet acknowledged experts throughout multiple fields.

Building physicists, energy simulation modelers and Life Cycle Assessment experts taught me engineering aspects in energy refurbishments and environmental performance assessment of materials. Working with energy collectives gave insight into group dynamics when facing decision-making. Behavioural economic research includes such dynamics and taught me methods to assess those. Finally, collaborating and learning from web developers and Linked Building Data experts showed me the power and potential of digitalisation processes to create a more resource-friendly built environment.

I am grateful for all these insights and the possibility to learn from others. I would like to give my gratitude to my two supervisors, Ioulia Ossokina and Pieter Pauwels for the support and guideline regarding technical and personal concerns. Martin Röck as long-term friend and consult regarding sustainable developments in the built environment. Special thank is dedicated to the energy collectives 040Energie and Best Duurzaam, without whom the research would not have been as successful.

Furthermore, I want to thank the experts who helped me with the technical developments. Among others, Marvin Spitsbaard who supported me in LCA data retrieval, Agata Rijs and Florent Gauvin from the TU/e with a great help in building physic related discussions. Jeroen Werbrouck, Rick van Fessem and Tanis Mohammed Karigar in supporting me to learn the LBD Server, JavaScript and R-Studio coding. Finally, Gert Regterschot for his constant tutoring through my whole time at the TU/e. After a long period of hard work and experiencing personal and scientific growth I want to thank my family, friends and boyfriend to have joined and supported me morally and emotionally throughout this journey. I could not have done it without you all.

I wish you all happy reading and browsing thought this very broad and divers' research.

Julia Katharina Kaltenegger

Eindhoven, October 2021

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# Executive Summary

**1) Motivation and research objective**

The European Union within its EU Green Deal policy packages aims to facilitate a 'Renovation Wave' for buildings across Europe, to address the climate and ecological crisis and enable meeting climate targets. Insulation materials represent the first and most important improvement measure when retrofitting homes. Insulation materials, however, differ on a wide set of criteria, including thermal properties, environmental, economic, health and safety-related characteristics. To date, the challenge is to identify trade-offs between these criteria, particularly in a participatory decision-making process.

The objective of this thesis is to introduce a web-based decision support tool for building refurbishments. The tool aims to find optimized decisions based on an equilibrium in engineering evaluation methods and consumer preferences.

"Can we design a web-based decision support tool for sustainable refurbishment projects that brings together engineering evaluation methods and consumers´ preferences assessment?"

The users of the web tool are primarily construction engineers who plan energy refurbishments. Second, the energy collectives who represent a group of homeowners that face collective refurbishment.

**2) Methodology**

The scope of the tool is based upon a decision support system that invites all stakeholders to make decisions together. The method consists of three parts. Firstly, the web-based assessment framework used to host the tool is explained. In the second part, a use case is defined, and refurbishment scenarios are analysed. Material performance assessments are done using the Life Cycle Assessment (LCA) method, cost and comfort assessment. Finally, the consumer research is built upon the results of the use case and applies the stated choice method to explore the market potential of the refurbishment solutions. The tool content is defined by the combined knowledge of engineering design evaluation and decision-making process based on the economic behavioural research.

2.1) Web based framework

An emphasise was given to enrich current engineering Building Information Modelling (BIM) practice with semantic web technology. Recent developments such as the Linked Building Data (LBD) server are used to establish a decentralized communication platform for the AEC industry. It enables to link digital building models (BIM) to interdisciplinary and building-related data throughout multiple web-based data sources [1]. The web-based assessment framework is based upon the web application architecture, see **Figure 1.** In this framework the user of the web tool activates the browser and interacts thereby with the web server. The Application Programming Interface (API) of the LBD Server is hosted on such a web server. We use the LBD server and identify further functionalities. User and system requirements are defined via the Unified Modelling Language (UML). Moreover, the web tool´s framework is defined with the Model View Controller (MVC) patterns. The backend builds upon NodeJS, MongoDB and graphDB, to host graphical and non-graphical information. The newly developed frontend is the focus of this thesis and will engage user queries in regard of digital building components assessed with externally held database (DB). JavaScript is used to develop interactive user interfaces (UI) in the React framework. The databases are established using MySQL Workbench. We focus on LCA data for early design and costing data, deriving from Dutch Nationale Milieu Database (NMD) and manufacturing cost data.

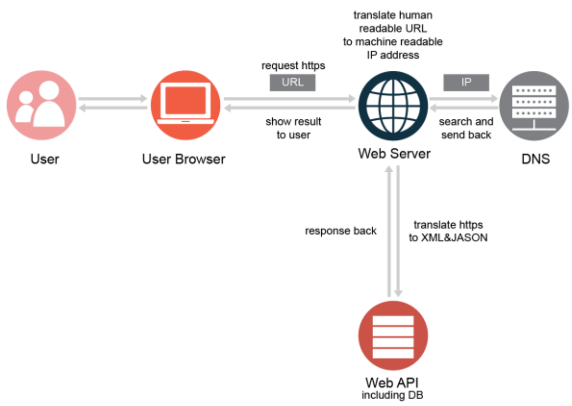



**Figure 1 Web application architecture**

2.2) The case study and engineering design analysis (comparative material analysis)

The potentials of the tool are showcased by application to a case study. A Dutch terrace house (Rijwoning) is used. The as-is performance shows poor insulation for wall and roof, low thermal comfort and too high energy costs [2, 3]. The goal is to refurbish while encompassing a holistic sustainable design process. Two refurbishment packages, each with several material scenarios, were designed. We used the LCA, cost assessment and material-related comfort assessment to analyse [4,5]. Our goal was to find comparable scenarios to make trade-offs between energy, cost, carbon and comfort, [6,7] see **Figure 2.**

The use case was modelled in the BIM Software Autodesk Revit. The as-built performance was analysed with the Primary Energy, operational Carbon and Energy Label calculation [8]. Energy modelling was conducted in VABI and verified with Design Builder. The BIM model of the use case is executed in LOD300. This includes separate building element layers with thermal properties [9]. Additionally, each component received classification codes, using the Dutch national construction nomination (NL-Sfb). This enables to detect building components and connect geometry to data of established databases (NMD and costing), using web-based user queries. A entity relationship diagram (ERD) is created to illustrate data cardinality.

| Functional Equivalent | P1 | P2 |
|---|---|---|
| What? | Low measure and no regret scenario. Includes the minimum thermal improvement.<br>- EPS<br>- Glass wool | Includes medium to high thermal improvement.<br>- Glass wool<br>- Rock wool<br>- Wood fibre |
| How much? | Includes wall and roof insulation into existing construction. Wall insulation thickness 6 to 8 cm, Roof insulation thickness 8 to 16cm. | Includes wall and roof insulation added as second layer inside. Wall insulation thickness 14 to 16 cm, Roof insulation thickness 22 to 26cm. |
| How well? | Energy Label C-B.<br>Wall Rc 1,7; Roof Rc 2,5<br>(opt. Window U 1.2) | Energy Label B-A.<br>P2: Wall Rc 4,0; Roof Rc 6,5,<br>(opt. Window U 0.7) |
| How long? | 10 years. | 10 years. |

**Figure 2 Refurbishment package system boundaries**

## 2.3) Market potential

### *2.3.1 Stated choice model*

The market potential study is based on behavioural research into the preferences of the homeowners. We analyse to what extent homeowners make trade-offs between various attributes of insulation when refurbishing their homes. The preference modelling is based upon the stated choice experiment. In this method, the participant is requested to choose between insulation options consisting of multiple attributes, while each attribute can perform in multiple levels. By letting individuals choose between options, the relative importance of each attribute can be derived.

For the base model the standard multinomial logit model is used to analyse and explain the discrete choices. Using the probability theory, the likelihood of collective decision making between two design alternatives and not to refurbish can be analysed. **Formula 1** is used to determine the utility of a package via combining a fixed number of attributes performing in different levels. **Formula 2** is used to identify the probability of choosing a package when comparing them to another package and no refurbishment [10, 11].

$$(1)\ U_{m=1,j} = V_{m=1,j} + \varepsilon_{m=1,j} = \sum_i (\beta_i * X_{i,j}) + \varepsilon_{m=1,j}$$

Where:
$U_{m=1,j}$ is the Utility for an alternative $j$.
$V_{m=1,j}$ is the Structural Utility when choosing alternative $j$.
$\beta_i$ is the parameter weight for $X_{i,j}$
$X_{i,j}$ is the value of the attribute $i$ of alternative $j$.
$\varepsilon$ is the Error component for the alternative $j$, that is assumed to be a standard Gumbel distribution.

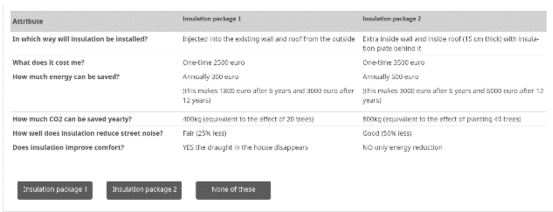
$$(2)\qquad P_{m=1,j} = \frac{exp^{V_{m=1,j}}}{exp^{\rho} + \sum_j exp^{V_{m=1,j}}}$$

Where:
$P_{m=1,j}$ is the probability that the analysed alternative $j$ is preferred over all alternatives.
$exp^{V_{m=1,j}}$ is the exponent of the structural utility of the observed alternative $j$.
$exp^{\rho}$ is the exponent of the structural utility of no refurbishment $\rho$.

### *2.3.2 Choice experiment*

The Stated Choice Experiment has been executed online amongst 500 respondents. Choice situations were offered consisting of three alternatives: two are refurbishment packages, and one is not to refurbish. The level definitions per attribute are the corner values resulting from the use case performance. While the number of attributes remains the same, the level definitions are presented using an orthogonal design, see **Figure 3.** Chosen attributes and levels were:

*(i) installation method (L0: injection, L1: second wall inside)*
*(ii) investment cost (L0: 2500€, L1: 3500€)*
*(iii) energy bill saving (L0: 300€/yr, L1: 500€/yr)*
*(iv) $CO_2$ saving (L0: 400kg/yr, L1: 800kg/yr)*
*(v) noise reduction (L0: fair 25%, L1: good 50%)*
*(vi) comfort improvement (L0: no, L1: yes)*


| Attribute | Insulation package 1 | Insulation package 2 |
|---|---|---|
| In which way will insulation be installed? | Injected into the existing wall and roof from the outside | Extra inside wall and inside roof (15 cm thick) with insulation plate behind it |
| What does it cost me? | One-time 2500 euro | One-time 3500 euro |
| How much energy can be saved? | Annually 300 euro<br>(this makes 1800 euro after 6 years and 3600 euro after 12 years) | Annually 500 euro<br>(this makes 3000 euro after 6 years and 6000 euro after 12 years) |
| How much CO2 can be saved yearly? | 400kg (equivalent to the effect of 20 trees) | 800kg (equivalent to the effect of planting 40 trees) |
| How well does insulation reduce street noise? | Fair (25% less) | Good (50% less) |
| Does insulation improve comfort? | YES the draught in the house disappears | NO only energy reduction |

Insulation package 1 | Insulation package 2 | None of these

**Figure 3 Experiment Design, Attributes and Levels**

# 3) Findings

## 3.1) Web tool ROTUNDORO

In this thesis the web-based tool ROTUNDORO is introduced. It illustrates a concept framework that combines the design and decision support within one online hosted platform, see **Figure 4.** The platform allows engineers to upload their as-is building model documentation. Refurbishment packages can be created on the platform that are then assessed with energy performance modelling, LCA and costing assessments. The related externally held data is communicated via the platform per user request. The final section, the market potential, shows the resulting refurbishment package performances. The consumer research is encompassed in here and shows for the chosen packages the probability of acceptance in percentage (%).

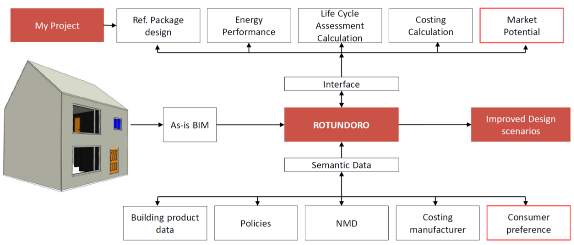



**Figure 4 System Design ROTUNDORO**

As for the web application integration, it was found that semantic enrichment of BIM has potential to interlink interdisciplinary data and design evaluation methods with each other. The LBD method was found as an attractive framework to create design scenarios that are updated in real time regarding their performance. Comparisons can be more easily established and dynamically visualised to the clients based on the 3D digital building model. The difficulty of this ambition was in matching multiple data sources with BIM models. For early BIM-based design evaluation, simple geometrical components with basic information are sufficient. However, accurate modelling skills remain in the engineer´s scope. Furthermore, databases proved to be difficult to access from the web. Database structures were manually adapted to make them relational towards the BIM model.

The React framework and the coding in JavaScript was identified suitable when working on the web. Other frameworks, such as Django in Python are alternatives, however lack on open source development documentation that include BIM and semantic data enrichment. The LBD Server provided the 3D Viewer and the possibility to access geometrical components information. Moreover, embedding the connection towards MySQL DB was successfully established. The connection between the user query of geometry and external data remains a development task for the future.

### 3.2) Material study

The material analyses for the refurbishment packages required increased preparation efforts. It was found that the LCA data of the NMD contains different system boundaries. This means that in theory the data cannot be directly compared with each other. The NMD does not contain a wide set of bio-based materials, and thus excludes a big domain. Material data from manufacturers vary per manufacturing process resulting in different performance scores within one product category.

We put emphasis on comparing materials that perform nearly the same in the system boundary. We choose EPS, glass wool, rock wool and wood fibre. Results show that bio-based materials perform best in environmental concerns, low embodied carbon, high noise reduction and humidity regulation. Fossil and mineral-based materials are however market-leading, due to low prices and easier application techniques in existing constructions (cavity injection).

### 3.3) Consumer research

The experiment was successfully performed with the help of energy collectives in Eindhoven Area (Netherlands). 040Energie and Best Duurzaam distributed the survey amongst their collective members. Nearly 500 participants contributed and shared their preferences. The relative importance of different insulation characteristics is presented in **Figure 5.**

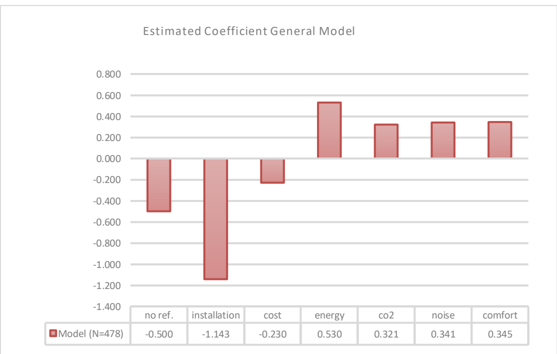



**Figure 5 Relative importance of coefficients**

The coefficients are analysed as the weighting factor of the level performance per attribute, L1 compared to L0. Findings reveal that the studied population showed a high willingness to invest in energy refurbishment. This can be seen in a very negative coefficient of no refurbishment. The likelihood that people prefer no refurbishment over renovating is low. The installation method of using a second insulation wall inside is clearly outperformed by the cavity injection.

An annual energy reduction of 500€/yrs is highly preferred by a positive coefficient of 0.53 (50% more than L0:300€/yrs). The investment cost shows a low negative effect of -0.230. This shows that people are willing to invest. The $CO_2$ reduction, noise reduction and comfort improvement show equally important and statistically significant weights. Psychosocial health and comfort assessment shows that the homeowners suffer from noise disturbance and draft in the attic. These insights applied in the ROTUNDORO tool to the use case, suggest that injectable insulation materials with higher energy reduction level have the highest attractiveness for homeowners, closely followed by low carbon and noise reducing materials.

## 4) Conclusion

This study offers a tool for enabling collective decision-making process in context of the European renovation wave. A video that introduces the tool can be found here. In order to verify design scenarios of the engineers, the potential market adoption inside the tool shows the probability of acceptance of the homeowners. A web-based building performance platform is proposed to improve communication amongst different stakeholders, see **Figure 6.**

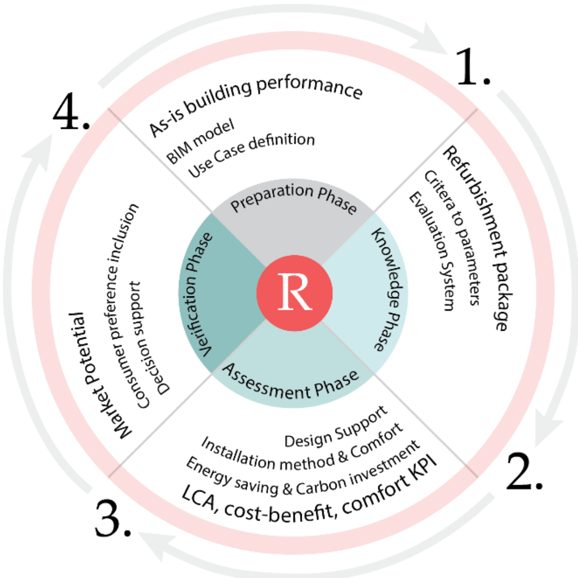



**Figure 6 ROTUNDURO**

It can be concluded that the harmonization between engineering methods and consumer research shows success. Homeowners find carbon reduction and comfort improvement equally important. This suggests performing refurbishment assessments in all key aspects of sustainable development. The use of LCA (operational and embodied impact assessment) in the design process can be encouraged by free to use LCA data, and easy to use assessment tools. A conscious material selection is thereby created that potentially leads to economic growth for renewable materials.

The web approach reveals great opportunity to provide such an easy to use tool. However, this can happen only when market developments shift stronger towards a free-to-use data policy in compliance with classification schemas.

Future research could include upscaling of such refurbishment solutions to a neighbourhood level. It is recommended to cluster target groups, for instance by building typology, building impairments, refurbishment goal and socio demographics.

## 5) References


[1] Malcolm, A; Werbrouck, J; Pauwels, P. (2020). LBD server : Visualising Building Graphs in web-based environments using semantic graphs and glTF-models LBD server : Visualising Building Graphs in web-based environments using semantic graphs and glTF-models, (2020).

[2] Agentschap a NL. (2011). Voorbeeldwoningen 2011 Onderzoeksverantwoording

[3] Agentschap b NL. (2011). Bestaande bouw Voorbeeldwoningen 2011.

[4] Schiavoni, S., D'Alessandro, F., Bianchi, F., & Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews, 62, 988–1011. https://doi.org/10.1016/j.rser.2016.05.045

[5] Kumar, D., Alam, M., Zou, P. X. W., Sanjayan, J. G., & Ahmed, R. (2020). Comparative analysis of building insulation material properties and performance. Renewable and Sustainable Energy Reviews, 131(July), 110038. https://doi.org/10.1016/j.rser.2020.110038

[6] García-Martínez, A., & Sánchez-Montañés, B. (2016). Life cycle assessment ( LCA ) of building refurbishment : A literature review, (November). https://doi.org/10.1016/j.enbuild.2016.11.042

[7] Röck, M., Ruschi, M., Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., … Lützkendorf, T. (2020). Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation ☆. Applied Energy, 258(October 2019), 114107. https://doi.org/10.1016/j.apenergy.2019.114107

[8] Daša Majcen. (2016). Predicting energy consumption and saving in the housing stock NL. A performance gap analysis in the Netherlands （2016）. Ccwg. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:00795500-6704-49c0-903f-6b6ba77dc544/datastream/OBJ

[9] Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM : Visualization of environmental potentials in building construction at early design stages, 140(May), 153–161. https://doi.org/10.1016/j.buildenv.2018.05.006

[10] Ossokina, I. V, Arentze, T. A., Gameren, D. Van, & Heuvel, D. Van Den. (2019). Best living concepts for elderly homeowners : combining a stated choice experiment with architectural design. Journal of Housing and the Built Environment, (0123456789). https://doi.org/10.1007/s10901-019-09716-5

[11] Ossokina, I. V., Kerperien, S., & Arentze, T. A. (2021). Does information encourage or discourage tenants to accept energy retrofitting of homes? Energy Economics, 103(August), 105534. https://doi.org/10.1016/j.eneco.2021.105534

# Management Samenvatting

**1) Motivatie en onderzoeksdoelstelling**

De Europese Unie wil met haar EU Green Deal beleid een 'Renovatiegolf' voor gebouwen in heel Europa faciliteren, om de klimaat- en ecologische crisis aan te pakken en het halen van klimaatdoelstellingen mogelijk te maken. Isolatie vormt de eerste en belangrijkste verbeteringsmaatregel bij het renoveren van woningen. Isolatiematerialen verschillen echter op een groot aantal punten, waaronder thermische eigenschappen en milieu-, economische, gezondheids- en veiligheids-gerelateerde kenmerken. Tot op heden is het een uitdaging om deze criteria onderling af te wegen, vooral in een participatief besluitvormingsproces.

Het doel van deze thesis is het introduceren van een web-based beslissingsondersteunende tool voor het renoveren van gebouwen. De tool heeft als doel om beslissingen te optimaliseren gebaseerd op een balans van technische evaluatiemethoden en consumenten-voorkeuren.

De hoofdvraag is derhalve: "Kan een web-based beslissingsondersteunende tool voor duurzame renovatieprojecten ontworpen worden die de evaluatiemethoden van technische ingenieurs en de voorkeuren van consumenten samenbrengt?"

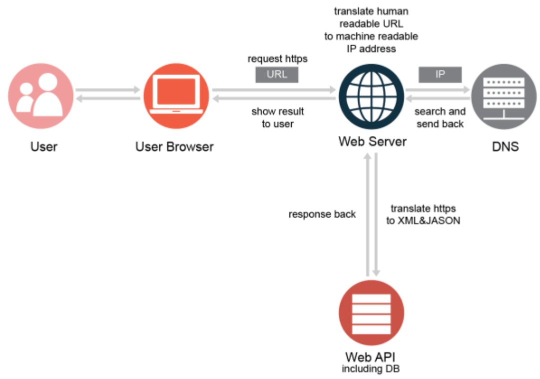
De gebruikers van de webtool zijn in de eerste plaats bouwingenieurs die energierenovaties plannen. Ten tweede, de energiecollectieven die een groep huiseigenaren vertegenwoordigen die te maken krijgen met collectieve renovaties.

**2) Methodologie**

De tool is een beslissingsondersteunend systeem dat alle belanghebbenden uitnodigt om gezamenlijk beslissingen te gaan nemen. De methode bestaat uit drie delen. Eerst wordt het web-based kader toegelicht dat wordt gebruikt om de tool te hosten. In het tweede deel wordt een use case gedefinieerd en worden renovatie-scenario's geanalyseerd. De materiaalprestaties worden beoordeeld met behulp van de methode van de levenscyclusanalyse (LCA), de kosten en het comfort. Tot slot wordt het consumentenonderzoek gebaseerd op de resultaten van de use case en wordt de stated choice-methode gebruikt om het marktpotentieel van de renovatie-oplossingen te onderzoeken. De inhoud van de tool wordt bepaald door de kennis uit de combinatie van de evaluatie van het engineeringontwerp en het besluitvormingsproces op basis van economisch gedragsonderzoek.

2.1) Web-based kader

Nadruk werd gelegd op het verrijken van de huidige engineering BIM-praktijk met semantische web-technologie. Recente ontwikkelingen zoals de Linked Building Data (LBD)-server worden gebruikt om een gedecentraliseerd communicatieplatform voor de AEC-industrie op te zetten. Het maakt het mogelijk om digitale bouwmodellen (BIM) te koppelen aan interdisciplinaire en bouwgerelateerde data uit meerdere web-based gegevensbronnen [1]. Het web-based beoordelingskader is gebaseerd op de architectuur van de web-toepassing, zie **Figuur 1**. In dit kader activeert de gebruiker van de web-tool de browser in interactie met de webserver. De Application Programming Interface (API) van de LBD-server wordt gehost op zo'n webserver. We gebruiken de LBD-server en beschrijven overige functionaliteiten. Gebruikers- en systeemvereisten worden gedefinieerd via de Unified Modelling Language (UML). Bovendien is het raamwerk van de webtool gedefinieerd met Model View Controller (MVC) patronen. De backend is gebaseerd op NodeJS, MongoDB en graphDB, voor het hosten van grafische en niet-grafische informatie. De recent ontwikkelde frontend is de focus van deze thesis en zal gebruikers queries laten uitvoeren met betrekking tot digitale bouwcomponenten afkomstig uit de externe database (DB). JavaScript wordt gebruikt om interactieve gebruikersinterfaces te genereren binnen het React framework. De databases worden opgezet met behulp van MySQL Workbench. Wij richten ons op LCA-data uit de ontwerpfase en kostengegevens, afkomstig van de Nederlandse Nationale Milieu Database (NMD) en productiekostengegevens.




**Figuur 1 Web applicatie architectuur**

2.2) De case-studie en de analyse van het engineering-ontwerp (vergelijkende materiaalanalyse)

De mogelijkheden van de tool worden getoond door het uitvoeren van een case-studie. Hierbij wordt gebruik gemaakt van een Nederlands rijtjeshuis (Rijwoning). De huidige situatie toont een slechte isolatie van muur en dak, een laag thermisch comfort en te hoge energiekosten [2, 3]. Het doel is om te renoveren en daarbij een holistisch duurzaam ontwerpproces te doorlopen. Twee renovatiepakketten, elk met verschillende materiaal-scenario's, werden ontworpen. We gebruikten de LCA, kostenbeoordeling en materiaalgerelateerde comfort-beoordeling voor de analyse [4,5]. Ons doel is vergelijkbare scenario's te vinden om afwegingen te maken tussen energie, kosten, koolstof en comfort, [6,7] zie **Figuur 2**.

| Functional Equivalent | P1 | P2 |
|---|---|---|
| **What?** | Low measure and no regret scenario. Includes the minimum thermal improvement.<br>- EPS<br>- Glass wool | Includes medium to high thermal improvement.<br>- Glass wool<br>- Rock wool<br>- Wood fibre |
| **How much?** | Includes wall and roof insulation into existing construction. Wall insulation thickness 6 to 8 cm, Roof insulation thickness 8 to 16cm. | Includes wall and roof insulation added as second layer inside. Wall insulation thickness 14 to 16 cm, Roof insulation thickness 22 to 26cm. |
| **How well?** | Energy Label C-B.<br>Wall Rc 1,7; Roof Rc 2,5<br>(opt. Window U 1.2) | Energy Label B-A.<br>P2: Wall Rc 4,0; Roof Rc 6,5,<br>(opt. Window U 0.7) |
| **How long?** | 10 years. | 10 years. |

**Figuur 2 Opties renovatie pakketten**

De use-case werd gemodelleerd in de BIM-software Autodesk Revit. De as-built prestaties werden geanalyseerd met de berekening van de primaire energie, de operationele koolstof en het energielabel [8]. De energiemodellering werd uitgevoerd in VABI en geverifieerd met Design Builder. Het BIM-model van de use-case is uitgevoerd in LOD300. Dit omvat afzonderlijke bouwelement-lagen met thermische eigenschappen [9]. Bovendien kreeg elk onderdeel classificatiecodes, op basis van de Nederlandse nationale bouwnominatie (NL-Sfb). Dit maakt het mogelijk om gebouw componenten te detecteren en de geometrie te verbinden met gegevens van bekende databases (NMD en kostenberekening), met behulp van web-based zoekopdrachten. Er wordt een entiteitenrelatiediagram (ERD) gemaakt om de omvang van de gebruikte datasets te illustreren.

## 2.3) Markt potentieel

### *2.3.1 Stated choice model*

Het marktpotentieelonderzoek is gebaseerd op gedragsonderzoek naar de voorkeuren van de huiseigenaren. We analyseren in hoeverre huiseigenaren bij het renoveren van hun woning afwegingen maken tussen verschillende kenmerken van isolatie. De voorkeursmodellering is gebaseerd op het stated choice experiment. Bij deze methode wordt de deelnemer gevraagd te kiezen tussen isolatie-opties bestaande uit meerdere attributen, terwijl elk attribuut op meerdere niveaus kan presteren. Door individuen tussen opties te laten kiezen, kan het relatieve belang van elk attribuut worden afgeleid.

Voor het basismodel gebruiken wij het standaard multinomiale logit-model om de discrete keuzes te analyseren en te verklaren. Met behulp van de waarschijnlijkheidstheorie, is het mogelijk om de collectieve voorkeuren tussen de twee renovatie-opties en de 0-optie, dus niet renoveren, te analyseren. De **Formule 1** is opgebouwd uit een vast aantal attributen elk met verschillend niveaus, die de effectiviteit van een pakket bepalen. **Formule 2** wordtgebruikt om de kans te bepalen dat een packet wordt gekozen wanneer deze wordt vegeleken met de vooraf eerder benoemde alternatieve opties [10, 11].

*(1)* $U_{m=1,j} = V_{m=1,j} + \varepsilon_{m=1,j} = \sum_i (\beta_i * X_{i,j}) + \varepsilon_{m=1,j}$

waarbij:
$U_{m=1,j}$ is de Utility voor alternatief $j$.
$V_{m=1,j}$ is de Structural Utility voor alternatief $j$.
$\beta_i$ is de parametercoefficient voor $X_{i,j}$.
$X_{i,j}$ s de waarde van attribuut $i$ oor alternatief $j$.
$\varepsilon$ is de error component voor alternatief $j$, ie per aanname volgens een Gumbel verdeling verdeeld is.

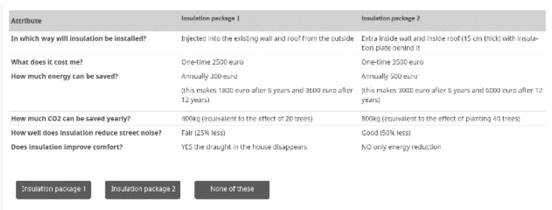
(2) $$P_{m=1,j} = \frac{exp^{V_{m=1,j}}}{exp^{\rho} + \sum_j exp^{V_{m=1,j}}}$$

waarbij
$P_{m=1,j}$ is de kans dat het beschouwde alternatief de voorkeur krijgt van alle mogelijke alternatieven.
$exp^{V_{m=1,j}}$ is de e-macht van de Structural Utility van het beschouwde alternatief.
$exp^{\rho}$ is de e-macht van de Structural Utility van het de 0-optie $\rho$.

### *2.3.2 Stated choice experiment*

Het Stated Choice Experiment is online uitgevoerd onder 500 respondenten. Er werden keuzesituaties geboden bestaande uit drie alternatieven: twee zijn renovatiepakketten en één is niet te renoveren. De niveaudefinities per attribuut zijn de hoekwaarden die voortkomen uit de use case performance. Hoewel het aantal attributen hetzelfde blijft, worden de niveaudefinities gepresenteerd met behulp van een orthogonaal ontwerp, zie **Figuur 3**. Gekozen attributen en niveaus waren:

*(i) installatiemethode (L0: injectie, L1: tweede laag inwendig)*
*(ii) investeringskosten (L0: 2500€, L1: 3500€)*
*(iii) energierekening besparen (L0: 300€/jaar, L1: 500€/jaar)*
*(iv) $CO_2$-besparing (L0: 400kg/jr, L1: 800kg/jr)*
*(v) geluidsreductie (L0: redelijk 25%, L1: goed 50%)*
*(vi) comfortverbetering (L0: nee, L1: ja)*



| Attribute | Insulation package 1 | Insulation package 2 |
|---|---|---|
| In which way will insulation be installed? | Injected into the existing wall and roof from the outside | Extra inside wall and inside roof (15 cm thick) with insulation plate behind it |
| What does it cost me? | One-time 2500 euro | One-time 3500 euro |
| How much energy can be saved? | Annually 300 euro (this makes 1800 euro after 6 years and 3600 euro after 12 years) | Annually 500 euro (this makes 3000 euro after 6 years and 6000 euro after 12 years) |
| How much CO2 can be saved yearly? | 400kg (equivalent to the effect of 20 trees) | 800kg (equivalent to the effect of planting 40 trees) |
| How well does insulation reduce street noise? | Fair (25% less) | Good (50% less) |
| Does insulation improve comfort? | YES the draught in the house disappears | NO only energy reduction |

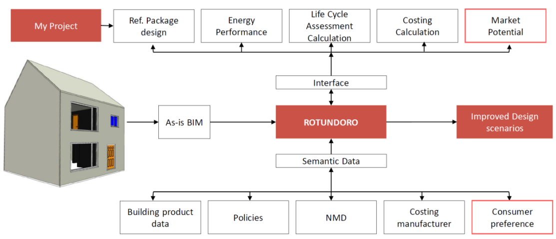
Insulation package 1 | Insulation package 2 | None of these

**Figuur 3 Experiment: Ontwerp, Attributen en Niveaus**

## **3) Resultaten**

## 3.1) Web tool ROTUNDORO

In deze thesis wordt de web-based tool ROTUNDORO geïntroduceerd. Het toont een conceptueel raamwerk dat ontwerp- en beslissingsondersteuning combineert binnen één online platform, zie **Figuur 4**. Het platform stelt ingenieurs in staat hun as-is gebouwmodel en bijhorende documentatie te uploaden. Op het platform kunnen renovatiepakketten worden gecreëerd die vervolgens worden beoordeeld aan de hand van energieprestatiemodellen, LCA's en kostenramingen. De gerelateerde externe data worden op verzoek van de gebruiker via het platform opgehaald. Het laatste deel, het marktpotentieel, toont de resulterende prestaties van de renovatiepakketten. Het consumentenonderzoek is hierin opgenomen en toont de waarschijnlijkheid van acceptatie in percentage (%).




**Figuur 4 Systeemontwerp ROTUNDORO**

Wat de integratie van webapplicaties betreft, werd vastgesteld dat semantische verrijking van BIM het potentieel heeft om interdisciplinaire data en ontwerpevaluatiemethoden met elkaar te verbinden. De methode van het koppelen van bouwdata bleek een aantrekkelijk kader te bieden om ontwerpscenario's te genereren die qua prestaties in real time worden bijgewerkt. Vergelijkingen kunnen gemakkelijker worden gemaakt en dynamisch gevisualiseerd voor de klanten op basis van het 3D digitale gebouwmodel. Het probleem van deze onderneming lag in het matchen van meerdere gegevensbronnen met BIM-modellen. Voor een eerste evaluatie van het ontwerp op basis van BIM volstaan eenvoudige geometrische componenten met basisinformatie. Nauwkeurige modelleervaardigheden blijven echter tot het werkterrein van de ingenieur behoren. Bovendien bleken databanken moeilijk toegankelijk te zijn vanaf het web. Database-structuren werden met de hand aangepast om ze relationeel te maken ten opzichte van het BIM-model.

Het React framework en de codering in JavaScript werd geschikt bevonden voor het uitvoering binnen een web-omgeving. Andere programmeertalen, zoals Django in Python zijn alternatieven, maar missen open source ontwikkelings-documentatie die BIM en de semantische dataverrijking omvatten. De LBD Server leverde de 3D Viewer en de mogelijkheid om toegang te krijgen tot geometrische componenten informatie. Daarnaast werd de verbinding met MySQL DB met succes tot stand gebracht. De verbinding tussen geometrie en externe gegevens echter blijft een ontwikkelingstaak voor de toekomst.

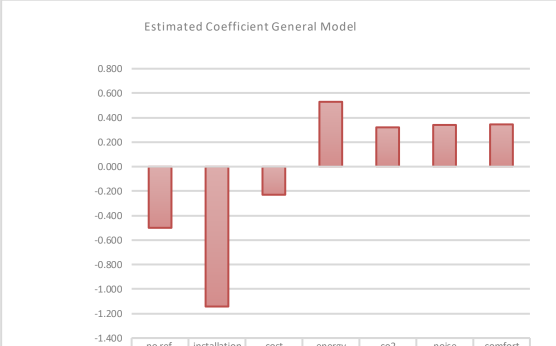
### 3.2) Materiaalstudie

De materiaalanalyses voor de renovatiepakketten vereisten een Groot voorbereidingsproces. Gebleken is dat de LCA-gegevens van de NMD verschillende systeemgrenzen bevatten. Dit betekent dat de gegevens in theorie niet rechtstreeks met elkaar kunnen worden vergeleken. De NMD bevat geen brede set van bio-based materialen, en sluit dus een groot gebied uit. Materiaalgegevens van fabrikanten verschillen per fabricageproces, wat resulteert in verschillende prestatiescores binnen één productcategorie.

Wij leggen de nadruk op het vergelijken van materialen die bijna hetzelfde presteren in dezelfde systeemgrenzen. We kiezen voor EPS, glaswol, steenwol en houtvezel. De resultaten tonen aan dat bio-based materialen het best presteren op het vlak van milieubelasting, lage koolstof, hoge geluidsreductie en vochtregulering. Materialen op fossiele en minerale basis zijn tot heden aantrekkelijker vanwege de lage prijzen en eenvoudigere toepassingstechnieken in bestaande constructies (spouwinjectie).

### 3.3) Consumentenonderzoek

Het experiment is succesvol uitgevoerd met hulp van energiecollectieven in Eindhoven Area (Nederland). 040Energie en Best Duurzaam hebben de enquête verspreid onder hun gezamenlijke leden. Bijna 500 deelnemers droegen bij en deelden hun voorkeuren. Het relatieve belang van verschillende isolatie-eigenschappen wordt weergegeven in: **Figuur 5**.




| | no ref. | installation | cost | energy | co2 | noise | comfort |
|---|---|---|---|---|---|---|---|
| Model (N=478) | -0.500 | -1.143 | -0.230 | 0.530 | 0.321 | 0.341 | 0.345 |

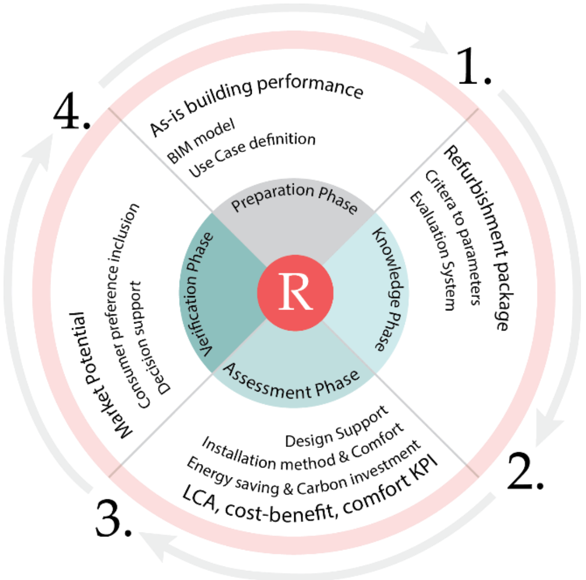
**Figuur 5 Relatief belang van coëfficiënten**

De coëfficiënten worden geanalyseerd als de wegingsfactor van de niveauprestatie per attribuut, L1 ten opzichte van L0. Uit bevindingen blijkt dat de onderzochte populatie een hoge bereidheid toonde om te investeren in energierenovatie. Dit kan worden gezien in een zeer negatieve coëfficiënt van geen renovatie. De waarschijnlijkheid dat mensen liever niet renoveren dan renoveren is zeer laag. De installatiemethode met een tweede isolerende binnenmuur wordt duidelijk overtroffen door de spouwinjectie.

Een jaarlijkse energiereductie van 500€/jr wordt sterk geprefereerd met een positieve coëfficiënt van 0,53 (50% meer dan L0: 300€/jr). De investeringskost vertoont een lage negatieve coëfficiënt van -0,230. Hieruit blijkt dat huiseigenaren weinig geneigd zijn te investeren in een lagere geldwaarde. De $CO_2$-reductie, geluidsreductie en comfortverbetering laten ook statistisch significante resultaten zien. Uit psychosociale gezondheids- en comfortbeoordeling blijkt dat de huiseigenaren last hebben van geluidsoverlast en tocht op zolder. Deze inzichten, toegepast in de ROTUNDORO tool op de use case, suggereren dat injecteerbare isolatiematerialen met een hoger energiereductie de grootste aantrekkelijkheid hebben voor huiseigenaren, op de voet gevolgd door koolstofarme en geluid reducerende materialen.

### 4) Conclusie

Deze studie heeft een tool opgeleverd om collectieve besluitvorming mogelijk te maken in de context van de Europese renovatiegolf. De tool benadrukt de interactie tussen de vraag van de stedelijke ontwikkeling op de markt en de verantwoordelijkheid van de ingenieurs om de globale klimaatdoelstellingen te bereiken. Een video die de tool introduceert, is hier te vinden. Om ontwerp-scenario's van de ingenieurs te verifiëren, toont de potentiële marktaanpassing in de tool de waarschijnlijkheid van acceptatie door de huiseigenaren. Er wordt een web-based platform voor de prestaties van gebouwen voorgesteld om de communicatie tussen de verschillende belanghebbende betrokken partijen te verbeteren, zie **Figuur 6.**




**Figuur 6 ROTUNDURO**

Er kan worden geconcludeerd dat de harmonisatie tussen technische methoden en consumentenonderzoek succes heeft. Huiseigenaren vinden $CO_2$-reductie en comfortverbetering even belangrijk. Dit suggereert het uitvoeren van beoordelingen van renovatie pakketten in alle belangrijke aspecten van duurzame ontwikkeling. Het gebruik van LCA (beoordeling van operationele en intrinsieke effecten) in het ontwerpproces kan worden aangemoedigd door vrij beschikbare LCA-gegevens, en eenvoudig te gebruiken beoordelingstools. Zo ontstaat een bewuste materiaalkeuze die kan leiden tot economische groei voor hernieuwbare materialen.

De webbenadering biedt grote mogelijkheden om een dergelijk gebruiksvriendelijk instrument aan te bieden. Dit kan echter alleen gebeuren wanneer de marktontwikkelingen sterker opschuiven in de richting van een open data beleid volgens eenduidige classificatieschema's.

Toekomstig onderzoek zou zich kunnen richten op het opschalen van dergelijke renovatieoplossingen naar wijkniveau. Aanbevolen wordt om de doelgroepen te clusteren, bijvoorbeeld op basis van gebouwtypologie, beperkingen van het gebouw, renovatiedoel en sociaal-demografische gegevens.

## 5) Referenties


[1] Malcolm, A; Werbrouck, J; Pauwels, P. (2020). LBD server : Visualising Building Graphs in web-based environments using semantic graphs and glTF-models LBD server : Visualising Building Graphs in web-based environments using semantic graphs and glTF-models, (2020).

[2] Agentschap a NL. (2011). Voorbeeldwoningen 2011 Onderzoeksverantwoording

[3] Agentschap b NL. (2011). Bestaande bouw Voorbeeldwoningen 2011.

[4] Schiavoni, S., D'Alessandro, F., Bianchi, F., & Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews, 62, 988–1011. https://doi.org/10.1016/j.rser.2016.05.045

[5] Kumar, D., Alam, M., Zou, P. X. W., Sanjayan, J. G., & Ahmed, R. (2020). Comparative analysis of building insulation material properties and performance. Renewable and Sustainable Energy Reviews, 131(July), 110038. https://doi.org/10.1016/j.rser.2020.110038

[6] García-Martínez, A., & Sánchez-Montañés, B. (2016). Life cycle assessment ( LCA ) of building refurbishment : A literature review, (November). https://doi.org/10.1016/j.enbuild.2016.11.042

[7] Röck, M., Ruschi, M., Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., … Lützkendorf, T. (2020). Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation ☆. Applied Energy, 258(October 2019), 114107. https://doi.org/10.1016/j.apenergy.2019.114107

[8] Daša Majcen. (2016). Predicting energy consumption and saving in the housing stock NL. A performance gap analysis in the Netherlands （2016）. Ccwg. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:00795500-6704-49c0-903f-6b6ba77dc544/datastream/OBJ

[9] Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM : Visualization of environmental potentials in building construction at early design stages, 140(May), 153–161. https://doi.org/10.1016/j.buildenv.2018.05.006

[10] Ossokina, I. V, Arentze, T. A., Gameren, D. Van, & Heuvel, D. Van Den. (2019). Best living concepts for elderly homeowners : combining a stated choice experiment with architectural design. Journal of Housing and the Built Environment, (0123456789). https://doi.org/10.1007/s10901-019-09716-5

[11] Ossokina, I. V., Kerperien, S., & Arentze, T. A. (2021). Does information encourage or discourage tenants to accept energy retrofitting of homes? Energy Economics, 103(August), 105534. https://doi.org/10.1016/j.eneco.2021.105534

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# Abbreviations

| | |
|---|---|
| **API** | Application Programming Interface |
| **BIM** | Building Information Modelling |
| **BITS** | Building Integrated Technical System |
| **CDE** | Common Data Environment |
| **EPDB** | Energy Performance and Building Directive |
| **EPD** | Environmental Product Declarations |
| **ERD** | Entity Relationship Diagram |
| **gbXML** | green building eXtensible Markup Language |
| **gLTF** | Graphics Language Transmission Format |
| **GHG** | Greenhouse Gas |
| **GWP** | Global Warming Potential |
| **HTML** | Hypertext Mark-up Language |
| **HTTP** | Hypertext Transfer Protocol |
| **IFC** | Industry Foundation Classes |
| **LBD** | Linked Building Data |
| **LCT** | Life Cycle Thinking |
| **LCA** | Life Cycle Assessment |
| **LCC** | Life Cycle Costs |
| **NMD** | Nationale Millieu Database |
| **nZEB** | net Zero Energy Building |
| **nZCB** | net Zero Carbon Building |
| **Rc-Value** | Thermal resistance in $(K \cdot m^2)/W$ |
| **UML** | Unified Modelling Language |
| **U-Value** | Thermal transmittance in $W/(m^2 \cdot K)$ |
| **SCE** | Stated Choice Experiment |
| **SSOT** | Single Source of Truth |
| **SQL** | Structural Query Language |
| **TTL** | Terse RDF Triple Language (Turtle) |
| **XML** | eXtensible Markup Language |

# CHAPTER 1
# Introduction

*"Progress does not amount to destroying the future,*
*but to preserving its essence,*
*to generate the impetus to do it better today"* [1]

[1] Y. Ortega Y Gasset, Bespiegelingen over leven en denken, historie en techniek (The Hague: H.P. Leopold N.V., 1951), 196 as cited in Zijlstra, 2009, page 9.

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# 1 Introduction

## 1.1 Background and context

Human activity is exceeding planetary boundaries. Amongst other negative effects, this contributes to climate change. To curb global climate change to manageable levels, emissions need to be reduced to return within the earth's carrying capacity *(Stockholm Resilience Centre, 2020; Steffen et al., 2015).* Due to its high resource and energy consumption, the building sector has been identified as a major factor in this transition. The building industry´s global ecological footprint represents a percentage share out of the respective categories, 40% of the global energy consumption, 30% of the global greenhouse gas (GHG) emission, 30% of the global raw material consumption, 25% of solid waste, 25% of water consumption and 12% of land use. While the buildings industry boosts the economy and gross domestic products (GDP), these numbers continue to increase rapidly while they need to decrease *(Ibn-Mohammed et al., 2013; Brejnrod et al., 2017).*

As part of its EU Green Deal policy, the European Union aims to enable a ´renovation wave´ for buildings across Europe. In this context, the goal of global climate protection policy applies. Striving to energy-neutral cities, it is aimed to switch to cleaner energy use and decarbonising the existing building stock *(European Commission, 2020).* In practice, these goals are pursued with the ambitions of net Zero Energy Buildings (nZEB) and net Zero Carbon Buildings (nZCB). To reach these ambitions, various refurbishment concepts have been developed that try to meet criteria of environmental, economic and social concerns *(Kamari et al., 2017; Taillandier et al., 2016).* The Intergovernmental Panel of Climate Change (IPCC) introduce the sustainable development framework in the construction industry.

One of the most important refurbishment concepts in housing refurbishment is the insulation of the building envelope. Choosing insulation materials includes a wide set of decision criteria. These reach beyond the thermal properties and address environmental footprint (embodied impact), investment cost, health, safety and comfort properties. No material performs overall best. Bio-based materials, such as wood fibre, perform best in environmental concerns, low embodied carbon, high noise and humidity reduction. Yet, fossil- and mineral-based materials, such as EPS and glass wool remain dominant on the market, due to low price and easier application techniques (cavity injection) in existing structures. Thus, a conscious selection process of insulation materials is inevitable when refurbishing sustainably (*Schiavoni et al., 2016; Visser et al., 2015; Kumar et al., 2020).*

There exist various methods to evaluate insulation refurbishment concepts. One has been suggested by the International Energy Agency (IEA) in 2014 (Annex IEA EBC 56). The idea is to use the Life Cycle Costing (LCC), the Life Cycle Assessment (LCA) methodology and the primary energy calculation to assess refurbishment design scenarios, such as insulation measures *(Almeida & Ferreira, 2015; Almeida & Ferreira, 2018).* The operational (energy use) and the embodied (environmental footprint) impact of buildings and their components are then summed up through the life cycle stages (cradle to grave) (*IEA EBC ANNEX 57, EN 15978:2011; Lützkendorf & Balouktsi, 2016; Passer et al., 2016; Ramírez-Villegas et al., 2019; Ortiz et al., 2020*). Another method *(Schiavoni et al., 2016; Kumar et al., 2020)* involves a comparative overview of the performance of different insulation materials on a large number of various criteria (cost, energy savings, fire safety, noise reduction, etc.). However, neither IEA (2014) nor Kumar (2020) offer solutions on how to join the different criteria in a single measure that can be used in a decision-making process. This thesis aims at filling this gap.

## 1.2 Problem Definition

The current decision-making process in Dutch housing refurbishments shows complexity in multiple aspects. Firstly, the existing residential building stock varies in a broad set of characteristics. Among others, it includes diversity in the building typology, the as-is construction, technical performances and occupants' behaviour (*Rijksdienst voor Ondernemend Nederland, 2013; Broers et al., 2019; Ebrahimigharehbaghi et al., 2019)*. This diversity further implies involvement of all stakeholders in setting goals and expectations to find the optimal refurbishment design scenario. Considered stakeholders reach from policymakers (governmental bodies), technical advisors (construction engineers and designers), energy collectives who support homeowners (end-users) in their decision to refurbish their homes. A high variety of interests result in different priorities regarding short-term and long-term benefits. Economic feasibility demands fast payback time to create attractive investments for the building owners. At the same time indoor comfort is essential for residents. On the other hand, the climate goals ask policymakers and construction engineers to implement environmental design guidelines to reach long-term climate targets *(Nault et al., 2018; Kamari et al., 2017; Malmgren & Mjörnell, 2015).*

Construction engineers and technical consultants use multiple software to assess building and refurbishment scenarios in a holistic sustainable assessment. The Building Information Modelling (BIM) method in combination with simulation tools is commonly used. They contain LCA analysis, energy use simulation and cost assessments. Current data exchanges between these tools lack a consistent translation scheme to make them reusable and readable for end-users (such as energy collectives and homeowners). Expert knowledge and use of involved tools are required to interpret and guarantee results. Moreover, end-users ask for designs scenarios that are visualised in comparison with each other and to the current construction. This requires simulation tools to be used in multiple combinations and redundant workflows. This leads to high time and communication costs between engineers and homeowners, and minders the interest by homeowners to perform such simulations *(Nault et al., 2018;* Jusselme *et al., 2020; Malmgren & Mjörnell, 2015; Röck et al., 2018*).

Further, the homeowner's preferences and consequentially the willingness to accept the solutions are often left out in engineering refurbishment software *(Chau et al., 2010)*. Energy Collectives in the Netherlands support homeowners in finding refurbishment solutions. It is challenging to represents individual preferences while seeking for solutions to purchase in collective groups. The end-user's choices when facing energy refurbishments are studied in behavioural economics and consumer research. Multiple studies discovered homeowners' interest to invest into energy efficiency measures, that are closely followed by criteria concerning carbon reduction and comfort improvement *(Alberini et al., 2013, Galassi & Madlener, 2017; Banfi et al., 2008, Ossokina et al., 2021).* Interactions with the participant of those studies are formulated with interviews, surveys and experiments, such as the Stated Choice Experiment (SCE). They examine trade-offs that homeowners make between multiple criteria when choosing design options. The results have however not been implemented in engineering decision support tools.

### 1.2.1 Research Gap

The harmonization of the engineering and behavioural methodologies within one decision-support tool is scarce in practice *(Thorpe, 2017).* Several studies propose decision support systems that include homeowners' criteria weighting at the very beginning of the process *(Nielsen et al., 2016; Gade et al., 2019).* Homeowners are meant to decide the criteria based upon their motives to refurbish. Guiding these criteria solely according homeowner's demands, risks an exclusion of a sustainable assessment framework, that harmonizes energy, carbon, cost and comfort criteria. Finding a balance between them remains challenging and requires a great number of engineering tools. The lack of communication of the engineering performance results as a basis for evaluating consumer preferences carries the risk of not meeting the expectations of the homeowner, resulting in disappointment with the solution *(Taillandier et al., 2016).* To this end, a platform is missing that includes construction engineering design assessment methods that stay in a sustainable framework and a consumer preferences model that accounts for the acceptance of the solutions for the homeowners. Novel developments are required that promote a participatory process of all these stakeholders on one easy-to-use and accessible platform *(Nault et al., 2018).*

### 1.2.2 Scientific relevance

The scientific relevance of such a platform lies in the harmonization of methods for engineering design evaluation and economic behaviour assessments. Both assessments are instruments that focus individually on the engineering and the end-user (homeowners) perspectives. Results of building performance assessments and consumers preferences are to be combined in an early project stage. Thereby transparency for both disciplines is created and leads to process optimization.

### 1.2.2 Practical relevance

The practical relevance of such the platform is the collaborative aspect. The platform is meant to be user together by construction engineers, energy collectives and homeowners. Communication in design and decision-making approach will be encouraged. Moreover, it can contribute to reaching climate goals and increasing the pace of refurbishments, in accordance with a sustainable framework (IEA methods and comparative material assessments). Engineers are supported by those methods, while energy collectives are helped in their decision of which design scenario to choose for a particular building use case.

## 1.3 Research Aim and Question(s)

The objective of this thesis is to introduce a web-based decision support tool for sustainable building refurbishments using building envelope insulation, bringing together an engineering and a consumer perspective. The platform aims to assist construction engineers and energy collectives to create refurbishment design scenarios for making decisions together. The main focus is on choosing the optimal insulation materials, while accounting for a number of objectives such as energy, carbon, cost and comfort. The main research question is defined as the following.

"Can we design a web-based decision support tool for sustainable refurbishment projects that brings together engineering evaluation methods and consumers´ preferences assessment?"

In order to answer the main research question, the following will list the defined sub-questions. Eight sub-questions are devoted to theoretical backgrounds (SQ1-SQ4) as well as practical and methodological applications (SQ5-SQ8). Terminologies that are used throughout the thesis are explained in **Table 1**.

SQ1) What are the ambitions of Dutch policymakers regarding building refurbishment and what role do insulation material measures play here? **2.1 Dutch refurbishment strategy**

SQ2) Which methodologies are currently used, that assess environmental performance of existing buildings, and evaluate possible refurbishment design scenarios? **2.2 Environmental performance of building**

SQ3) Which digital evaluation methods (tools) to assess building performances are currently on the market and what are the benefits of a BIM and web-based information exchange? **2.3 Digital evaluation methods**

SQ4) Which instruments for consumer preference modelling exist and how to translate multi-criteria objectives into a decision support system? **2.4 Decision Support System and Consumer Preference**

SQ5) What can a program of requirements for a web-based assessment framework look like that contains multi-criteria objectives in an engineering evaluation system and takes consumers preferences into account? **3 Program of Requirements**

SQ6) How can an engineering evaluation method be designed that assesses insulation material measures according a sustainable evaluation framework? **4 Evaluation System** 4 Evaluation System

> Which insulation material parameters influence the buildings' sustainable performance?
> How to set up a use case and utilize BIM together with LCA, cost and comfort assessment to appraise design scenarios?

SQ7) How do homeowners´ value sustainable criteria of such design scenarios, including energy, carbon, cost, health and comfort attributes? **5 Preference Modelling**

> How to utilize the stated choice experiment to investigate trade-offs made by homeowners when choosing design scenarios in the form of insulation packages?
> How can criteria weighting be used to verify the likelihood of acceptance of design scenarios?

SQ8) What can a web-based assessment framework look like that combines the evaluation system and the preference modelling together with BIM technology and semantic data enrichment? **6 Web-based assessment framework**

> How can the requirement engineering (RE) approach be used to elicit functional user and system requirements?
> How to create a relational database of multiple data sources and how to use React and JavaScript for frontend development?

| | |
|---|---|
| Web-based decision support tool: | A platform that is accessible online to all users. |
| Users of the web tool within an participatory decision-making process: | (i) construction engineers who plan energy refurbishments<br>(ii) energy collectives who represent a group of homeowners that face collective refurbishment. |
| Design scenarios: | Refurbishment packages and insulation material packages. |
| Sustainable evaluation framework: | A set of diverse assessment criteria including energy, carbon, cost and comfort assessment. |
| Engineering evaluation system: | A combination of building performance assessment methods. |
| Consumer preferences: | Homeowners' tastes for different attributes of the refurbishment, resulting in a higher or lower likelihood to adopt refurbishment solutions. |

**Table 1 Terminology definition**

## 1.4 Research Design

This thesis focuses on a tool development that combines engineering evaluation methods with urban research methods. Six Chapters address the problem definition to answer the research questions reaching from a theoretical part to practical implementation. Chapters 1 to 3 are focusing on theoretical reviews and approaches, Chapters 4 and 6 focuses on practical implementations, see **Figure 7**.

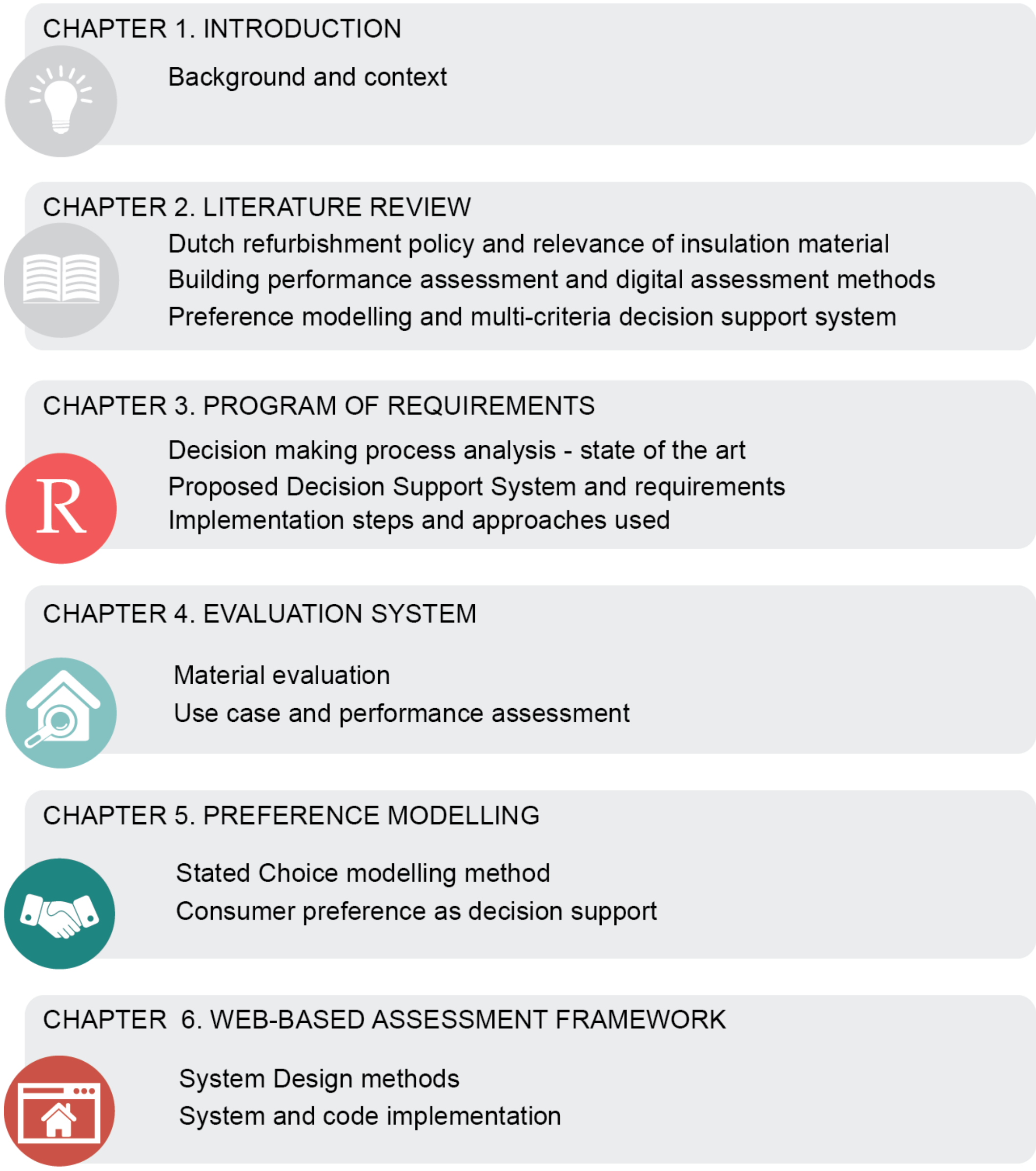


**Figure 7 Research Design and Paper outline**

The literature review is designed to discuss ambitions of Dutch policies regarding climate related targets and building improvements. The scope of building refurbishment is explained in life cycle stages. Feasible refurbishment measures are discussed, with a focus on insulation materials measures. The next section will elaborate on current building performance assessment methods. The digitalization aspects in the area of BIM and web-based information exchange are highlighted. Next, the decision-making process and the motives of involved stakeholders are juxtaposed to identify to what extent refurbishment harmonizes with the sustainability framework. The preference modelling will be introduced as a tool to assess multi-objectives of end users in refurbishment projects. Decision support tools are listed and explained.

**Chapter 3 Program of Requirements** introduces the requirements of the web-based tool ROTUNDORO. Firstly, the bottlenecks of current collective decision-making processes are discussed to define the in this thesis proposed decision support system. The proposed decision support tool introduces the implementation steps to combine engineering design methods with consumer research in one web-based assessment framework. It explains that the following Chapters 4, 5 and 6, introduce the methods and outcomes.

In **Chapter 4 Evaluation System**, an evaluation system is established that allows a holistic performance assessment of housing refurbishments. A use case is explained in refurbishment packages, applying energy and cost reduction, as well as material scenarios, that analyses the carbon footprints and investment cost per package.

In **Chapter 5 Preference Modelling**, preference modelling is introduced. It studies consumer preferences when collectively investing in insulation material packages. The conceptual framework of the Stated Choice Modelling introduces the utility and probability theory. The performance results of **Chapter 4 Evaluation System** are thereby used to design the experiment that is presented to the homeowners. Statistical results explain the homeowners' likelihood of investment. Finally, the probability of acceptance for different design scenarios (insulation packages) is used to support the collective decision-making process.

In **Chapter 6 Web-based assessment framework**, the web-based assessment framework introduces the methodologies and the actual development process of the online tool. Here, the implementation of the evaluation system (from **Chapter 4 Evaluation System**) and the decision-making support (from **Chapter 5 Preference Modelling**) inside the web tool are combined. The user and system requirement elicitation are showcased in engineering process modelling. Fundamental components to develop web-based system architectures are discussed. Finally, the systems code implemention is performed and evaluated.

# CHAPTER 2

# Literature Review

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# 2 Literature Review

*In the second Chapter, the literature review will answer the research questions Sq1 to Sq4. Firstly, the focus is on the Dutch building stock and the definition of refurbishment processes and the consideration of national ambitions. The relevance of choosing insulation materials as the foremost measure to meet these ambitions are discussed. The second and third Sections are dedicated to elaborating on the environmental building performances methods and on digital evaluation in the form of BIM and LCA workflows/tools. Current challenges are addressed that are subject to web-based developments in the AEC industry. The fourth Section discusses decision support systems and instruments that study consumer preference. Motives and multi-criteria objectives are explained in behavioural economics and translated in decision support tools.*

## 2.1 Dutch refurbishment strategy

*In the first Section of this Chapter, the first research sub question is aimed to be answered: SQ1) What are the ambitions of Dutch policies regarding building refurbishment and what role play insulation material measures? Firstly, the Dutch residential building stock and the characteristics of the typologies are introduced. Then the term and scope of refurbishment is introduced, according to buildings` life cycle stages. This is followed by discussing Dutch strategies and ambitions to improve the existing building stock via refurbishment actions. Feasible refurbishment measures are introduced, while the focus is on insulation materials.*

### 2.1.1 The residential building stock

The large variety of buildings throughout the European Union (EU27) and the Netherlands can be divided into non-residential and residential buildings. Non-residential buildings such as office, retail and school buildings can be understood as utility buildings, as they serve public needs. On the contrary, residential are to be understood as non-utility buildings and are the focus of this thesis. The residential sector dominates, as it represents 2/3rd of the total European floor area (EU Buildings Datamapper [1], 2020). Beyond the significant share of space demand, the energy consumption of EU residentials represents ¼th of the total EU demand and has to be reduced by 38% by 2050 (compared to 2005) *(Filippidou & Navarro, 2019).*

To propose qualified and reasonable refurbishment solutions for buildings, the as-is (or as-built) state of a building has to be documented. This encompasses the gathering of information concerning the building's original intention, the present situation and the future objective *(Zijlstra, 2009).* The original purpose and the constructive execution should be assessed against the technologies used in the past and the context of the architectural heritage. This needs to be followed by identifying the functional and technical bottlenecks and insufficient performances to meet the future demand of the building.

*"History contains much, if not all, of what still concerns us today. Without history we can never understand the present."*[2]

The current building state is evaluated by a collection of characteristics, mediated by the building typology. Specialising in residentials, considered variables are the time of construction, the housing typology, ownership, style of construction, distinguished by the structural elements, the envelope, and

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[1] https://ec.europa.eu/energy/eu-buildings-datamapper_en?redir=1

[2] J.J. Vriend, Links bouwen rechts bouwen (Amsterdam: Contact, 1974), 12, as citied in Zijlstra 2009, page 13.

therefore the technical equipment, finally the energy and its related carbon performance *(Filippidou & Navarro 2019; Konstantinou, 2014).*

### 2.1.1.1 Construction Period

Considerable differences can be noticed in buildings from the period 1946 until 1970, and 1971 until 1990. According to Filippidou & Navarro (2019), more than 40% and 90% were constructed before 1960 and 1990 respectively and do not meet up-to-date building codes. In fact, only after the '70s insulation standards were mandatory to acquire building permits, which results in approx. 75% insufficient energy performances nowadays. Zijlstra (2009) argues that post-war buildings (1946-1971) experienced a large production push due to a great demand for residential housing. A lack of material resources and the positive integration of industrialisation technology asked for a rational standardization of building systems. Concrete and brick became the most used materials in residential buildings in the Netherlands. Furthermore, since 1975 (after the oil crises) it became a trend to rethink construction regarding material and energy resources, which led to a higher pace of refurbishing and repurposing rather than demolishing. The building stock in the Netherlands can be listed according to the RVO Archetypes (RVO, 2014), see **Table 2** *(Agentschap b NL., 2011).*

<table>
<tr><th></th><th colspan="6">Construction Period</th></tr>
<tr><th>Archetype</th><th>until 1946</th><th>1946-1964</th><th>1965-1974</th><th>1975-1991</th><th>1992-2005</th><th>total</th></tr>
<tr><td>Detached houses</td><td colspan="2">6.5 %</td><td>1.8 %</td><td>3.3 %</td><td>2.6 %</td><td>14.1 %</td></tr>
<tr><td>Semi-detached houses</td><td colspan="2">4.2 %</td><td>2.1 %</td><td>3.3 %</td><td>2.6 %</td><td>12.1 %</td></tr>
<tr><td>Terrace house</td><td>7.7 %</td><td>7.0 %</td><td>8.9 %</td><td>12.9 %</td><td>5.2 %</td><td>41.7 %</td></tr>
<tr><td>Duplex apartments</td><td colspan="2">3.3 %</td><td>0.3 %</td><td>1.4 %</td><td>0.6 %</td><td>5.6 %</td></tr>
<tr><td>Gallery homes</td><td colspan="2">1.0 %</td><td>2.6 %</td><td>1.6 %</td><td>1.7 %</td><td>6.8 %</td></tr>
<tr><td>Portico houses</td><td>3.8 %</td><td>3.9 %</td><td>1.7 %</td><td>2.1 %</td><td>1.0 %</td><td>12.5 %</td></tr>
<tr><td>Other apartment houses</td><td colspan="2">1.5 %</td><td>1.8 %</td><td>1.8 %</td><td>2.0 %</td><td>7.1 %</td></tr>
<tr><td>Total</td><td colspan="2">38.8 %</td><td>19.1 %</td><td>26.4 %</td><td>15.6 %</td><td>100.0 %</td></tr>
</table>

**Table 2 Building Stock according RVO Archetype and Construction Period**

### 2.1.1.2 Housing Typology

For residential buildings, commonly classified types are (semi)detached house, terrace house and multifamily houses. By classifying typologies, in respect to their construction period, a transparent framework is offered for benchmarking and decision-making. European Programs such as the TABULA (Co-founded by the Intelligent Energy Europe Program[3]) initiate the building stock modelling on a European level according to type and year. The database offers insight in energy performance indicators and saving potentials due to refurbishment measures. According to Voorbeeldwoningen 2011, the Dutch residential building stock is statistically recorded and categorized per archetype, by construction year, see **Table 2**. The Dutch enterprise agency, Rijksdients voor Ondernemers (RVO), defines the housing archetypes as the following. Detached houses *(Vrijstaande woning)*, 2 under 1 roof *(semi-detached house),* terrace house *(Rijwoning),* duplex apartments *(Maisonnettewoning*), gallery homes *(Galerijwoning*), portico houses (Portiekwoning) and other apartment houses (Overig flatwoning) *(RVO, 2014).* Additionally, the building´s characteristics, such as materials used, and energy consumption are monitored *(Agentschap a NL, 2011).* With regard to the Building Decree Act (2012), houses in the Netherlands must remain within these archetype classifications and therefore offer an

[3] https://episcope.eu/welcome/

attractive framework for aggregation models for the application of environmental and economic information.

#### 2.1.1.3 Construction

Housing typology and age alone do not give enough insight to observe the full scope of a building as-built. To guarantee an equal improvement of diverse housing typologies and their building period, the construction of the buildings shows a direct correlation. Over time, changes occurred due to improvement in living standards, technology enhancement and more environmental awareness by the building owner. The advantage of the above-mentioned building documentations, TABULA and RVO, is the insight regarding structural and building envelope material properties. Especially, load and non-load bearing layers such as Roof, Wall, Floor and Window/Door are introduced by their thermal resistance and transmittance factor (Rc- and U-Value). This information plays a decisive role as it determines energy and cost-related decision criteria. Taking the terrace housing (Rijwoning) in the Netherlands as an example, commonly used constructions were cavity walls made of bricks with air gaps acting as an insulating layer, roofs made out of wooden beams and cladded with bricks, and prefabricated floors made out of concrete. According to EPISCOPE (2016)[4] (TABULA), the Roofs (as an example) improved when comparing constructions made before and after the 1970s. The U-Value was set at 3 W/m²K and changed to 1 W/m²K (the lower the better) while adding insulation materials (*Filippidou & Navarro, 2019).*

#### 2.1.1.4 Ownership and Occupation

The ownership of the Netherlands housing stock lies in the hands of private owners and social housing associations. The occupation of the housing is to be distinguished by homeowner occupation, privately rented and social housing tenants. From a total residential stock of approx. 7.9 million (CBS 2019[5]), around 30% is non-profit housing, around 65% is owner-occupied, and the remaining 5% privately rented *(Filippidou et al., 2016; Ebrahimigharehbaghi et al., 2019; Spithoven, 2020).*

The ownership matters in terms of refurbishment ambitions. Economic aspects and legislations are the main drivers for private owners and mid-rent apartments. The market value (net present value) of the house is positively affected by the investment. Financing schemas are mainly based on pension funds and government subsidies and are promoted when interventions strive to high energy standards. The intentions to intervene in a non-profit housing organisation is slightly different, as the asset does not increase in its market value by the time of renovation, but only at the time of sale. This has to do with the different calculation methods used for social housing and different funding systems, as defined in Waaderingshandboek *(Spithoven, 2020).*

#### 2.1.1.4 Energy Collectives

Policymakers in the form of national campaigns and energy collectives such as Hier Opgewekt[6], Regionaal Energieloket[7], 040Energie[8] and Best Duurzaam[9] motivate and persuade owners and residents to take part in the `renovation wave`. To ensure building owners a profitable solution for the expected life span of the building and the applied measures, it is aimed to strive towards no-regret

[4] http://webtool.building-typology.eu/#bm
[5] https://opendata.cbs.nl/statline/#/CBS/en/dataset/81955ENG/table
[6] https://www.hieropgewekt.nl/
[7] https://regionaalenergieloket.nl/
[8] https://040energie.nl/
[9] https://www.bestduurzaam.nl/

renovation models *(Dutch Ministry of Economic Affairs and Climate, 2019).* Financial stimulations are part of this, such as subsidies and tax regulations. Difficulties occur due to inconsistent policies and too little knowledge share of refurbishment concepts from the policy level to the end-user *(Schilder, 2020).* Energy Collectives overcome these communication lacks and guide homeowners to find the solutions to refurbish their homes.

### 2.1.2 Refurbishment process

Due to long lifespans of residential buildings, the existing housing stock will remain over the upcoming decades and represent potential to be investigated, optimized and eventually improved.

*"Refurbishing buildings offers long-term investments and the opportunity to create a sustainable living and built environment for the future generations."*[10]

#### 2.1.2.1 Terminology

Building interventions throughout the building`s operational stage can be divided in multiple steps. This includes small interventions, such as maintenance and renovations, as well as bigger interventions such as refurbishments towards demolition, see **Figure 8**.

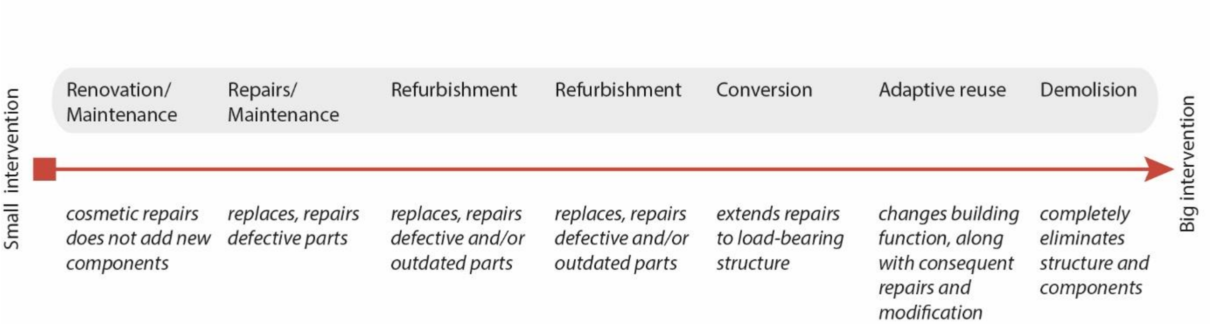


**Figure 8 Level of interventions *(Giebeler et al., 2009)***

Giebeler (2009) defines renovations, repairs and maintenance as cosmetic upgrades and replacements of defective components. On the other hand, refurbishment is the replacement of not sufficiently performing building elements. This refers to non-load-bearing elements. Upgrading of building elements to increase performances, such as fire protection and thermal performances is part of this stage. Further, three categorisations are defined by Giebeler (2009). *Partial refurbishment* addresses only one or a few elements. *Normal refurbishment* is the replacement of building elements covering the total building. Lastly, *total refurbishment* indicates that the building is entirely emptied until its structural skeleton. *Conversion* is defined as an extensive repair of the structural load-bearing element. Finally, adaptive reuse and demolition focus on the reusability of the building's purpose (functionality) and the complete elimination of the structure.

#### 2.1.2.2 Refurbishment Process

The process of refurbishment is similar to the construction of a newly constructed building. The difference is the already existing building that is occupied and brings history in terms of its building characteristics and occupation *(Nielsen et al., 2016).* To better understand the scope of refurbishment, the entire lifecycle of a building is explained at one glance. Building lifecycles are commonly understood as a series of events, that encompasses design, construction, operation, demolition and

[10] Citied by Julia Kaltenegger

waste management. The building life cycle is defined by the EN 15978 as shown in **Figure 9** and explained as following.

PRODUCT stage (A1 to A3) can be set equal to the design stage (including conceptual and predesign). In this stage designers and engineers collaborate closely with the owner's requirements to design a building`s shape, construction elements, materialisation, etc. to fulfil the building requirements. CONSTRUCTION stage (A4 to A5) represents the stage before handing over the asset to the building owner and focuses on the execution including transportation and construction work (prefabrication or onsite). USE stage (B1 to B7) is the actual occupation of the building. Maintenance and repair, as well as replacements and refurbishments, represent a fundamental part. END OF LIFE stage (C1 to C4) and Beyond (D) explain whether to demolish and dispose of buildings or to reuse, recycle and recover buildings and their elements *(Hasik et al., 2019).*

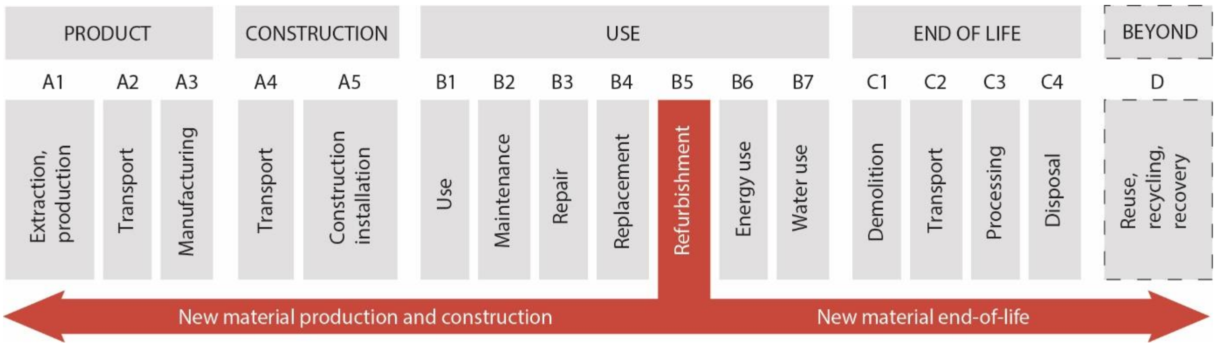


**Figure 9 Building Life Cycle stages according to the EN 15978 *(Hasik et al., 2019)***

Refurbishment represents one part of the overall life cycle of a building (use phase B5). It is commonly understood as adding features to improve insufficient building performance, to improve energy reduction, technical errors and indoor comfort *(Hasik et al., 2019).* In this regard, various options are offered to perform actions that overcome problems. Their effectiveness can be evaluated by comparing the building`s as-is state against as-refurbished. Deciding upon refurbishing, a new project in the form of a nested building lifecycle is introduced which allows an extension of the building lifetime. It asks for a clear definition of project boundaries, stakeholder involvement and task definition.

According to Hasik (2019), the life cycle stages for refurbishment according to EN 15978 lack on definitions. For instance, it is not clearly defined in which stage waste management is part of the process, and who would be responsible. In their paper they elaborate the boundary of B5 as the following, see **Figure 10**.

The existing building production and construction stage (A) is the existing product and construction stage to achieve the as-is state.

- Existing building, use stage (B), represented by the operational as-is definition.
- Existing building End of Life stage (C/D), defines the brittle building components that are demolished due to refurbishment actions.
- Renovated Building, Reused Use stage (B), refers to the building components that are reused, repaired and maintained from the as-is stage.
- Renovated Building, Reuse End of life stage (C/D), represents the eventual demolishing and disposal of the reused elements from the as-is.

- Renovated Building, new product and construction stage (A), are the newly produced and assembled products due to refurbishment.
- Renovated Building, new use stage (B), includes of the above explained newly added products maintenance, repairments and replacements over the new use phase of the refurbished buildings.
- Renovated Building, new End of Life stage (C/D), represents the demolishing and disposal of the elements added during refurbishment actions.

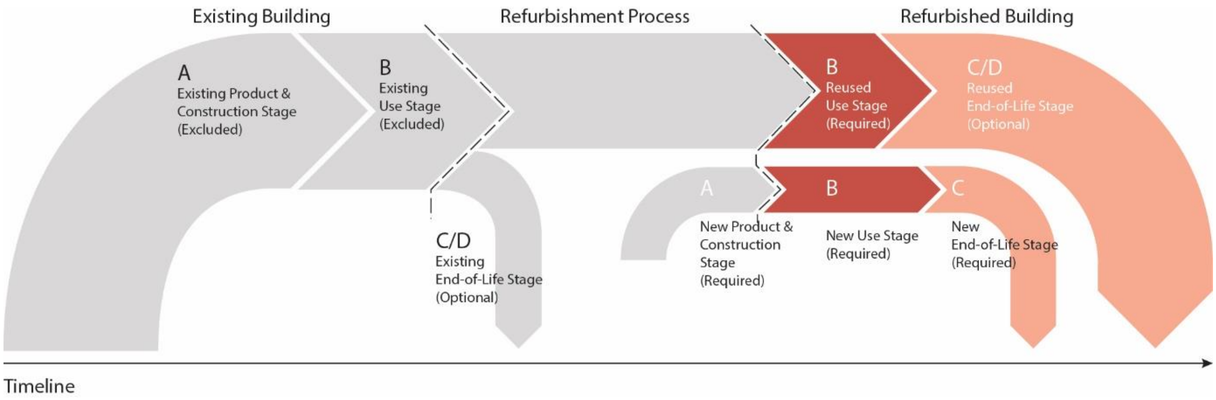


**Figure 10 System boundaries of Refurbishment projects *(Hasik et al., 2019)***

### 2.1.3 Ambitions

Ambition levels are used to describe the national strategies to make housing energy efficient, for new and refurbished buildings. The most progressive strategy is Plus Energy Building and requires the building to produce more energy than it consumes, on a yearly basis. Secondly, Net Zero Energy Building (nZEB) and Net zero-carbon buildings (nZCB), a synonym to `nul op de meter` (NOM), balances out the consumed and the produced energy and carbon emission. Reaching Energy Label B describes the least progressive strategy, by reducing the operational annual energy consumption *(Schilder, 2020; Haytink et al., 2015).*

The European Commission precisely outlines the European building stock and the definition of energy renovations. In Europe, approx. 12% and 9.5% of residential and non-residential floor areas are affected by one of the following measures. Energy renovation reaching from building envelope insulation and technical improvements (e.g., heating and ventilation). Four refurbishment stages for residentials are introduced according to the energy saving potential. (i) Energy renovation “Below threshold” < 3% savings, (ii) “Light renovations” < 30% savings, (iii) “Medium renovations” ≥ 30% < 60% savings and (iv) “Deep renovation” ≥ 60%. The first two, “below the threshold” and “light renovation” are most commonly applied in the form of a step-by-step renovation. This highlights that not only “Deep renovation” can accomplish a climate-neutral building stock, but also gradually implemented renovation approaches *(Esser et al., 2019)*.

#### 2.1.3.1 Trias Energetica

The strategy Trias Energetica represents a strategy striving at energy-saving measures in the built environment. It encompasses three steps that evaluate the building`s environmental performance and can be described as energy-efficient, using a maximum of local renewable energy sources within a cost-effective manner *(Rijksdienst voor Ondernemend Nederland, 2013).* **Figure 11** describes the three-step approach in consecutive order.

### Reduce energy demand

The first step to reducing the energy demand of buildings is to make use of passive measures. This can be understood as an efficient managing of heat demand/supply, the use of passive solar radiation and avoidance of overheating of the indoor environment. Thereby insulation of the envelope plays a major role to ensure all three aspects. Managing space heating as efficiently as possible starts with airtight constructions of the building envelope in combination with highly insulating windows. This reduces infiltration of cold air in winter and can prevent the room from overheating in summer while allowing maximum natural light and heat gain.

### Use sustainable renewable energy sources

The use of sustainable renewables is performed via active measures and builds upon the first measure, by means of the utilization of electricity production, active solar use and heat generation. Speaking in a Dutch context, this is often performed using self-produced electricity and energy using photovoltaic and solar panels, in combination with solar boilers and high-performance heat pumps. Other heat generations are renewables such as geothermal and biomasses, that are provided by the market.

### Use fossil energy, if necessary, as efficiently as possible

In the last step, it is expected to make use of the remaining fossil fuels as efficiently as possible. Thus, equipment for heating, cooling, ventilation and light appliance is based on electricity with a high energy label. Furthermore, also energy production and fossil fuel consumption for material resources is taken into consideration *(Rijksdienst voor Ondernemend Nederland, 2013; Konstantinou, 2014, Haytink et al., 2015).*

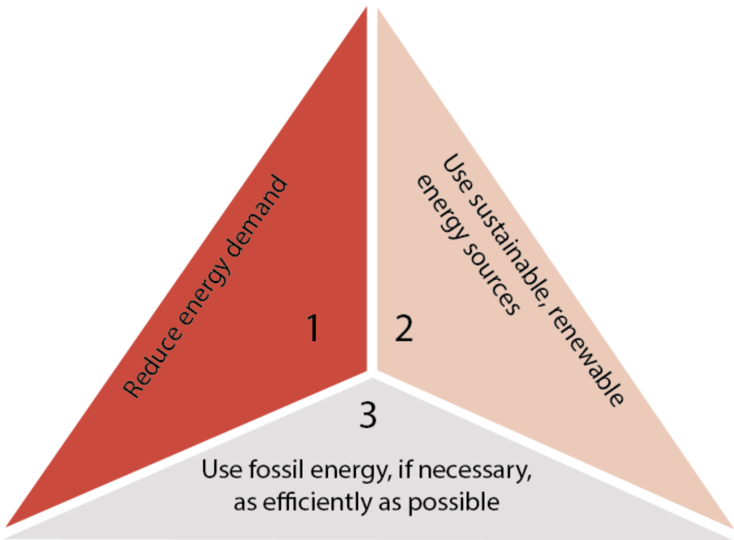


**Figure 11 Trias Energetica**

## 2.1.4 Feasible refurbishment measures

The choice of refurbishment measures can be generally distinguished between material-based and building integrated technological systems (BITS) *(CREEM, 2020; Hirsch et al., 2020).* The literature study in García-Martínez & Sánchez-Montañ (2016) shows that the most common and efficient material-based refurbishment measures for the housing sector are foundation insulation, external wall insulation, façade systems, floor insulation, roof insulation, roof cladding as well as window and door replacement. Additionally, building integrated technical systems (BITS) related renovation measures are heat production and ventilation system optimization, solar or PV acquisition, efficient Domestic Hot Water (DHW) systems and a change from fossil fuel-based gas towards alternative heating systems.

#### 2.1.4.1 Building Integrated Technical System

The technical systems for heating, cooling and ventilation are used to gradually reduce the use of natural gas in the built environment. The Energy Agenda has described the strategy to achieve $CO_2$ neutral low-temperature heating in the Netherlands by 2050 *(van Eck, 2018).* Moving away from gas requires a stepwise shift from the existing heat supply for entire urban districts to a local or collectively generated energy and electricity supply. Thereby renewables, such as district heating, all-electric solutions, biogas networks or geothermal heat are considered *(Dutch Ministry of Economic Affairs, 2016).* Challenges remain, due to shortages of national electricity providers. Closing down the gas-fired power stations results in higher dependency of purchasing electricity from neighbouring countries. This in return requires energy for logistics that releases carbon emissions which would hinder an international decrease of $CO_2$ emissions *(Dutch Ministry of Economic Affairs, 2017).* Therefore, the current solution in the Netherlands is to keep gas as a source until 2030 whilst the industry is developing more efficient renewables to eventually cover the total energy demand with electricity.

There are more ways for heating the house without gas, these are hybrid heat pump (with gas), full electric heat pump, district heating network, infrared panels, pellet central heating boiler or biomass boiler. A common practice in the Netherlands are hybrid heating pumps, as they are the first attempt to reduce gas consumption. However, gas remains to be used as an energy source. Totally shifting away from gas is possible with an electric heat pump[11]. Whether to use an air-, water- or ground-based heat pump depends on criteria such as cost, efficiency factor (COP), space available, noise disturbance while operating and the existing delivery system inside the building. Further combinations are allowed with photovoltaic and solar panels. However, to guarantee the maximum efficiency of a new heating system, the heating distribution (from high temperature, radiator, to low temperature, floor panels) must be considered in the costing. A study of Havinga & Rijs (2020) shows that for typical Dutch houses good ventilation and a balanced ventilation system[12] with heat recovery allows high inside air quality while keeping the already existing high-temperature systems.

#### Investment Subsidy for sustainable energy ISDE[13]

Current building owner and homeowner policies are heavily aligned towards financial-economic policies. This is due to the homeowner´s interest in an optimal cost-benefit assessment to earn back the investment cost in an attractive payback time. Due to a lack of mandatory policies to refurbish, however, the scenario of doing no improvement is still an option for many homeowners. As stated in the national climate agreement, a no-regret renovation scenario must be possible *(Dutch Ministry of Economic Affairs and Climate, 2019)*.

[11] https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/volledige-warmtepomp/
[12] https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/ventilatiewarmtepomp/
[13] https://www.rvo.nl/subsidie-en-financieringswijzer/isde/voorwaarden-apparaten

The ISDE entitles homeowners to receive a subsidy when purchasing solar water heater, heat pump, biomass boilers and / or PET stove[14]. Heat pumps subsidy amount is between 500 and 2,500 €[15] and for solar water heating boilers[16] around 500€ per device. Even though solar panels, pellet stoves and biomass boiler are not part of this government program, subsidies for energy-efficient ventilation systems[17] can be asked, see **Table 3**.

| Energy efficient systems | Investment Cost | Grant amount (subsidy) | Energy production potential |
|---|---|---|---|
| Heat pump air (COP 3.5)[18] | € 6,500 – € 14,000 | € 500 – € 2,500 | 3000 kWh |
| Solar boiler DHOW (panel 2m²², 80lt)[19] | € 2,500 | € 500 | 120 m³ |
| Solar panels (1 panel)[20] | € 520 | - | 300 kWh |
| $CO_2$ -controlled ventilation system | n.a | 30% of the costs approx. € 1,200 | n.a |
| Balanced ventilation system with heat recovery (HRV)[21] | € 3.600 tot € 5.800 | 30% of the costs approx. € 1,200 | 1.200 m3 gas + 1.600 kWh |

**Table 3 Technical System subsidy**

Since energy prices in the Netherlands largely consist of taxes, changes in energy tax have a major impact on the variable gas and electricity costs that owner-occupiers owe each month *(Schilder, 2020).* At the beginning of 2019, the tax on natural gas was increased and the tax on electricity decreased at the same time. Furthermore, $CO_2$ or carbon taxations experience a high chance to become mandatory in the building industry. They represent a percentage share of the total fuel combustion. Thus, shifting to renewable energy sourcing stands in the interest of building owners. Aiming to make gas-free sources attractive, other stimulations are feed-in tariffs and low-interest rates for mortgages *(Somanathan et al., 2012).*

Loonen argues in an interview that the innovative aspects in traditional refurbishment concepts is missing. The motivation should not be alone the financial surplus, but also the sustainable and comfort characteristics. *"Even when reducing monthly operational costs up to 150€ and having investment costs of approx. 50,000€, the payback time of 28 years would be relatively long. This and the fact of maintenance and replacement costs for technical equipment within that long payback time makes such extensive renovations rather less attractive and creates a limitation in the practical application." (Loonen, 2020, page 1).*

Considering that not every homeowner is committed to refurbishing the entire home, a stepwise measure is to be guided by the government. As explained earlier, partial refurbishment is an option that allows building owners to perform minor refurbishments and to expand in the future towards

[14] https://english.rvo.nl/subsidies-programmes
[15] https://www.rvo.nl/sites/default/files/2020/10/2020%20ISDE%20apparatenlijst%20warmtepompen%2029-10-2020.pdf
[16] https://www.rvo.nl/sites/default/files/2020/10/2020%20ISDE%20apparatenlijst%20zonneboilers%2029-10-2020.pdf
[17] https://www.rvo.nl/subsidie-en-financieringswijzer/seeh/eigenaar-en-bewoner/subsidie-energiebesparende-maatregelen/aanvullende-maatregelen
[18] https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/volledige-warmtepomp/
[19] https://www.milieucentraal.nl/energie-besparen/duurzaam-warm-water/zonneboiler/
[20] https://www.milieucentraal.nl/energie-besparen/zonnepanelen/kosten-en-opbrengst-zonnepanelen/
[21] https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/ventilatiewarmtepomp/

major refurbishments. Interviews with building designers and engineers have shown that frequently applied measures start with airtight construction measures, highly insulating windows such as HR++ and door replacement. This is followed by insulating the facade[22], roof[23], and floors[24] with higher thermal resistance. Eventually, homeowners apply heat systems with low-temperature radiators and on-site energy sourcing (e.g.: heat pump, solar panels, wind turbines) *(Loonen, 2020; MilieuCentral, 2020, Lünenschloß, 2020).*

#### 2.1.4.2 Material Based

In the paper of Majcen (2016) they refer to the minimum thermal performance values per major or minor refurbishments, see **Table 4**. To start with, the minor refurbishment (mainly thermal improvement due to add-in solutions) of the building's envelope is practical and cost-effective with a relatively short payback time. However, the maximum achieved improvement is limited to an energy Label B**.** To reach energy level A, the insulation level must achieve a higher Rc-Value for the building envelope. This in fact can only be achieved when having enough space available, either with external or internal insulation layers (mainly done via wrap-it solution) *(Rovers, 2020)*.

| | **Major refurbishment (25% envelope) (Label A to nZEB)** | **Minor refurbishment (Label C -B)** |
|---|---|---|
| Wall | Rc-Value ≥ 4.5 m²K/W | Rc-Value ≥ 1.3 m²K/W |
| Roof | Rc-Value ≥ 6 m²K/W | Rc-Value ≥ 2 m²K/W |
| Floor | Rc-Value ≥ 3.5 m²K/W | Rc-Value ≥ 2.5 m²K/W |
| Windows | U-Value < 2.2 W/m²K | U-Value < 2.2 W/m²K |

**Table 4 Minimum requirements for major and minor renovation *(van Ecker et al., 2018[25])***

#### Energy saving insulation measure subsidy (SEEH) [26]

The SEEH provides homeowners with the possibility to receive a subsidy when performing a minimum of two energy-saving insulation measures. **Table 5** shows the measures and minimum surfaces (m²) to be renovated per building typology. It includes (cavity) wall, a façade, roof, floor insulation and a thermal improvement of windows (including glass and frame). The minimum insulation values are defined according to minimum Rc-Values.

| | **Detached houses** | **Corner houses / Semi-detached houses** | **Terraced houses** | **Multi-storey houses** | **Insulation value** | **Subsidy per m²** | **Insulation bonus value** |
|---|---|---|---|---|---|---|---|
| Cavity wall | 50 m² | 33 m² | 15 m² | 13 m² | Min Rc-Value 1.1 | 8 € | - |
| Roof | 57 m² | 38 m 2 | 31 m 2 | 15 m 2 | Min Rc-Value 3.5 | 30 € | Min Rc 6.5 |
| Attic / loft floor | | | | | Min Rc-Value 3.5 | 8 € | Min Rc 4.0 |
| Facade | 55 m² | 40 m² | 18 m² | 13 m² | Min Rc-Value 3.5 | 38 € | Min Rc 5.0 |
| Floor and / or bottom | 44 m² | 32 m² | 27 m² | 20 m² | Min. Rc-Value 3.5 | 11 € | Min Rc 4.0 |
| High efficiency glass HR++ | 15 m² | 12 m² | 10 m² | 8 m² | Max. U-value 1.2 | 53 € | - |

22 https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/spouwmuurisolatie/

23 https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/dakisolatie/

24 https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/vloerisolatie/

25 https://epbd-ca.eu/ca-outcomes/outcomes-2015-2018/book-2018/countries/netherlands

26 https://www.rvo.nl/subsidie-en-financieringswijzer/seeh/eigenaar-en-bewoner/subsidie-energiebesparende-maatregelen/energiebesparende-isolatiemaatregelen

| | | | |
|---|---|---|---|
| High efficiency glass triple | Max. U-value 1.1* | 150 € | - |

**Table 5 Building insulation subsidy**

**average value of a max U value (W/m²K) of 0.7 for glass and 1.5 for frame*

So far it can be argued that no strict guidelines exist regarding which envelope improvements and technical systems need to be applied. It can be seen that due to subsidy and collective decision-making processes the choices must stay in the common interest. In this way, building owners have much freedom within planning phases to brainstorm and to choose the most effective solution according to their objectives *(van Eck, 2018).*

The targets are set high and require not only energy reductions but also mitigation of fossil fuel-based sources. Reducing energy use and shifting to sustainable energy production in building operation is thereby strong in focus. The previous highlighted, while shifting the operational energy to its lowest, that it can be outperformed by the embodied performance of materialisations. Thus, a conscious decision of materialisation can act in favour of all aspects of the Trias Energetica.

### 2.1.5 Relevance of Insulation Materials

Choosing insulation materials includes a wide set of requirements that considers the whole life cycle of a building. It reaches beyond the thermal properties and addresses environmental, economic, health and safety characteristics. As explained in the previous Section, insulation materials represent the first and most important improvement in refurbishment projects. They represent the thermal layer that defines the indoor thermal behaviour by responding to the outdoor climate. Therefore, the right choice of material and its thermal properties undoubtedly contribute to a very big extent to operational energy consumption and therefore also to the energy bill *(Schiavoni et al., 2016).*

Aditya (2017) argues that the cost optimum insulation thickness represents the second biggest decision-making parameter. Thereby the LCC is used as a method to decide upon if the energy-saving is worth the materials` investment cost, determined by the thickness. It is necessary to define the optimum thickness since high insulation thickness decreases the thermal loss however increases the market costs *(Aditya et al., 2017).* Kumar (2020) describes this behaviour as logical since building owners seek to cost incentives, whereas public and social housing groups do consider energy and emission reduction through the entire building's life cycle. They point out that with the shift to nZEB the importance to consider low embodied energy and carbon emissions of materials becomes increasingly important. This also includes local sourcing and labour utilization *(Kumar et al., 2020).*

Schiavoni (2016) confirms the life cycle thinking approach as materials have indeed a higher life expectancy than for instance technical equipment. In fact, materials must guarantee an acceptable performance throughout the expected/extended lifetime of the building. Therefore, also non-thermal performance criteria, in the form of indoor environment quality (IEQ) criteria, become relevant to investigate. Among other factors, IEQs are sound insulation level, material fire rating defined by the resistance and the toxic hazards and water vapor permeability show significant impact on human health and comfort *(Schiavoni et al., 2016).*

Visser (2015) argues that high demands of a material`s thermal insulation property plus mechanical or balanced ventilation systems can lead to too little natural ventilation and results therefore in accumulation of indoor air contaminants, microorganisms and moisture. Considering that people are approx. 90% of their time indoors, of which 70% in their own home[27], the WHO[28] issued that the indoor air quality contributes drastically to human health *(Visser et al., 2015).* Ortiz (2020) agrees and highlights that IEQ shortcomings result in increasing health risks when performing non-suitable refurbishments on buildings while focusing solely on energy efficiency. Complaints include mould growth, thermal comfort stress (people feel too cold, or too warm, draught), noise disturbance from the outside. To summarize, there are three aspects to cover: Comfort, Safety and Health *(Ortiz et al., 2020).* Aspects of comfort are depending on a set of external parameters, which are subjectively interpreted. Every occupant experience comfort differently. Konstantinou (2014) outlines a basic set of characteristics according to European norms. Thermal properties, explaining the minimum and maximum degrees in the form of heating and cooling setpoints (20.0-25.00 °C and 23.00-26.00 °C), the relative humidity (25 to 60%), indoor air quality due to a regular air change flow (natural or mechanical) and an ideal noise level of max 40dB in the living area and 35dB in the sleeping area *(Konstantinou, 2014).*

In the question of which package and material to use, occupant's behaviour is crucial to know to make the right decision. Next, governmental ambition aims to contribute to the energy transition at a high level while manufacturers aim to sell their products and contractors in making the realization with maximum profit. At the same time, innovative material solutions are required which stay in an attractive framework considering all the above-mentioned criteria. The research mentioned for instance the vacuum insulation panels and gas-filled panels of aerogel. In this research the bio-based materials are chosen as an alternative, due to low environmental footprint, high comfort and health-related characteristics *(Visser et al., 2015; Kumar et al., 2020; Ortiz et al., 2020).*

#### 2.4.3.1 Insulation Material Types

Insulation measures (wall, roof, floor, window) represent a different set of responsibilities, that need to be fulfilled by the chosen materials. For instance, the facade insulation, representing the border of interior and exterior, is highly contributing towards the annual energy bill and is therefore expected to mitigate thermal conductivity. On the other hand, the floor insulation is expected to absorb sound to mitigate noise disturbance. Further, an increasing number of environmental and economic concerns rise that consider the extraction of local products and materials, to restrain embodied emissions *(Schiavoni et al., 2016).* Finally, concerns to secure human health and safety stand in line with the social housing/homeowner long term perspective *(Spithoven, 2020).*

In this research, the insulation materials are categorized according to their sourcing material and are distinguished between conventional (not renewable) and sustainable (renewable) insulation materials. The conventional materials are further split in biochemically produced materials (EPS, XPS and PUR) and inorganic mineral-based products (Glass wool and Rock wool). Sustainable materials are defined as bio-based materials. **Figure 12** is aligned to the classification schema of building insulation material by Kumar (2020) *(Kumar et al., 2020). (Further information about the environmental friendliness of insulation materials can be found from the material pyramid [29]).*

[27] http://www.rivm.nl/Documenten_en_publicaties/Wetenschappelijk/Rapporten/2003/juli/Ionising_radiation_exposure_in_the_Netherlands

[28] http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf

[29] http://www.materialepyramiden.dk/

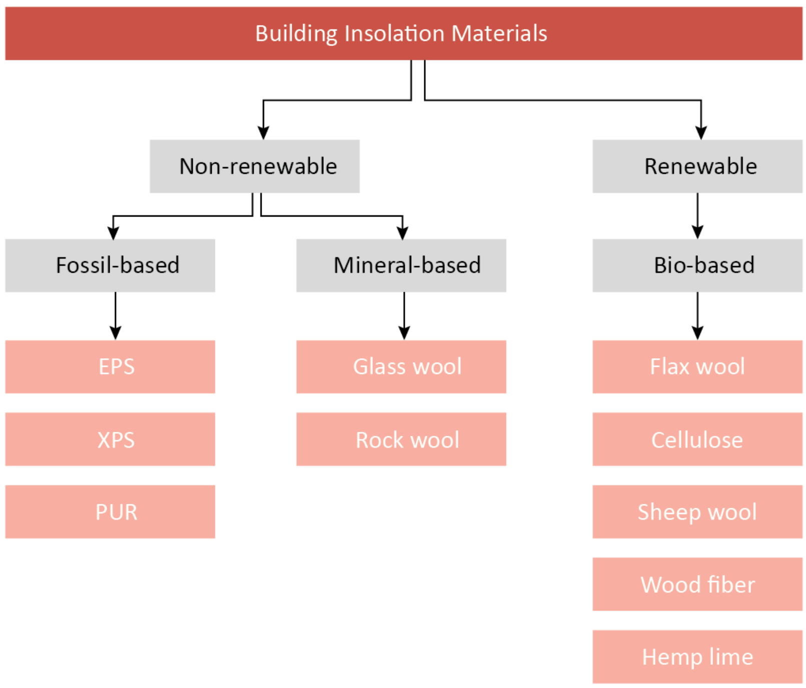


**Figure 12 Classification schema of building insulation material**

#### 2.5.1.1 Conventional insulation materials

Conventional materials, that are often used in the built environment are based on fossils and mineral sources. For instance, Extruded polystyrene (EPS), Expanded polystyrene (XPS) and Polyurethane (PUR) are made from benzene, ethylene and pentane. They are produced from solid beads of polystyrene, based on fossil fuels that are extracted from the ground. The production process runs through (multiple) chemical processes including additives and has a very high share of non-renewable energy and related carbon emissions. The final product can be applied via panels or foam to be injected.

Mineral-based materials, such as Glass wool, are produced out of cullet, quartz sand and dolomite stones. Glass fibres are added that are made out of the sand, sandstone, and recycled glass. Using recycled materials leads to a significantly lower share of non-renewables in the production line. The manufacturing process itself is done via melting the glass fibres in (gas) ovens (burned up to 200°C) to transform thick layers of glass fibres to thin and hard wool plates, panels or rolls. Rock wool is made out of mineral fibres that are made of basalt rock. Volcanic rocks are extracted from deep in the earth. The molten fine rock fibres are further combined with slag which commonly results as a by-product from the steel and copper industry. This in return also allows rock wool to have a moderate share of non-renewables. The products themselves are offered in panels, roles or plates.

#### 2.5.1.2 Sustainable insulation materials

Bio-based materials are based on renewable materials. Generally, they are nature-based grown or recycled materials. Little chemical additives are added in the manufacturing process to accomplish physical properties, for instance, fire resistance. Due to the little number of additives, regional growing and manufacturing processes, they show lower embodied impacts than conventional materials. For instance, flax wool is produced from plants grown in nature and dried to flax straw. The flax fibres are further processed to grey wool containing polyester binder.  They show open porous structures and perform well in humidity regulation. Cellulose is purely made out of by-products from paper productions. It is a combination of recycled paper and wood fibres in the form of small paper snippets. snippets are cut into tiny pieces and added with additives (fluoric acid). It can be used as flocks or are formed to panels. Properties are high humidity regulation due to the porous structure. Other materials show benefits in health and comfort attributes. Hemp lime for instance has potential to increase the thermal resistance if the temperature difference between in and outside increases. Also, Sheep wool shows improved humidity regulation when the increase of humidity in the air. Mainly, bio-based products are offered in panels, roles and flocks *(IsoHemp n.d., Isovwer 2021, IsoVlas, 2021, Kalkhennepbouw, 2021, Dijksta draaisma, 2021).*

## 2.2 Environmental performance of building

*The second Section of Chapter 2 is dedicated to answer the second sub* question: *SQ2) Which methodologies are currently used, that assess environmental and economic performance of existing buildings, and evaluate possible refurbishment design scenarios. It will introduce the reader to evaluation techniques and definitions of environmental performances of buildings, in the EU and the Netherlands. The industry`s state of the art and latest developments in practice and in academia are presented.*

Energy efficiency measures in the Netherlands are introduced since 2008 and are based on the EU Energy Performance of Buildings Directive (EPBD). It implies that the Dutch real estate sector must establish a minimum energy performance model for new and existing buildings. The energy index (EI) is introduced. It offers a theoretical energy classification of residential buildings based on building type and construction year. However, $CO_2$ emission measures are neglected in this procedure *(Filippidou, & Navarro, 2019).* Therefore, since 2013, the Dutch norm NEN-EN-ISO 14040:2006 (NEN 8006: § 5.2.2) and Milieumanagement – Levenscyclusanalyse – Principes en raamwerk require an environmental performance measure, in particular a Life Cycle Assessment (LCA), for every new building to be submitted when applying for a building permit *(Nen-en 15804, 2016)*. It does not impose any environmental performance requirements to refurbishment actions *(SBK, 2019)*.

*The following will explain the energy performances of buildings in the form of certifications and will elaborate on the Life Cycle Assessment.*

### 2.2.1 Energy Performance

#### 2.2.1.1 Energy Performance Certifications and Energy Index

The purpose of an energy certification is the informative aspects for the building owner with the aim to stimulate the owner to reduce energy consumptions. The EPBD requires a minimum energy performance of buildings (new and existing constructions). The Energy Performance Certificate (EPC) Netherlands is mandatory for the building permit for new constructions. To evaluate the existing buildings, the Energy Index (EI) is used as a labelling system. Building owners are only required to purchase a certificate in case of ownership transaction *(Thorpe, 2017)*.[30]

Both calculations are based on the primary energy consumption of a building, however, differ slightly in the level of detail *(Majcen, 2016).* The EPC is defined as a policy tool according to the Dutch standard NEN 7120. It is based on very detailed information about the building's properties, construction and geographical context. Among others, thermal bridges, air infiltration, efficiency factors of heating systems, solar gains and heat accumulations are included *(van Eck, 2018)*. Additionally, the EPC considers carbon emissions associated with heating, cooling, ventilation and lighting *(Thorpe, 2017).* Seldom is information in such a detailed manner available for existing buildings. The EI is a deterministic method and is based on building characteristics, such as the building dimensions, construction year, the thermal resistance of insulation for walls, roof, floor, their material type as well as the window insulation (glass and frame). Additionally, the installations for heating/cooling, domestic hot water (DHOW) and ventilation are considered *(Filippidou et al., 2016)*.

[30] https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels/bestaande-bouw/energie-index/verschil-energie-index-en-epc

Majcen (2016) argues that the theoretical energy label measure often diverges from the real energy performance of buildings. It can be described as a theoretical value as it does not take the occupation patterns into account but rather classifies building typologies by construction year and energy consumption. Conventional energy share for a household can be split in four groups, which are space heating (57%), water heating (25%), electrical appliance (11%) and cooking (7%). The label certificate in the Netherlands does specify energy use for heating (space and water) with gas ($m^3$) and for cooking and appliances with electricity (kWh), expressed in the total primary energy (in MJ). **Table 6** shows energy labels, the related energy index and the mean actual primary energy consumption (kWh/m²/yr) *(Majcen, 2016)*.

| Energy Label | Energy Index | Primary energy consumption (kWh/m²/yr) |
|---|---|---|
| A ++ | <0.50 | 138.84 |
| A + | 0.51 – 0.70 | |
| A | 0.71-1.05 | |
| B | 1.06-1.3 | 162.08 |
| C | 1.31-1.6 | 174.27 |
| D | 1.61-2.0 | 195.60 |
| E | 2.01-2.4 | 211.55 |
| F | 2.41-2.9 | 223.83 |
| G | >2.9 | 232.10 |

**Table 6 Energy Labels and the related primary energy consumption *(Majcen, 2016)***

### 2.2.1.2 Net Zero Energy and GHG-mission

As a follow up, the net Zero Energy Building (nZEB) was introduced by the EPBD in 2010 and requries that all newly built buildings from 2020 onwards must requrie low amount of energy that should mainly be covered by renewables *(Konstantinou, 2014).* According to the European Program TABULA, if the EPC is equal to 0, the building performance can be described as net Zero Energy Building (nZEB). This observation stands in line to the definition according to Agentschap b NL, 2011. Refurbishments of residential buildings must have an EI of 0.6 (equals to Label A++). To achieve this, the commission recommends taking major actions to improve the building envelope, the heating systems and shifting the energy source to renewables for a minimum of 50% *(European Commission, 2015).*

The concept of the net Zero Carbon Building (nZCB) is part of the nZEB approach. As energy consumption reduces, supposedly so does the emitted carbon emissions. The sourcing of energy but also materials play a major role. To evaluate $CO_2$ emission of existing buildings the primary energy must be multiplied by a carbon factor that depends on the country of origin and consumption. Thus, environmental building performance assessments such as the Life Cycle Assessments (LCA) are introduced *(Weißenberger et al., 2021; Thorpe, 2017; Konstantinou, 2014).*

Since energy certifications for refurbishment projects are not mandatory, national plans are yet to be drawn that define a consistent concept that describes a precise calculation method. This is followed by a target value definition for the reduction of $CO_2$ emission. Only few statistics exist that give insight whether the Dutch building stock meets those requirements or is yet required to shift towards nZEB and nZGHG standard.

### 2.2.2 Environmental Performance

The United National Environment Program revealed the building industry environmental footprint globally is presented as a share out of the respective categories: 40% energy consumption, 30% raw material consumption, 25% solid waste, 25% water consumption and 12% land use *(Ibn-Mohammed et al., 2013).* In order to understand these impacts in refurbishment projects the Life Cycle Assessment (LCA) is suggested.

#### 2.2.2.1 Life Cycle Assessment (LCA)

The LCA is a well-recognized method to estimate the environmental footprint of a building from cradle to grave and/or cradle to cradle. Aiming towards a systematic approach, the International Organisation for Standardization (ISO) published, within its standard series 14040:2006, four LCA phases as the framework to describe the life cycle of products/objects/systems. The following stages are included 1) Goal and Scope, 2) Life Cycle Inventory (LCI), 3) Life Cycle Inventory Assessment (LCIA) and 4) Interpretation phases, reporting results, usability and significant limitations *(García-Martínez & Sánchez-Montañés, 2016).*

The LCA for buildings depends on a number of parameters, such as building characteristics, including the building typology, shape, gross building area (GBA), occupation patterns, followed by context-related parameters, such as the climate zone and weather input, as well as the operational energy performance, and finally the construction of the load bearing and finishing layers *(Röck et al., 2020).*

Therefore, defining the system boundaries are crucial in order to meet expectations for further benchmarking of results. To allow common scopes, a building life cycle is divided into four stages: A 1-5 Product & Construction Stage, B 1-7 Use Stage C 1-4 End-of-life Stage and C Recovery. **Figure 13** highlights the life cycle stages and introduces the operational and embodied impacts *(Passer et al., 2016).*

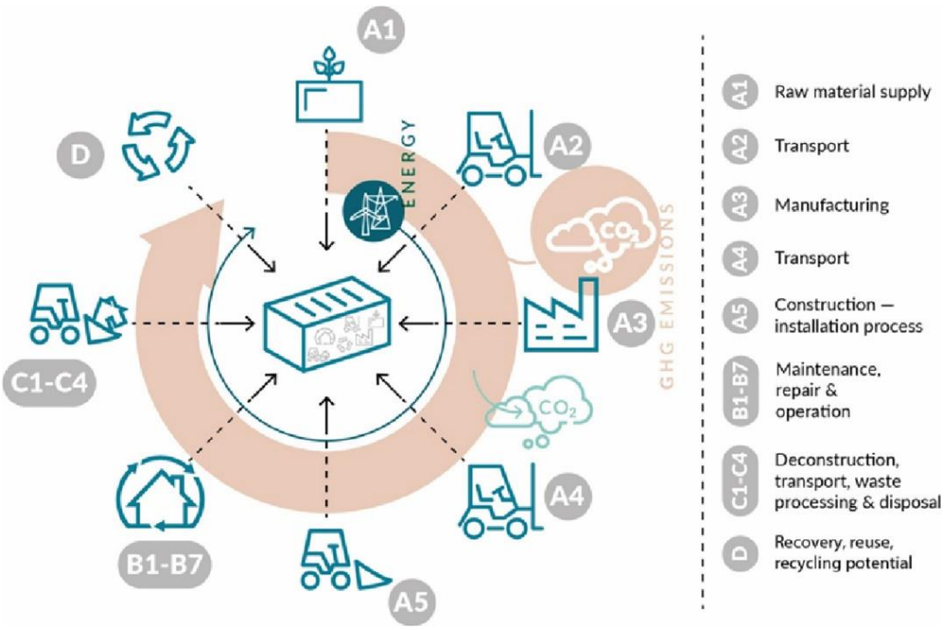


**Figure 13 Building life cycle stage in a modular structure, IEA EBC ANNEX 57, adapted from EN 15978:2011 *(Passer et al., 2016)***

As can be seen there, the red circle represents the operational emissions caused due to energy consumption (heating, cooling, ventilation) and electricity. The embodied emissions, blue figures, are emitted due to sourcing and manufacturing of materials in production, construction, and end of life. Conventionally, the ratio of operational to embodied emissions is around 80-90% to 10-20% (*Gomes et al., 2017).* The impact assessment can be measured in the form of eleven impact categories.[31] In relation to climate target-oriented policies, LCA in the built environment focuses commonly on two impact categories - Global Warming Potential (GWP) and the Primary Energy use (PE). The GWP measures the carbon-related GHG emissions in $kgCO_2$ equivalent (eq) and the PE demand in megajoule (MJ) *(Mastrucci et al., 2017).*

#### 2.2.2.2 LCA in Refurbishment

Due to its accuracy and consistency, the LCA methodology needs a high level of information regarding the building's construction and is therefore mainly applied after the design phase happened. However, as the Society of Engineers and Architects (SIA) already mentioned: *"important decisions for the achievement of the target values are made in the early planning phases (strategic planning, preliminary studies and preliminary project)"*[32] *(Slavkovic et al., 2019).* The application of an LCA should thus reach beyond a detailed planning stage for new buildings and find its application also in conceptual building design for refurbishment projects *(García-Martínez & Sánchez-Montañés, 2016; Lotteau et al., 2015; Mastrucci et al., 2017; Lavagna et al., 2018).*

Compared to a new building, the system boundaries for refurbishment projects have an overlap of life cycles of the existing to newly added components. As their impacts occur in the beginning and at the end of a building's life, the question arises if there is a need to evaluate existing buildings in regard to their past embodied impacts.

**Figure 14** showcases the trend of operational and embodied impact over a building lifetime. It can be seen that embodied carbon spikes occur at the time of the initial construction, the refurbishment act, and the end of life stage *(Röck et al., 2020)*. Considering this curve for refurbishment, the end of life spike experiences an extension, that is normalised over the expected lifetime. García-Martínez & Sánchez-Montañés (2016) demonstrates the system boundaries for the module B5 (Refurbishment), according to the EN 15804:2012. They argue to include new embodied impacts with the product stage (A1-5), as well as the new operational use stage (B1-7).

The operational energy performance is to be evaluated by comparing the as-is performance towards the future scenarios. The embodied impacts, on the other hand, are solely compared between the future scenarios *(Hasik et al., 2019).* This definition stays in line with the EN 15978: as described there, the refurbishment should include the production, transport, construction and waste management as well as the end of life stage of all components added in the course of the refurbishment process.

Vilches (2017) argues that usually the existing building elements, and even the structural layers within the components of interest are not taken into consideration, neither for economical nor for environmental evaluations. The study from Menzies (2011) argues that the energy and carbon related emissions that have been invested to create a building have already been spent and could only be analysed when using historical records. The so-called sunk energy and carbon therefore do not contribute to the current emission reduction targets. Instead, the focus is on evaluating refurbishment measures regarding their future embodied impacts for the new refurbished life cycle *(Menzies, 2011).*

[31] https://ecochain.com/knowledge/impact-categories-lca/

[32] SIA. SIA 2040 La voie vers l'efficacité énergétique. Zurich: SIA; 2017, as cited in Slavkovic et al., 2019, page 2

So called simplified LCA in refurbishment can help designers to make the first step towards a holistic LCA performance. Even though simplified LCA neglects future climate predictions and reusability of buildings, it is nonetheless useful to evaluate scenario thinking in a decision-making process *(Oregi et al., 2015; García-Martínez & Sánchez-Montañés, 2016).*

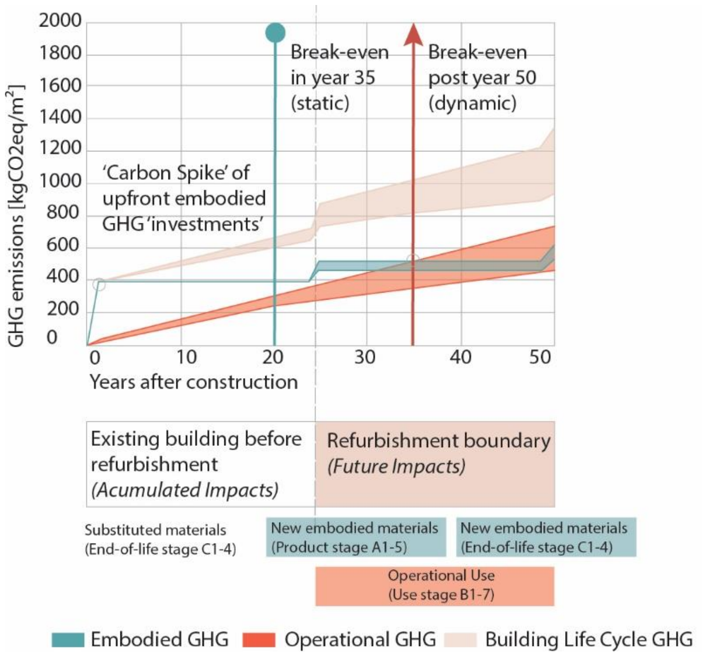


**Figure 14 Embodied Carbon spike in refurbishment projects** ***(Röck et al., 2020; García-Martínez & Sánchez-Montañés, 2016)***

#### 2.2.2.3 Challenges of operational and embodied impacts in refurbishment projects

Operational energy and carbon are closely related to each other. Depending on the energy demand of a building and the energy supply (fossil-fuel or on-site energy production) the carbon emitted can be high or rather low *(Ibn-Mohammed et al., 2013).* To evaluate operational energy, it is commonly recommended to assess the primary energy demand and compare the as-is state to the as-refurbished state. This in fact relates to the energy evaluation methods as described in the previous **Section 2.1.1**. On the contrary, the embodied energy and emitted carbon due to fabrication of materials do not have a direct but a rather implicit relation. This is because some materials emit carbon while others capture it. Taking the production of insulation materials as example, bio chemically produced materials, such as expanded polystyrene (EPS) emit carbon in production, while bio-based materials such as wood flax captures more carbon when growing than they emit via manufacturing the product *(Ibn-Mohammed et al., 2013)*.

Even though operational and embodied energy and emissions are emitted throughout the whole building's lifecycle, over the years common practice for building refurbishment has focused on the reduction of the operational energy consumption. While improving the building`s energy performance, efficient technology equipment with high performances is added, that results in a great number of embodied emissions *(Ramírez-Villegas et al., 2019).* This assumption was confirmed by the study of Röck (2020), which analyses the results of absolute and relative embodied and operational GHG emissions of a wide set of buildings. LCA performances for existing, new and advanced building standards show a lowering trend in their total GHG performances. However, advanced buildings show a significantly higher share of embodied emissions. The carbon saved via energy efficiency could be outperformed by the embodied carbon caused due to materialisations and other operating systems. Thereby the percentage of the hidden emissions takes up to 50% for highly energy efficient buildings, see **Figure 15** *(Röck et al., 2020).*

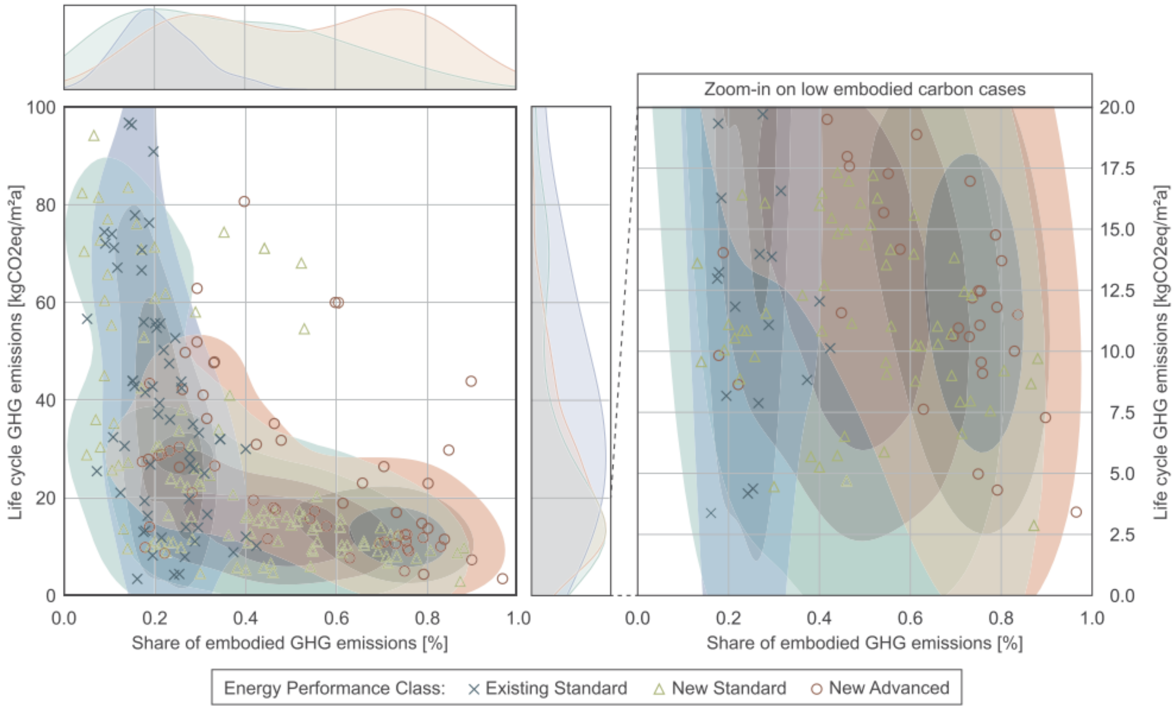


**Figure 15 LCA GHG emissions and share of embodied emission *(Röck et al., 2020)***

To counteract, a local sourcing of materials as well as considering circularity aspects, by using recycled or second-hand materials, is suggested to reduce waste and other emissions due to manufacturing processes (*García-Martínez & Sánchez-Montañés, 2016).*

#### 2.2.2.4 Future steps in LCA for refurbishment projects

More extensive LCA studies of refurbishments are shown in the study of Gomes (2017). They focus on both the operational and embodied impact evolving over time. They consider changing climates in the future and a mixed mode of space usage for a precise prediction of future energy consumption. Further by analysing various envelope retrofit solutions with different materialisations, the embodied emission intensity over time is highlighted and compared towards the operational impact evolution. With this scenario-driven method, it is aimed to find the best-case model for a use case in glance of changing climate and occupation situation.

A similar scenario-driven approach was conducted in the research of Passer (2016) where refurbishment scenarios were defined for housing. Firstly, for the energy generation on site, three sources were defined, which are the basic gas consumption, use of solar thermal, and photo voltaic. In combination with these three operational energy scenarios, building element improvements were considered in the form of insulation for external walls, windows, top ceiling, and basements. U-values were defined that can be expressed in \`no improvement\`, \`minimum improvement\`, and \`high quality\`. Climate change scenarios and the effect towards the energy demand were considered. Results show that the higher the efficiency of the operational energy sourcing the higher the embodied impact. The

Payback Time (PBT) was used to evaluate and compare the scenarios. The sum of the embodied impact per scenario was divided by the operational impact *(Passer et al., 2016)*.

Ramírez-Villegas (2019) analyses the effect of energy efficiency measures towards the building's environmental performance on the example of one use case. Measures were performed to increase indoor comfort via the ventilation system with heat recovery, and improvement of thermal properties by upgrading building materials. The biggest impact identified was the operational energy use followed by a significant contribution of building materials. It is argued that deep renovations, such as upgrading of HVAC systems, are economically more feasible than material-based refurbishments, as they can decrease up to 40% energy annually. Secondly, LCA impact categories, such as the global warming potential (GWP), Air pollution (AP), Eutrophication (EP) and Abiotic resource depletion potentials (ADPs) were analysed. Highlight is the time perspective, that the live time and the duration of the building may differ and ergo affect the total LCA performance of the building *(Ramírez-Villegas et al., 2019;*).

Even though there is awareness about the necessity to apply LCA in new design projects and to evaluate the energy and carbon performances of already existing buildings, there is a lack on national guidelines or definitions of energy and carbon refurbishment procedure which would accomplish nZEB and nZGHG implementation in the Netherlands *(Filippidou et al., 2016).* This consequently results in a clear lack of interest by the building owners to consider LCA-based requirements for refurbishment projects *(Nault et al., 2018; Jusselme et al., 2020).*

### 2.2.3 Economic Performance

Building owners focus on economic investments as environmental and life cycle related requirements are not their expertise and/or primary interest *(Seghezzi et al., 2019)*. To overcome these problems, expert knowledge is needed for consulting which requires much time and consequently high costs *(Nault et al., 2018; Jusselme et al., 2020; Seghezzi et al., 2019).* In addition, the complexity of the integration of the expert's input/data/results in refurbishment projects creates a high-risk factor for owners *(Miyamoto et al., 2019; Ebrahimigharehbaghi et al., 2019).*

The deterministic model of LCC is a commonly used method to assess economic feasibility *(Jafari, 2017).* Cost-related characteristics, amongst others, are initial costs (including market renovation costs and design fees), maintenance costs, energy savings, increase/decrease of rent income, payback costs, payback time and the difference of the market value before and after the refurbishment *(Nault et al., 2018; Jusselme et al., 2020; Seghezzi et al., 2019).* It is important to highlight these economically oriented aspects, because the decision for an refurbishment will only be made if the renovation costs won't exceed the market value of a newly built dwelling *(Zavadskas & Kaklauskas, 2004).* These economic aspects are contributing highly to decision-making processes for refurbishment projects. The process of assessing cost-related assessments is similar to the above-explained LCA assessments. However, do not represent a major part of this thesis and are thus not elaborate in more depth.

## 2.3 Digital evaluation methods

*In the following Section, digital evaluation methods are discussed to answer the third research sub question: SQ3) Which digital evaluation methods (tools) are currently on the market and what are the benefits of a BIM and web-based information exchange? This encompasses current tools focusing on LCA in design used in the Netherlands. Furthermore, the Building Information Modelling (BIM) in combination with LCA tools are discussed. Eventually, this Section will close by highlighting the current bottlenecks of information exchange between building information and environmental data such as the LCA.*

### 2.3.1 LCA tools

As already explained earlier, since 2013, the Dutch norm NEN-EN-ISO 14040:2006 (NEN 8006: § 5.2.2) requires LCA performances for building permits. For several years the development of software solutions, such as publicly available and paid LCA tools, encourages building owners and engineers to make use of the LCA methodology in the design process. The use of non-graphical tools (such as excel based or web browser-based tools) are discussed as well as the trend to implement graphical LCA tools within engineering's workflows using BIM, see **Table 7**. Note, the graphical data refers to the 3D geometries, the objects of a digital building models. They are established as virtual models and are referenced with each other. Non-graphical data describe the additional information, object attributes, that can be used with or without the geometry. These object attributes can be connected with the 3D objects, and thus be queried and multiplied by the building components quantity. An example would be a window that is defined as object (graphical data) that contains multiple data points that describe the geometry. Non-graphical data would be LCA information that are related to the window geometry. Unit of measure of the graphical and non-graphical data is important to consider for the scalability of results.

#### 2.3.1.1 Non graphical evaluation

MPG (Milieu Prestatie Gebouwen) is a public tool that accesses environmental data from the National Milieu Database (NMD). NMD contains Environmental Product Declarations (EPD) from manufacturers in the Netherlands. Products within this database contain LCA information such as impact categories (Acidification, Total Energy and GWP) per product and material unit. Additionally, more advanced LCA tools used in the Dutch real estate market are BREEAM and GPR Gebouw, assessing operational and embodied emissions for constructions based on the NMD, see **Figure 16**.

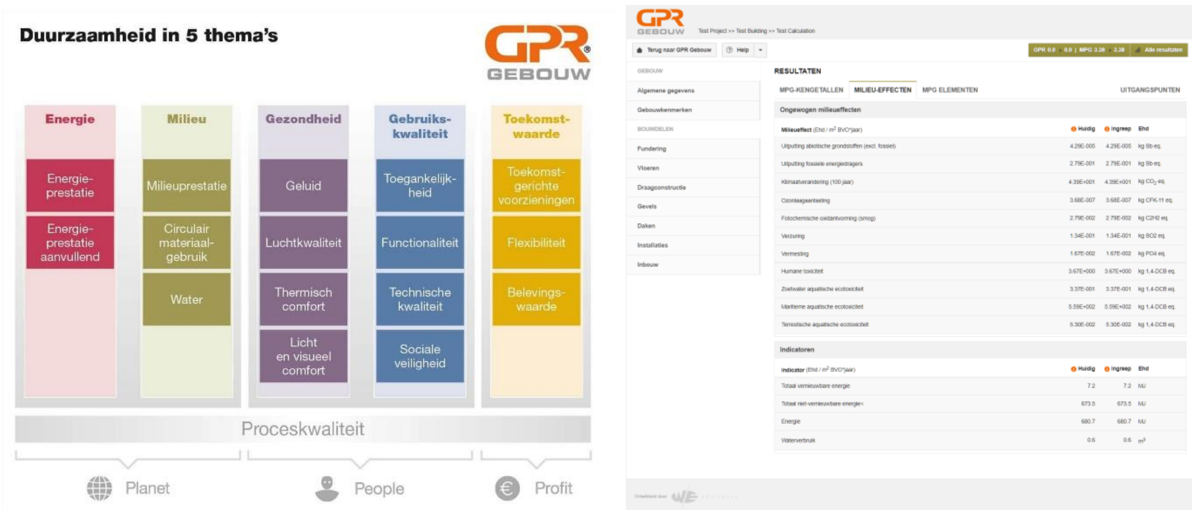


**Figure 16 GPR Gebouw Online tool**

Amongst other participatory stakeholders, W/E Consultants[33] develops GPR Gebouw under policies delegated by the Stichting Bouwkwaliteit GWW *(SBK, 2014).* In their document a holistic stepwise approach explains the LCA methodology for building assets and building products. Next to operational energy performances and embodied environmental assessments also health, functional usage and asset value are discussed in the tool. Zooming in closer to the module "Environment" (Dutch: "Milieu"), a modular user interface provides users the ability to define their building assets and assign materials for each component, see **Figure 16** right-hand side. While analysing the tool, it could be identified that the selection process of materials is done by defining the thermal resistance (Rc-Value). Depending on the level of improvement the embodied impacts increase. This means that the higher the Rc-Value is, the better the thermal improvement becomes, and the higher the embodied impact is.

The advantage of GPRGebouw is that new and existing buildings can be relatively easily established and analysed within all eleven impact categories. However, someone needs the expertise to read and interpret the LCA data. LCA experts are often consulted, which leads to high investment costs for the builder/project owner. Furthermore, challenges remain with regard to a limited design scenario for refurbishment projects, and no insights in investment cost and operational cost-saving.

Providing visualisation in the form of maps, spreadsheets, or even digital geometrical models would create an attractive solution for these advanced LCA tools. When focusing on LCA for refurbishment projects, Nault (2018) argues that LCA studies could be performed per refurbishment scenario and simultaneously show the financial impact per scenario. Thereby the missing insight of economic benefits can be overcome and can help decision-makers to evaluate various scenarios regarding the best trade-off of environmental and economic solutions *(Nault et al., 2018;* Jusselme *et al., 2020; Malmgren & Mjörnell, 2015).*

To support this idea, recent studies suggest making LCA more accessible within the AEC industry by introducing LCA within Building Information Modelling (BIM) tools *(Röck et al., 2018; Ariyaratne & Moncaster, 2014).*

**LCA Tools**

| **Name[34]** | **Required knowledge** | | | **Paid license** | **Database** |
|---|---|---|---|---|---|
| Non-graphical | Low | Medium | High | | |
| SimaPro | | | ✓ | ✓ | Amongst others EPD, Swiss Input/Output |
| GPRGebouw | | ✓ | ✓ | ✓ | National Milieu Database (NMD) |
| MPG calc | ✓ | | | | National Milieu Database (NMD) limited edition |
| DGBC | | ✓ | | ✓ | National Milieu Database (NMD) |
| Graphical (BIM and LCA) | | | | | |
| Tally | | ✓ | ✓ | ✓ | ECOINVENT |
| One-Click LCA | | ✓ | ✓ | | EPD, NMD, Ecoinvent. |
| Semantic BIM and LCA | | | | | |
| H\B:ERT | | | | | Semantic connection |

**Table 7 LCA Tools**

[33] https://www.w-e.nl/we-consultants/

[34] A reference list of the tools can be found in the Chapter 8 References

### 2.3.2 Building information modelling

Building Information Modelling (BIM) in the AEC industry is a well-known method due to its three-dimensional (3D) representation and its possibilities for information enrichment. A meaningful combination of geometry and information enables object-oriented data retrieval, such as automatic quantity take-off and component material information. Furthermore, BIM methodology is often understood as the basis of Virtual Design in Construction (VDC). It allows model-based collaboration and communication and sharing information between multi- and interdisciplinary stakeholder. Connecting the life cycle-related data with the building quantities in a BIM tool, one can create attractive solutions to perform environmental and economic impact assessments of the corresponding materials *(Santos et al., 2018)*.

#### 2.3.2.1 Graphical evaluation using BIM and LCA

Some BIM-LCA tools and workflows have been developed over the past years. For instance, Tally, IMPACT, eveBIM-ELODIE, Arquimedes, and One-Click LCA, are plug-ins for BIM software such as Autodesk Revit. Material selection and the related LCA data is implemented as a generic database, such as ECOINVENT, and not as product-specific EPDs. Due to their consistency and high demand on data entry, the data structures of LCA models show uncertainties when applied to the conceptual stage of building design. The required high level of detail (LOD) of building elements is not available in simplified and aggregated 3D building shapes. Thus, there is a big challenge in defining precise and detailed building characteristics from relatively basic building typologies *(Österbring et al., 2019).* Building planners must make many compromises which result in an inaccurate LCA and misleading design decisions *(Santos et al., 2018)*.

Studies regarding building stock aggregation modelling established schematics to define building typologies by archetypes. A bottom-up approach classifies the LOD per building element and applies them to building characteristics, elaborated by the building shape, height, number of levels, mechanical system, and quantity estimation of material *(Mastrucci et al., 2017; Slavkovic et al., 2019).* The connectivity of various LOD´s to LCA aggregated datasets plays thereby a major role. A more user-oriented approach is to develop custom workflows, using Visual Scripting (VS) in combination with BIM. This kind of method gives the freedom to connect any database towards the BIM model. However, this also raises another challenge such as managing the very broad and detailed LCA data structure and trying to align the information towards the BIM model.

Röck (2018) established such a workflow on a building material level, see **Figure 17**. Three steps are performed, this is aggregating the LCA database for building elements using Microsoft Excel, establishing a BIM model using Autodesk Revit, and finally using a custom script in Dynamo that merges the excel-based data towards the building element´s materials *(Röck et al., 2018).*

Advantages of this workflow are an enhancement of scenario thinking, using different materials, data ownership and reusability of data and scripts (considering software and package versioning). The disadvantage would be that data are assigned and applied within the BIM model that results in low-performance capacity and too high data content within one model that cannot be easily shared with other disciplines. The data exchange plays thereby a major concern.

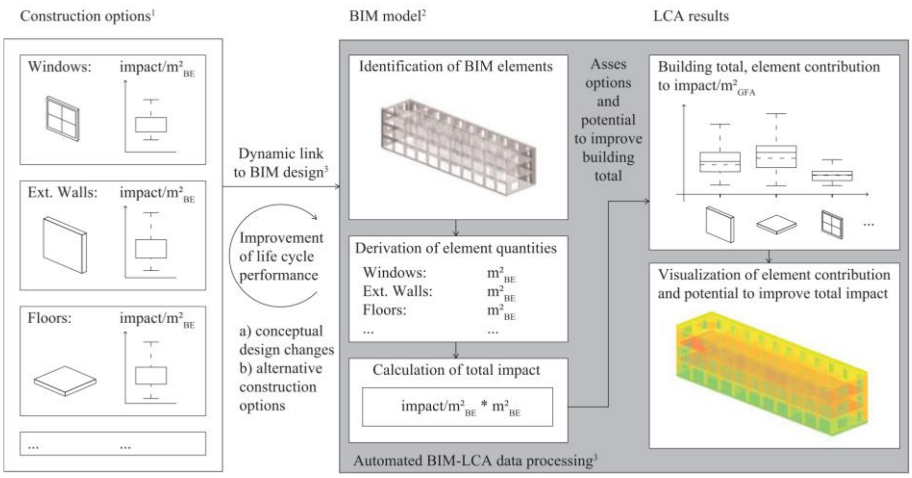


**Figure 17 LCA and BIM using Visual Scripting (Dynamo)** ***(Röck et al., 2018)***

#### 2.3.2.2 Data exchange

The consideration of environmental and economic criteria, (LCA, cost, and other object-related assessment), requires a multi- and interdisciplinary working method. The engineer is asked to make use of several different tools, as explained above, or to collaborate with other disciplines. Either way, this form of collaboration efforts requires a complex data exchange mechanism between all included stakeholders throughout the project life cycle. Sharing cross-domain information efficiently can help to overcome challenges such as meeting predicted performance with actual performance results *(Hu et al., 2021).* The creation of graphical and non-graphical information (such as BIM models and calculation documentation) is commonly performed in centralized data environments. BIM-based collaborations and models have been established on discipline-dependent software. When sharing this information amongst stakeholders, various data and files with different native file formats are being exchanged mainly via emails or shared folders. When trying to merge different disciplines' data with each other it appears that data is repeatedly touched and manipulated which results in risking data loss. While neglecting the data amalgamation to other disciplines the information distribution and exchanging becomes inefficient and ineffective *(Tao et al., 2021).*

For this reason, the ISO standard 19650 "the Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)" issued by the end of 2018, provides experts in the built environment with recommendations for a framework to manage information including exchanging, recording, versioning and organizing for all actors. In this context, a Common Data Environment (CDE) is recommended to be used. A CDE per definition is "the agreed source of information for any given project or asset, for collecting, managing and disseminating each information container through a managed process"[35] (ISO 19650-1, page 3.3.15). When working with BIM models and using a specific software API it is possible to manage the collected building data on a local information storage. Challenges remain in sharing and disseminating building projects data. The data exchange between stakeholders and different CDEs is addressed and the focus of future BIM-related work *(Pont et al., 2014; Tao et al., 2021).*

Current solutions in the industry that avoid significant data loss between project stakeholders offer cloud-based collaboration platforms as a solution, such as BIM360 from Autodesk, BIMSync, Aconex

[35] https://bimcorner.com/cde-within-iso-19650-a-process-or-a-solution/

from Oracle, and proCore. These solutions provide construction management tools, that manage documentation and BIM model in open file standards, such as Industry Foundation Classes format (IFC) *(Tao et al., 2021).* While models are published and become insightful to other disciplines it is often asked how to bring back the data from the cloud-based collaboration model to the locally saved BIM model.

Software solution providers, such as Speckle[36] and Hawkins Brown, revise this question and doubt to store interdisciplinary data. Instead, they shift the discussion towards web-based data querying to establish a discipline agnostic framework that allows enriching any base model (BIM) with relevant product data (potential national NMD database). In the solution of Speckle, different vendor APIs (such as Rhino, Revit, Archicad) make use of an API-integrated web browser that allows querying interdisciplinary data from project members. Based on one central digital model data are queried rather than duplicated. Crucial thereby is to rely on classification schemas (like IFC, gbXML, COBie) which offer object-related identification schemas. Another approach and more specific for LCA performance (using embodied impact assessment), Hawkins Brown developed an open-source LCA - BIM plug-in (for Autodesk Revit). It allows users to connect to national LCA databases and can thus be linked and queried based on the BIM quantities. The saving of data is avoided, and rather querying of demand is allowed.

### 2.3.3 Web-based information exchange

Following the idea of web-based communication systems, recent developments in the built environment, such as the Linked Building Data (LBD) initiative are aiming for a complete separation of the data level and local BIM software (APIs). This means, instead of sending data back and forth, federated and decentralized data containers (data pods) on the web are applicable towards any building model *(Malcolm et al., 2020; Werbrouck & Rasmussen, 2020).* The idea of the "single source of truth" (SSOT)[37] of graphical and non-graphical data is thereby applied. Every data drop is solely defined by its source. The data structure is mastered in only one place and underlies a vocabulary. Data skeletons, in the form of ontologies, help to define how other information can be interlinked *(Malcolm et al., 2020; Werbrouck et al., 2019)*. For instance, a graphical BIM model (geometry and parametric information) can be created as a central model and stored on a CDE. The data structure of the model is defined via an ontology and a classification schema of the object. Amongst other ontologies in the built environment the Property set definition ontology (Props), Product ontology (PRODUCT) and Building Topology Ontology (BOT)[38] developed by the W3C LBD Community Group, are commonly used. BOT describes in essence the building composition[39] including spaces that contain elements that are further described as object-oriented classification schemas *(Rasmussen et al., 2020).* The Industry Foundation Classes (IFC) is the most common vendor-neutral file format that describes schematically buildings and assets throughout their building life cycle. Such a schematic documentation approach of building elements qualifies the connectivity towards a web-based information container of any sort.

This web-based data enrichment is based on semantic web technologies. Due to the nature of the semantic web (linking sources), building data is not limited to only one ontology. The exchange of interdisciplinary information models happens by referencing information among each other through

[36] https://speckle.systems/
[37] https://en.wikipedia.org/wiki/Single_source_of_truth
[38] https://w3c-lbd-cg.github.io/bot/
[39] https://w3c-lbd-cg.github.io/bot/bot.ttl

link information in all federated (distributed) data models *(Malcolm et al., 2020; Rasmussen et al., 2017)*. Multiple ontologies can be connected that allow enriching the data structure unlimited *(Werbrouck, et al., 2019; Rasmussen et al., 2017*). For instance, recent developments created an LCA ontology[40] that could be combined with all other ontologies, including for example the BOT ontology and the IFC ontology. Inevitably this leads to higher transparency and reusability of already existing data that in return encourages data harmonization throughout multiple disciplines, beyond the building industry *(Kuczenski et al., 2016; Flore et al., 2021).*

#### 2.3.3.1 Link Building Data (LBD)

The Linked Building Data (LBD) method represent the result of applying web-based information exchange (using semantic web technology) in the AEC industry. The web-based building data in the form of raw data (the SSOT) can be exchanged and declared amongst stakeholders. The data entity is stored as node-based graphs including nodes and relations, defined in a triple (subject-predicate-object). Open standards to do so are Resource Description Frameworks (RDF) data models. Data can be linked with each other using the uniform resource identifier (URI) and a uniform resource locator (URL). As the names indicate, the identifier refers to a unique source identification number while the locator references the location of the source on the web. The Hypertext Transfer Protocol (HTTP) is used to permit dedicated user access rights to read the stored information from the URIs. Query languages such as RDF Query Language (SPARQL) allow to query the graph-based information. Finally, while a user queries URI-specific information, he/she should be able to retrieve more related information towards the primary asked URI. By connecting or linking URIs to elements, the user experiences information browsing based on the building models deliverables and possibilities *(Flore et al., 2021; Werbrouck & Rasmussen, 2020).* With this methodology, engineers receive great freedom to perform building assessments while linking building elements to particular data entry points of any database, rather than storing all the data on the local machine. While the engineer can create evaluations of building performances the linked data is temporarily stored on the local user. Only once the engineer made a final decision, the information link is stored and made accessible to other stakeholders, by referring towards the single source of truth of the data *(Werbrouck & Rasmussen, 2020; ArchHive, 2020).*

Information sharing and data transparency enhances the ability for engineers to make use of wide sets of available data, great competition of software vendors hinders the data to become open and freely accessible. Giving full access to background data of APIs creates competition and hinders APIs to collaborate in a machine-readable way *(John Egan, AECHive, 2020).* A shifting mindset is required to rather create a data-independent software API to allow the querying and alignment of openly accessible data containers in the form of manufacturer data, national environmental data, or governmental policies. On the contrary, working groups, such as the aforementioned LBD initiative from the W3D LBD Community Group[41] have a strong focus on combining BIM methodologies with web technology, with a focus on data and information exchange. However, there is a lack of implementation of web-based tools that encompass multiple data structures and thus enable multidisciplinary areas to be merged *(Werbrouck et al., 2019)*.

[40] https://github.com/tishchungoora/lca-ontology/blob/master/LifeCycleAssessmentMethodology.owl
[41] https://www.w3.org/community/lbd/

## 2.4 Decision Support System and Consumer Preference

*This Section aims to answer the research sub-question: SQ4) Which instruments for consumer preference modelling exist and how to translate multi-criteria objectives into a decision support tool? Firstly, fundamental knowledge about decision support systems in refurbishment projects is introduced. It shows a standard procedure of collective decision-making and explains the goal and criteria definition. Environmental behaviour explains homeowners' motives that should stay in a sustainable framework. Multi-criteria objectives are to be assessed via preference modelling instruments. It helps to determine homeowners' willingness to accept refurbishment concepts and explains their decision-making process. Finally, decision support tools are introduced that were developed for participatory decision-making in practice.*

Refurbishment projects are undoubtedly a complex process. The longer the building`s history and the higher the number of involved stakeholders, the higher the requirements. In the following, the focus is on participatory decision-making processes for energy collectives, that represented big groups of homeowners as the end users. *(Find relevant information about the complexity of residential building refurbishments and stakeholders in Section 2.1).*

A decision support system is required to include the opinion of all decision-makers (end-users) to act in their interest. To satisfy end-users and technical requirements, the refurbishment process is primarily dominated by the planning stage in the early design phase. Thorpe (2017) highlights to pay special attention and time to the planning stage. Decision quality can be increased while the risk of drawbacks can be minimized. A lack or even misinformation causes primary insufficient solutions and unsatisfied building owners. For instance, the urgency to install electrical energy generation systems while using poor building insulation does not lead to expectations being met. Finding common interests between decision-makers can help to define goals and expectations *(Thorpe, 2017)*. Multiple studies suggest supportive decision-making steps. Bazerman & Moore (2012) elaborate on six decision-making steps. Defining the problem, identifying the criteria, weigh the criteria, generate alternatives, rate alternatives on criteria and finally compute the optimum decision *(Bazerman & Moore, 2016).* Nielsen (2016) describes a similar approach for a decision-making process of refurbishment projects. Firstly, goal-setting represents the key aspect and can be seen as the *"rational heart of the entire process" (Nielsen et al., 2016, page 166).* Emphasise is devoted to setting goals in a sustainable framework, that includes environmental, economic and social goals. Followed by the goal, the criteria and sub-criteria can be defined accordingly. The relative importance of these criteria can be weighed in multiple ways. It allows decision-makers to judge alternatives based on their preferences and the weights they give towards the criteria *(Wilson et al., 2018)*. According to these definitions, the building and refurbishment alternatives are designed by technical advisors. The calculation results are then juxtaposed to the initially set goals and evaluated to find the final decision. This stepwise approach allows project participants to decide reflectively rather than intuitively. A conceptual diagram explains a tree structure when defining goals, criteria, sub-criteria and measures, see **Figure 18**.

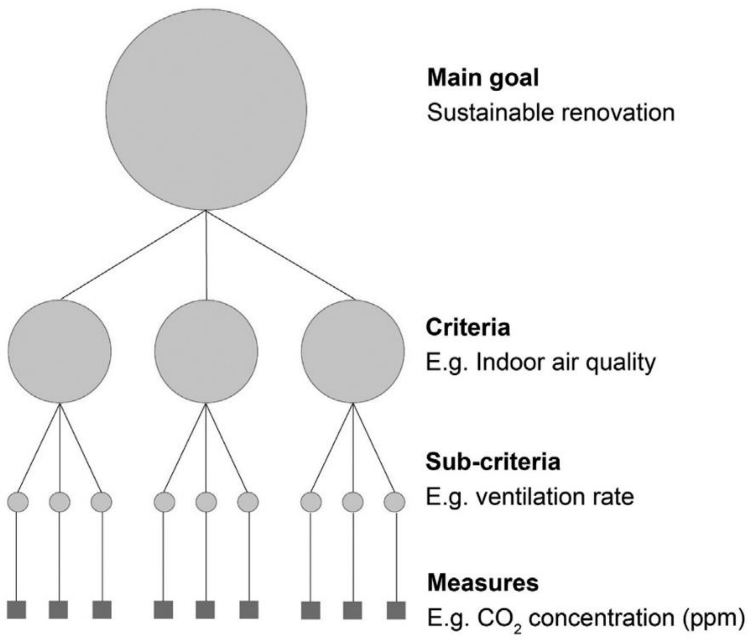


**Figure 18 Decision Support System *(Nielse et al., 2016)***

Collective groups of building owners and occupants vary in their ambitions to refurbish their homes. Multiple aspects influence the goal definitions. They result from socio-demographic backgrounds, households and building characteristics, and pro-environmental behaviour. The following will discuss motives for decision-makers and will introduce research performed in a Dutch context.

### 2.4.1 Goal and multi criteria definition

At the beginning of each project, the objective (the goal) has to be defined. The paper of Steg (2014) presents an underlying theoretical framework that studies the pro-environmental behaviour of people. Three motives are defined: hedonic goals, gain goals and normative goals *(Lindenberg & Steg, 2007; Steg et al., 2014).* These goals are used to identify reasons for people acting in pro-environmental behaviour. Actions made depend on people's environmental awareness. It is argued that by providing information to the decision-makers, new insights can be gained (covering hedonic, gain and normative motives). In this way, decision-making processes can steer the achievement of goals and identify future decisions. All three motives influence the decisions differently. The hedonic motive focuses on the way how people feel towards solutions, and how enjoyable they are. The gain motive is based upon what people could gain, such as financial and status benefits. The normative motive encourages people to choose solutions regarding societal norms and the rightness of things. For instance, protecting the earth's biodiversity is the right thing to do. It is often argued that when acting in pro-environmental behaviour there are sacrifices towards other criteria. For instance, choosing bio-based materials as insulation would be the right thing to do for the environment, however, would cost twice as much. The gain and the hedonic goal would stay in focus while the normative goal has to be encouraged too *(Steg et al., 2014).*

Behaviour economics in refurbishment projects is a broad subject and requires further investigation for Dutch homeowners' motives to refurbish their homes. Generally, goal definitions and related criteria to be evaluated by project stakeholders (decision-makers) can vary per project group. Ebrahimigharehbaghi (2019) investigated Dutch homeowners' motivations for energy renovations. A linear regression model has been created that analyses the dependency of decision-making factors, such as ‘drivers’ and ‘barriers’ towards renovation concepts. Studied factors are household and building characteristics, socio-demographics and financial benefits. Results show that homeowners are mainly motivated to refurbish because the living quality increases (hedonic motive) and the advantage of monetary benefits (gain motive). The limitations of energy renovation are shown in high costs when investing in reliable experts and the complex renovation process. In addition, lacking informative aspects of subsidies means that the homeowners do their research and thus need a lot of time *(Ebrahimigharehbaghi et al., 2019).* Similarly, the study of Broers (2019) argues that the informative aspect in combination with socio-demographic, household and building characteristics dominates the motivation to renovate. They conducted a series of interviews with Dutch homeowners and analysed factors that are important in early decision-making steps. Technical advisors, for instance, government or energy collectives, contribute highly to motivation. Especially drivers are seen in economic relevance as well as environmental concerns to improve the existing building performance *(Broers et al., 2019).*

Homeowners are commonly driven by goals that are financially feasible and have maximum effect in comfort (short-term targets). On the other hand, homeowners also show pro-environmental behaviour (long-term climate targets). Seeking to find balance throughout these criteria, to satisfy short and long terms goals, the sustainable development framework is proposed. It is subject to economic, environmental and social developments, see **Figure 19** *(UN, 2013; Nielse et al., 2016; Gade et al., 2019; Kamari et al., 2017; Taillandier et al., 2016).*

*“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”*[42]

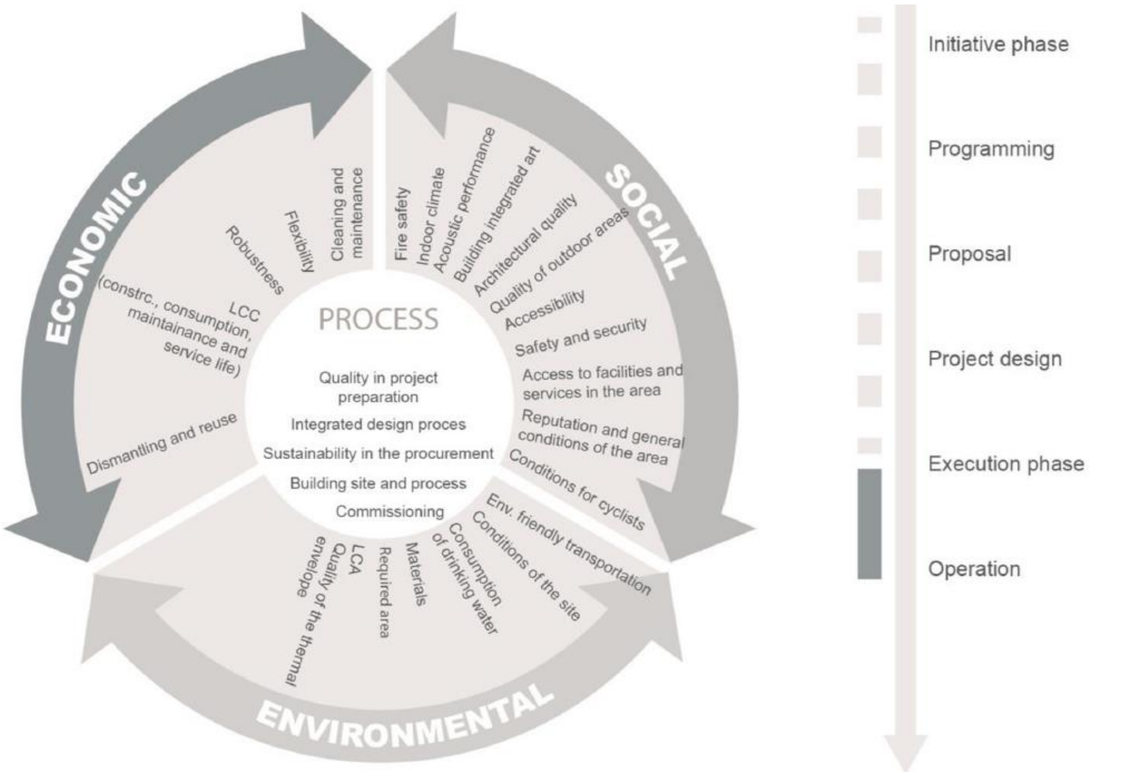


**Figure 19 Concept of Sustainability *(Kamari et al., 2017)***

[42] *WCED, 1987, Chapter 2.1*

While the goal and criteria definition seem to be a systematic process, identifying the criteria, prioritising them and finding the relative importance requires more attention. This is especially the case in participatory decision-making processes that include a high number of homeowners.

### 2.4.2 Criteria weighting using consumer preference modelling

This Section is dedicated to analysing the acceptance of such criteria in quantitative consumer research. Consumer preference modelling is introduced to analyse end-user's willingness to accept and invest in multi-criteria objectives of refurbishment concepts. In energy refurbishment, the focus is often dedicated to energy reduction measures that consequentially lead to cost reduction. The economic goals are used to describe operational cost saving, investment and payback time. Increasingly important are the social goals, which include comfort improvements. Lastly, attention is given to $CO_2$ reduction measures.

The following will study different approaches and methods used to examine consumers' decision-making process. Attention is given to the level of pro-environmental awareness people have when making a decision. The willingness to pay (WTP) is introduced as a tool to understand the economic motive that enforces the environmental and social components. Special attention is also dedicated to comforting improvements and the willingness for people to choose $CO_2$ reduction measures.

The consumer preference model for energy efficiency renovations was studied by Alberini (2013). Thereby they assessed the acceptance of homeowners regarding economic and environmental awareness. A conjoint choice experiment surveyed 473 Swiss homeowners, living in row houses and single-family houses. In total five attributes were defined. It included monetary values in the investment cots in swiss franc (CHF), subsidy and energy saving per year as a % of the total investment cost and annual heating expense. Moreover, comfort improvement and payback time were included. The economic and environmental awareness was surveyed by asking the participants about their estimations regarding future energy costs and climate change. The estimated results reveal that homeowners who cannot estimate any future energy prices (12% of the sample) prefer choosing the option not to renovate. While homeowners who have a high environmental awareness tend more to renovate their homes. At the same time, it was found that if governmental subsidy would increase, the willingness to accept energy renovation would increase too. They conclude, to make homeowners aware of future energy scenarios and climate change happenings, that the informative aspect is missing *(Alberini et al., 2013)*.

A study that provides solutions regarding information and knowledge sharing is provided by Ossokina (2021). It was studied to what extent information influences social housing tenants when making a decision for energy refurbishments. The research is based upon the pro-environmental behaviour research by Steg (2014). A stated choice experiment was performed with 688 social housing tenants in the Netherlands. They could choose between three options. Either two refurbishment packages that contained six attributes, or not to refurbish. Some participants were exposed to information regarding improvements after refurbishing. Firstly, the hedonic group received information about comfort-related improvements. Secondly, the gain group receives information about financial savings. Results show that information provision influences the choice. A positive effect to refurbish was found when providing comfort information, while the financial information reduced the willingness of the tenants *(Ossokina et al., 2021).*

A similar study was performed by Banfi (2008) that studied the environmental and social motives. The importance of these criteria was explained in the form of the willingness to pay (WTP) into refurbishment concepts. They argue that only when knowing the economic motive to refurbish, the environmental and social components can be enforced. A stated choice experiment has been conducted. Instead of presenting attributes that concern comfort and energy reduction, the experiment introduced technical upgrades. Windows, façade and ventilation improvements varied on levels from efficiency standards. Reaching from no improvement to medium and high improvements. Moreover, investment costs were introduced in five levels. Similar to the study of Ossokina (2021), also here they used information cards introducing comfort and environmental improvements. It was found that both, homeowners and tenants, have a high WTP into measures that improve comfort and environment. Homeowners are willing to invest up to 12% for ventilation systems (compare to the reference price), which leads to better air quality. This is followed by a 7% WTP for façade insulations and up to 13% for window insulations that results in better thermal comfort and energy reduction *(Banfi et al., 2008)*.

Special attention was given to the comfort component by Galassi & Madlener (2017). They studied the role of environmental concerns and expectations of comfort improvement when facing a deep thermal energy renovation. More than 3000 owner-occupants and housing tenants were surveyed with a Discrete Choice Experiment. It was proposed to renovate the façade, with insulation and window replacement and change the heating system. Seven attributes discussed the energy reduction, indoor air quality, payment per month for the heating system, room temperature improvement, noise reduction potential and the level of regulating natural ventilation and heating system settings. A mixed logit model reveals that the comfort attributes show most relevance, dominated by indoor air quality improvement, followed by high utility results for lower investment costs and the risk of losing control of mechanical regulations. Finally, the noise reduction shows significant relevance. It is mentioned that the actual interpretation of comfort-related attributes remains challenging. Indications of improvements were solely based on a dichotomous variable, such as improved or not improved *(Galassi & Madlener, 2017).*

A similar study by Chau (2010) aimed to verify construction engineering design regarding comfort improvements in an urban development project. The satisfaction of occupants of green buildings in Hongkong after construction was investigated. Chosen attributes were the monthly management costs, available landscape usage in $m^2$, the saving of annual drink water consumption in %, the annual energy saving potential in %, indoor noise level and air quality improvements. Results show a high WTP for improvements of indoor air quality and noise level reduction, 21% and 22% respectively. Also, in this study, the interpretation of attributes was challenging. An expert would measure improvements like air quality in humidity level and carbon dioxide levels as well as noise level improvements with decibel level (db). No intuitive explanation exists at this moment that describes indoor air quality improvement, or level of noise improvements intuitively *(Chau et al., 2010).*

The studies so far have investigated energy efficiency and comfort-related measures. However, when performing in the framework of pro-environmental behaviour, next to energy also the reduction of $CO_2$ is equally important. A focus on $CO_2$ reduction measures was given in the study of Achtnicht (2011). They argue that the preference of homeowners to invest in heating systems and envelope improvements is crucial to mitigate energy consumption and related $CO_2$ emission. A choice experiment in Germany was conducted that included owner-occupants of single-family houses, detached, semi-detached and terrace houses. The participants could choose between two improvement scenarios, either the heating system or the insulation of the façade. The mixed logit assessment of the choice data was used to derive the preferences and the WTP for $CO_2$ reductions. The experiment included seven attributes. These are the investment costs reaching from 10,000€ to 40,000€, yearly energy saving reaching from 25% to 75%, payback period reaching from 10 years to 30 years, $CO_2$ reduction reaching from 0% to 100%, opinion on choosing an independent energy provider, public or private funding and period of guarantee, reaching from 2 years to 10 years. Results show a positive effect for $CO_2$ savings in both measures. However, the hypothesis that the $CO_2$ coefficients in both scenarios are of equal importance has been rejected. Apparently, homeowners do value $CO_2$ reduction differently depending on whether they choose a heating system or thermal insulation. The homeowners who choose thermal insulation consider environmental benefit much higher than the homeowners who choose the heating system. Behavioural reasons could be that heating systems can yet rely on fossil fuels *(Achtnicht, 2011)*. This behaviour was further investigated by Michelsen & Madlener (2012). They studied homeowners' behaviour towards $CO_2$ reduction measures when adopting the residential heating system (RHS). Instead of using measures (such as façade insulation), the willingness to reduce the $CO_2$ emission was studied depending on the energy resource (gas, oil, heat pump and pellet). The study assesses the discrete choices made by homeowners towards heterogeneity in socio-demographics and behavioural aspects. Context-related characteristics, such as spatial and household characteristics were included to determine correlations of the likelihood to accept RHS. Results show that participants who adopt fossil fuel-based heating systems (so low $CO_2$ reduction) have a higher propensity to reduce energy. Participants who switch to renewable energy sources enjoy independence from fossil fuels and thus have a high potential for $CO_2$ reduction. Moreover, findings show that the spatial attribute has the highest relevance for homeowners to choose for RHS. Homeowners of existing buildings experience constraints due to characteristics that are not easily changeable. For instance, existing building infrastructure does not allow an upgrade of heating systems, unless more investment is made. Thus, it happens that decisions may result differently than desired *(by Michelsen & Madlener, 2012)*.

The presented studies about consumers preferences in refurbishment projects show different approaches. Firstly, differences are seen in the attributes they present to the participants. Some show attributes in the form of technical upgrades, for instance, heating systems or envelope insulation. Others focus rather on the effects those upgrades have after the refurbishment happened. Throughout all studies, the economic criteria of refurbishment projects are included. Investment costs and monetary savings dominate the decision. However, the environmental and social criteria play an increasingly important role. Environmental concerns include next to energy reduction also $CO_2$ reduction measures. Regarding the social component, the comfort improvements, such as noise reduction and indoor air quality attracts homeowners and tenants to refurbish. However, difficulties are shown in the way how these criteria are presented to the participants. Measurable and intuitive definitions are missing, taking noise interpretation as an example. This issue can either be overcome by information cards or implementing a holistic performance assessment that calculates the expected performances per use case.

### 2.4.3 Decision support tools

The following introduces decision support tools that include stakeholder participation in the early decision-making processes of refurbishment projects. The literature review so far introduced the scope of decision support systems (goal and criteria definition) and highlighted methods that include consumer demands with preference modelling. This Section intends to study which platforms and tools are used in practice, that combine these assessments. It is to mention that most decision support tools focus on qualitative decision making, using multi-criteria weighting in a participatory decision-making process. Limited number of tools are used in practice that include the consumers' preferences in the form of a quantitative model.

Four practical decision support tools are introduced by Gade (2019), Kamari (2017), Taillandier (2016) and Ossokina (2021). Firstly, all tools aim to predefine goal and criteria definitions that stay within the sustainable development framework. It is commonly argued that the informative aspect of the value of sustainable criteria must be communicated to influence the behaviour regarding economics, environment and social aspects. Taillandier (2016) argues that decisions are often based upon a single criterion, such as building energy and financial criteria, and the owner preferences and sustainable multi-criteria are excluded. The study of Kamari (2017) agrees and adds that it is important to encourage the involvement of building occupants from the early beginning onwards. Knowledge management for sustainable refurbishment plays a major role. Certain dialogs are required that enable other decision-makers to understand its relevance. Gade (2019) adds that surveys and discussions before using the tool were found to contribute positively to the understanding of the terminology. In the study of Ossokina (2021) a dedicated information treatment about comfort and economic behaviour is included before the decision-making starts. It is argued that it stimulates the choice of the participants. This observation stands in line with the research of preference modelling *(Banfi et al., 2008, Alberini et al., 2013; Ossokina et al., 2021).*

Even though similarities are seen in approaches, the goals differ. The research of Gade (2019) aims to support decision-makers in the question of whether to refurbish a building or not. In Kamari (2017), Taillandier (2016) and Ossokina (2021) the goal is to assess building refurbishment performances and make a final decision regarding technical refurbishment concepts (for instance building envelope insulation). All tools were chosen in this review because the general approach is universally applicable to other goals. The following goals, criteria, and sub-criteria are defined per study, see **Table 8**.

| Decision tool by | Goal | Criteria | Sub Criteria |
|---|---|---|---|
| Gade et al., 2019 | Weather to refurbish a building or not | Indoor environment | indoor surface, indoor lighting, ventilation, building management system, accessibility, etc. |
| | | Outdoor renovation | Roof, Façade, window improvement. |
| | | Indoor renovation | Heating system, fire safety, sanitation, etc. |
| Kamari et al., 2017 | Selection of refurbishment concept | Functionality | Indoor comfort, energy efficiency, material & waste etc. |
| | | Accountability | Aesthetic, security, sociality, spatial, etc. |
| | | Feasibility | Investment cost, operational cost, stakeholder engagement, innovation, etc. |
| Taillandier et al., 2016 | Selection of refurbishment concept | Environment | Energy efficiency, including embodied impacts of materials. |
| | | Economic | Investment cost, annual energy saving, housing value gain |
| | | Social | Comfort in summer and winter, including lost surface, fire performance and durability. |
| Ossokina et al., 2021 | Selection of refurbishment concept | Environment | Energy efficiency measure, natural gas replacement |
| | | Economic | Upfront investment (rent increase), Gross return of investment (energy bill reduction) |

| | | |
|---|---|---|
| | Indoor renovation (Comfort) | Bathroom, kitchen and toilet renewal |

**Table 8 Decision Support tool criteria definition**

The criteria weighting and the resulting refurbishment concepts are differently approached. Project groups were asked to use the defined criteria and evaluate them via criteria weighting methods. In the tool of Gade (2019) they focus mainly on the criteria weighting method and suggested using Multi-Criteria Decision Analysis (MCDA), encompassing analytical hierarchy process (AHP) and the weighting, ranking and calculating method (WRC). In the study of Kamari (2017) they introduce a new weighting method. The value-focused thinking process (VFT) in sustainable retrofitting is introduced. Thereby every objective will be aligned with a certain value that explains the reasoning of its importance. All decision-makers assign numeric values for each criterion. Even though they prioritize the importance of the criteria, they do not offer guidelines for the technical design of the concept. Additional consultancy with construction engineers is needed to find refurbishment concepts.

Differently is the study of Taillandier (2016). There the criteria-weighting implies technical solutions. The users of the tool proceed in three steps. Firstly, a use case is defined in the existing building performance. The user is asked to define the current building characteristics and energy consumption. Secondly, the criteria, as listed in **Table 8**, are prioritized in the form of a ranking system. As a result, a preliminary refurbishment concept is presented, reaching from mechanical ventilation systems to insulation measures. The user selects the preferred solutions. Thirdly, the tool takes the user selection and proposes an in-depth solution for technical execution. They focused on insulation materials and show multiple materialisations that can be applied. The great advantage of this tool, compared to the others, is in the inclusion of technical solutions. For instance, multiple material scenarios are assessed regarding the sustainable criteria. Nevertheless, the tool lacks precise building simulations. The scenarios result from conceptual detail level, meaning that no quantitative building component assessment is included, which would allow an accurate embodied impact assessment. They recommend further development to focus on the integration of energy simulations, LCA analysis and feasibility studies (financial and technical).

In the study of Ossokina (2021) the approach of weighting criteria was done using quantitative consumer research. As explained in Section 2.4.2, a Stated Choice Experiment invited the participants to choose between packages that perform in six attributes (sub-criteria). The results of this experiment, which are the weighing factors of the sub-criteria, are then used to conduct the probability of accepting refurbishment packages. Pre-defined packages reach from small (S) to extra-large (XL) interventions. The packages vary in the sub-criteria performances. For instance, as energy efficiency measures a building envelop insulation or solar panels is included. It is to note that these package definitions were aligned to the actual decision-makers' demands, the social housing company. The benefit of this approach over all others is that the criteria weighing is retrieved from a larger group of people. Meaning, that statistical evaluation methods can be applied to determine the probability of people accepting refurbishment packages. Thereby multiple design scenarios can be created while including all attributes (sub-criteria) and can be assessed in their acceptance rate. This approach is also pursued in this thesis.

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# CHAPTER 3

# Program of Requirements

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# 3 Program of Requirements

This thesis presents the first step towards a web-based decision support tool for residential refurbishments following the framework of sustainable developments. It introduces engineers, energy collectives and homeowners to methods that help establishing refurbishment design scenarios and finding trade-offs between energy, carbon, cost and comfort criteria. The primary focus is thereby on the materialisation of refurbishment measures, in particular insulation materials. Engineering evaluation methods are used to design insulation material packages. A consumer preference model is implied to verify the design scenarios. Thereby, the willingness to accept the engineering solution can be validated by energy collectives when deciding collectively with their members, the homeowners. A strong social component in this decision-making process highlights the informative aspect of sustainable key performance criteria. The program of requirements of a web tool is proposed in this Chapter.

*This Chapter aims to introduce the process scope of the developed tool in this thesis. It will elaborate and outline tool requirements to answer the research sub question: SQ5) What can a program of requirements for a web-based assessment framework look like that contains multi-criteria objectives in an engineering evaluation system and takes consumers preferences into account?*

*Firstly, Section 3.1 will analyse current collaboration processes of owner-occupied housing refurbishments. It will help to discuss bottlenecks and to formulate a decision support system. In Section 3.2, the in this thesis developed framework is introduced and lists the program of requirements (competencies) of the web tool ROTUNDORO. The connection between the engineering design evaluation methods and the consumer research as the market potential is introduced. Finally, in Section 3.3, proposed decision support tool introduces the implementation steps and shows how the evaluation system and the preference modelling can be implemented in a web-based assessment framework. This Chapter will help to understand how the following Chapters 4, 5 and 6 correlate with each other.*

## 3.1 Stakeholder and process analysis

The literature review has shown that refurbishment is a complex process, encompassing multiple stakeholders, such as building owners, governmental bodies, energy collectives, designers and construction engineers. While refurbishment by itself is defined to be sustainable due to a more resource-friendly dealing of investments (material and cost), the decision-making process among all these stakeholders appears not as sustainable and efficient. Each stakeholder represents a different role and responsibility when refurbishing. It should not be seen separately from each other but rather as a collective knowledge exchange throughout the process *(Spithoven, 2020; Leusden energy collective, 2021; 040Energie, 2021).* To understand better what the interests of most relevant stakeholders are and to what extent they cover environmental and economic performance assessments, a state-of-the-art analysis of decision support processes was conducted. A systematic literature review (SLR) according to Passer (2018) reveals 25 studies/papers that focus on the integration of environmental and economic performance assessments. LCA, LCC and energy performance are chosen to support the sustainable decision-making process in building projects and housing retrofit. The used data sources and software applications were listed and compared. Eventually, the results list bottlenecks of the missing role of government policymaking, economic interest, and an easy-to-use assessment method of environmental key criteria.

The SLR aimed to find out to what extent environmental and economic performance assessments, such as LCA and costing, are currently included in decision-making processes in housing refurbishments. Results show that all studies agree in the first place on the relevance of upgrading the existing building stock and its inevitable role when striving towards a nearly zero energy and $CO_2$ emission policy. Environmental performance assessments act as an instrument to directing design and decision-making among all involved stakeholders. The key stakeholders are analysed and their responsibilities and roles in current processes are highlighted to detect bottlenecks, that eventually will lead to a unification of both parties within one decision support system in Section 3.2.

### 3.1.1 Energy Collective and Homeowners

The energy collective represents the common interests of building owners when facing refurbishment projects. Homeowners that are living in certain neighbourhoods have the possibility to collaborate in groups and to decide upon refurbishing and purchasing solutions collectively. Project groups are created in pre-design phases to discuss common goals to act in the best interest of the decision makers. Interviews with multiple energy collectives show challenges in the process of goal definition.

Energy collectives and their members (homeowners) collaborate to evaluate current buildings' impairments and conclude with the goal to refurbish. The ambition for homeowners to refurbish is commonly based on reducing energy consumption and thus lower operational costs. Technical advisors of the energy collective, such as project leader(s) search for refurbishment concepts accordingly. A strong focus is on collective heat networks, new heating systems (stepping away from gas) and building envelope thermal insulation, including wall, floor, roof and windows *(040 Energy, 2021; Leusden energy collective, 2021; Best Duurzaam, 2021).* Solutions for these concepts are dominated by financially attractive no-regret scenario. This means low investment costs with the most governmental subsidy and short payback time. Conscious materialisation selection is often left out, which consequentially neglects sustainable criteria.

While focusing heavily on energy reduction and payback times, relevant themes such as Life Cycle Assessment (LCA) and indoor comfort assessments are often left out. Engineering design evaluation assessments would help to create sensitive design analysis to optimize energy, cost, carbon and comfort. Experts argue that the lack of legal obligations to perform LCA in refurbishment projects diminishes the interest of the homeowners. Secondly, too high costs and communication processes occur when outsourcing such services to third parties, such as construction engineers. Building owners often question the essence of such additional efforts which however sacrifices sustainable aspects in the decision-making process. An imbalance of decision criteria weighting does not comply with climate-related targets neither with the findings in the literature review (Section 2.4).

There is a lack of consumer research that helps to recognize to what extent consumers (homeowners) value sustainable criteria in housing refurbishments. When analysing the willingness to invest in insulation measures that reduce the energy and $CO_2$ footprint, increase comfort and improve safety and health criteria, this can lead to new insights in order to find compromises among these criteria. The lacking role of using construction engineers' design methods to assess such criteria plays an essential role and is a major motivation in this thesis. The visualisation of performance results of the assessments is missing as informative input to homeowners. It is however needed to account and guarantee for the compromises and decisions that the homeowners take. The next section will observe the engineering point of view in the refurbishment project.

### 3.1.2 Engineers

Construction engineers in the AEC industry face challenges in the process of refurbishing the existing building stock. On one hand, they have to comply with legislation and policies, such as energy index and (the in the future mandatory) LCA performance for refurbishments. On the other hand, they are asked to consult building owners in a financially feasible framework.

The literature review shows that the environmental performance of buildings has the potential to become a common procedure to evaluate design improvements for existing buildings. The combination of digitalisation of building models using BIM methodology and multi- and interdisciplinary working approaches using open standards IFC, allows engineers to extend their capability to evaluate LCA and cost assessment. The working steps in a collaborative process are represented within four major circles, that dynamically correlate, see **Figure 20.**

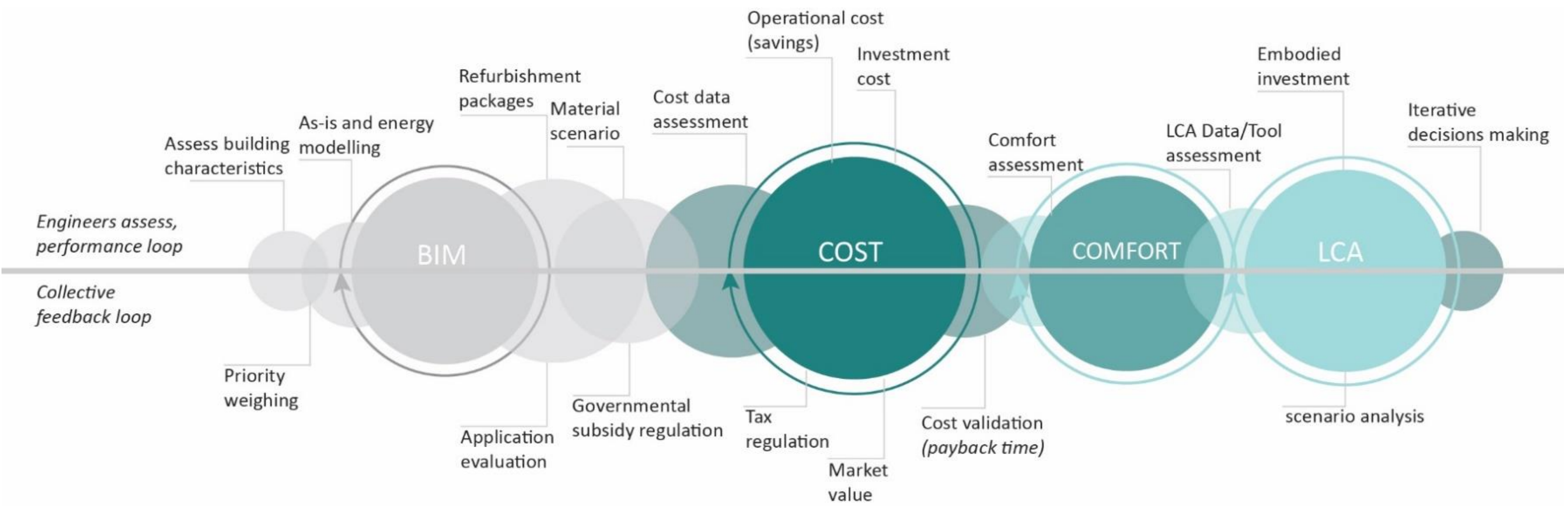


**Figure 20 Sustainable evaluation process**

Energy modelling is fundamental knowledge to create feasibility studies. It encompasses the BIM practice including parameters to perform operational energy simulations. Scenarios in materials' thermal properties and BITS highlight energy reduction potential within a 3D model (visually and numerically). Examples of BIM-based software is Energy Plus inside Autodesk Revit, Design Builder for parametric performances and non-graphical evaluation using VABI EPA, based on the deterministic energy performance for buildings (NL), national NTA 8800 *(NEN 8800, 2020)*. The cost-saving potential is the primary most important aspect of refurbishment projects. The engineers are responsible to find refurbishment solutions that comply with the client's (homeowners) demands regarding the often used decision criteria, the payback period. The foremost important step in common practice is the energy reduction potential expressed in annual cost savings juxtaposed to the investment cost. Engineers are using BIM to make design analysis and use parametric rules to apply cost assessments. By doing so, the quantity assessment in compliance with costing can be automatically calculated.

Although energy modelling finds its place in practice, automation workflows for LCA performance models are yet lacking. Several studies highlight the potential use of LCA data in combination with BIM and its applicability from conceptual urban design towards detailed planning stages. Global and national LCA stand-alone tools and BIM tool plug-ins are discussed in the literature review. Even though a wide spectrum of software solutions is available, LCA for buildings is not yet a standard procedure. Non-graphical environmental performance assessment tools in the built environment (such as GPR Gebouw, MPG calc, SimaPro) rely heavily on the experience of consultants. The outsourcing of such tasks guarantees the accuracy of the results but can add cost and time due to the redundant evaluation process of design scenarios. Graphical LCA evaluation, such as BIM and LCA, provides the advantage of assessing LCA data within a BIM-based working framework. This means LCA data can be applied to BIM elements and further be visually evaluated, done via hotspot analysis in 3D models *(Röck et al., 2018).* Whether this process is done by BIM tool plugins or visual programming interfaces (VPI) depends on the engineering effort and knowledge about data aggregation and programming skills (One-Click LCA, Dynamo). Storing big LCA datasets on local machines and BIM environments leads to a reduction in performance and risks to mismatch data and geometry. Accurate data application/data aggregation in the design phase of geometries with a little level of detail remains often challenging. LCA datasets such as environmental product declaration (EPD), are commonly used. However, the difficulty of EPD data is that often different LCA system boundaries are defined. This means that results of LCA scenarios cannot be compared with each other. Moreover, while only applying LCA data to BIM building elements, no design scenario is guaranteed. Using LCA as a design tool requires results that are comparable in design options. This asks more effort in terms of performance visualisation in graphs, 3D BIM models and relative numbers. Last, the combination of LCA data towards cost-related material data is often missing in such workflows. A market-oriented LCA and cost harmonization could offer a holistic evaluation approach that helps to satisfy a multi-objective approach *(GPR Gebouw tool, MPG, OneClick LCA, Röck (BIM and LCA), more information can be found in the literature).*

To conclude, current workflows primarily lack collaboration efforts between energy collectives and engineering design methods. Energy collectives account for the solutions they make for their members and engineers strive to accommodate climate-related targets in their design. Therefore, this thesis focuses on the harmonization of the engineering evaluation method and consumer demands.

## 3.2 Decision Support System

As explained above, homeowners and energy collectives have different interests than engineers that can be overcome by finding a common framework. On one hand, it should enable engineers to design digital building performances assessment scenarios, and on the other hand, the energy collective should be able to verify the design according to the demands of their members. The decision support system as presented in **Figure 21** is built upon the knowledge from the literature and in-field interviews with experts. The refurbishment process (B5) according to the EN 15978 and the multi-criteria decision-making procedure, according to Hasik (2019), Nielsen (2016), Nault (2018), was used as a reference. Furthermore, interviews with experts in the field could enrich the system with Dutch refurbishment know-how *(see list of held personal interviews in the reference list).* The proposed decision support system involves homeowners, energy collectives, and engineers to be part of four project phases.

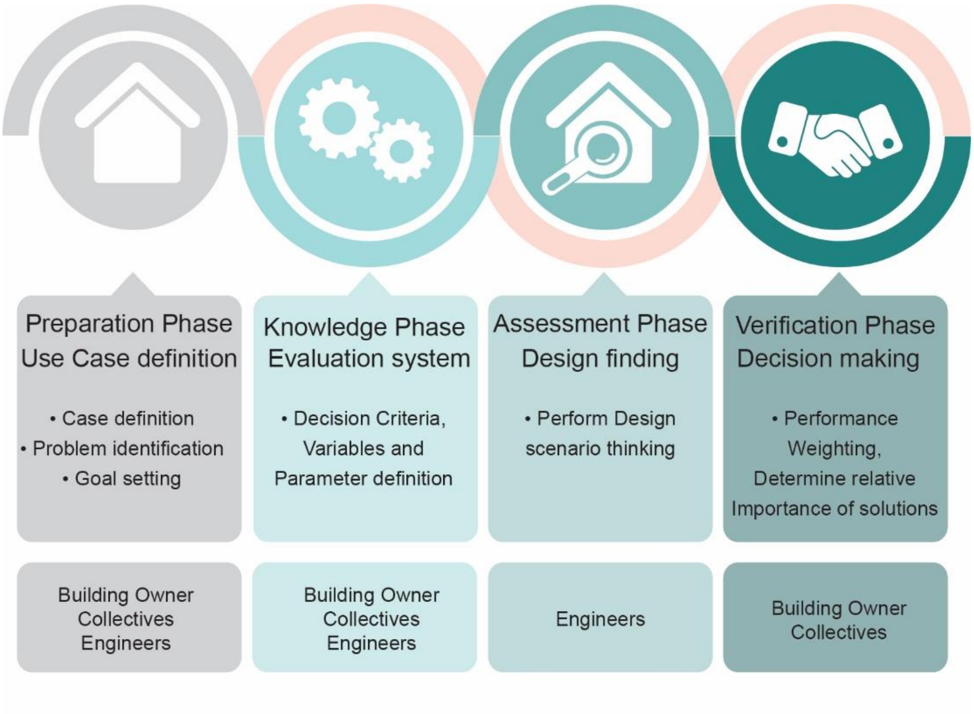


**Figure 21 Decision Support System**

(I) Preparation Phase, use case definition

In the first phase, building owners, energy collective and engineers are part of defining a use case. The goal is to identify the building´s as-is performance. Performance criteria can be clustered regarding building typology, building lifetime (construction year, refurbishment year, extended lifetime), operational energy and carbon performances. The problem identification reaches from technical and performance impairments to indoor comfort and facility improvements. Therefore, the goals can be set. Goals can be, to establish a better energy label, to improve thermal comfort, to reduce street noise or to reduce overall $CO_2$ footprint.

(II) Knowledge phase, evaluation method

In the knowledge phase, additional meetings are held between the project stakeholders. The goal definitions are discussed in the group to define the decision criteria. Decision criteria are based upon the sustainable framework, environmental, economic and social key indicators. According to the decision criteria, the decision variables and parameters are defined by the engineers. For instance, the goal is to reduce carbon footprint and enhance thermal comfort, then operational and embodied carbon stands in focus. Depending on this evaluation method, certain refurbishment solutions can be formulated. For this example, thermal insulation packages can be created at different levels, and diverse material scenarios can be applied.

(III) Assessment phase, design finding

The engineers use the earlier defined refurbishment formulations and apply evaluation methods to assess the designs. Assessment methods in combination with the latest performance data is supposed to be easily applicable to their current BIM practice. The assessment framework enhances digital building models with the LCA method, cost assessments and material-related health and comfort assessment. It is aimed to find an automated workflow to make the engineering design workflow more effective and efficient to reduce cost and time. Moreover, design scenarios should be easy to make on clients' demands. Thereby the homeowners are more involved in the process and can see the results interactively. Letting the clients be part of the design process, creates better service and leads to a higher satisfaction rate of the designs scenarios. The platform is open and accessible to everyone in the process.

(IV) Verification phase, decision-making

This phase is meant to verify the design scenarios from the engineers by using the consumer's adoption potential. Design scenarios can vary in their performances that lead to difficulties understanding how to make the final decision between them. This is especially the case when the design solution contains not only cost and energy reduction but also carbon and comfort measures. Energy collectives account for their member's preferences. To include their member's choice of preference in a participatory process, this step is aimed to include a quantitative consumer research. The decision support tool introduces the percentage of potential market adoption per design scenario. Every design criterion reveals an importance level, that represents the homeowner's likelihood to accept.

### 3.2.2 Proposed Scope

Based on the above, this thesis introduced a web-based tool, ROTUNDORO. It promotes a framework that harmonises the above-listed decision support system to overcome communication challenges in collectives. The tool requirements are discussed, and the system scope is illustrated in **Figure 22**.

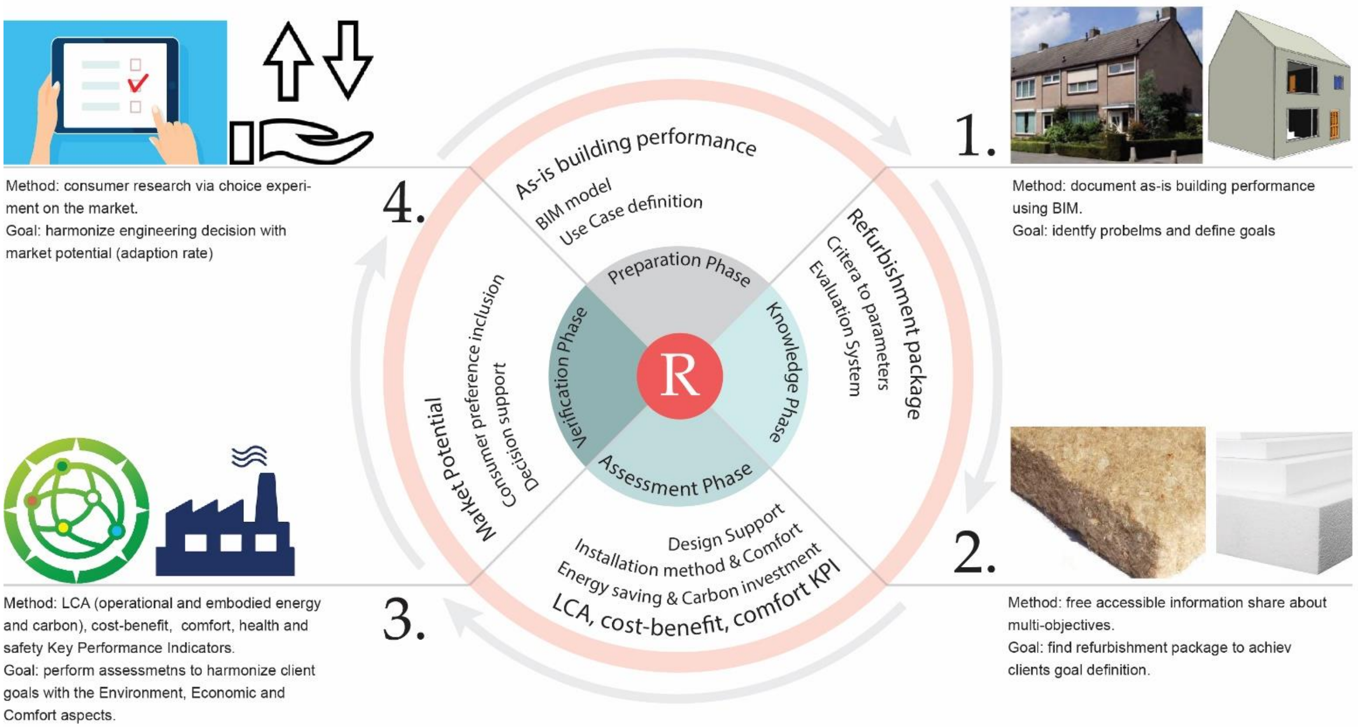


**Figure 22 ROTUNDORO Scope**

1) Use Case Definition: A 3D BIM model, that is established by the engineer before the process, is used and will be uploaded on the web tool. Thereby it must be possible to enhance the geometrical model with as-is building performances. The information will be stored on the web. A 3D view environment is required that allows the stakeholders to discuss the goals and interact with the current building performances. Prerequisites for the user (the engineer) are basic understanding regarding BIM, information exchange (IFC) and data management. A knowledge platform could be provided within the platform that informs the user about this.

> It must allow the user (engineer) to make use of their current BIM practice and visualize the digital building model online in a 3D view.
> It must enable to complement the geometrical BIM model with non-geometrical as-built information, such as building typology, construction years, current energy consumption.
> It must contain general knowledge about refurbishment policies and governmental subsidies.

2) Evaluation system: The tool seeks to provide design support and will inform stakeholders about all three key sustainability criteria and the correlating evaluation methods. Product and material performance information must be accessible via the tool. Required databases are the Dutch national

LCA database (NMD), Costing database (from manufacturers) and other material-related information (kennisbank.isso.nl[43]).

> It must allow to receive static data regarding material performance, such as environmental data, manufacturer's cost information and health-related information.
> It must allow a filter mechanism to guarantee material applicability to the use case.

3) Design Support: The engineering methods are the focus. It includes internally held calculations for operational performances using energy consumption, the LCA analysis and cost assessments. The assessment must be based on the BIM model. In this regard, refurbishment packages, that focus on operational improvements, and material-related assessments need to be formulated. The package definition must be comparable to the base model (no refurbishment). The interactive and responsive tool allows updating computed results depending on refurbishment packages.

> It must contain LCA, cost-benefit, comfort improvement.
> It must allow a semantical enrichment of the BIM model with externally held data.
> It must allow to compute refurbishment and material packages, that are comparable with each other. This contains a query logit of static data towards package definitions.

4) Decision support: The probability of acceptance in percentage is shown per refurbishment package. The energy collectives will find the engineering design performance results as an overview. This enables a pairwise comparison between the new packages and the based model. The differences in probabilities depend thereby on the choice of insulation material. The probability will amend interactively when choosing another material package.

> It must provide an overview of the environmental and economic results per package.
> It must be possible to apply different material scenarios.
> It must be possible to see the probability of acceptance per package and the applied material scenarios.

Moreover, some of the basic system requirements can be stated as the following:

> The web-based tool should be hosted on a server and be accessible via the web browser.
> The web-based tool should allow access to multiple federated data sources.
> The web-based tool should allow a connection between graph-based and non-graph-based information, meaning a connection between the BIM geometry and another data.
> The web-based tool should allow the user to interactively add and query project-related information.

A video of the established solution, the tool ROTUNDORO, can be found on YouTube.

[43] https://kennisbank.isso.nl/publicatie/energievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen/2017/bijlage-3

## 3.3 Proposed Decision Support Tool

The proposed decision support tool is formulated as a web-based assessment framework. As can be seen in **Figure 23**, web application architecture (WAA) can be understood as the common architecture for web development. In this framework, the user activates the user browser and sends requests towards the webserver. The web server handles these requests by searching for solutions (answers) that are sent back to the user. Thereby HTTP describes how the content is transferred between the user browser and the webserver. This standard procedure in web development is called synchronous communication *(Kappel et al., 2013).*

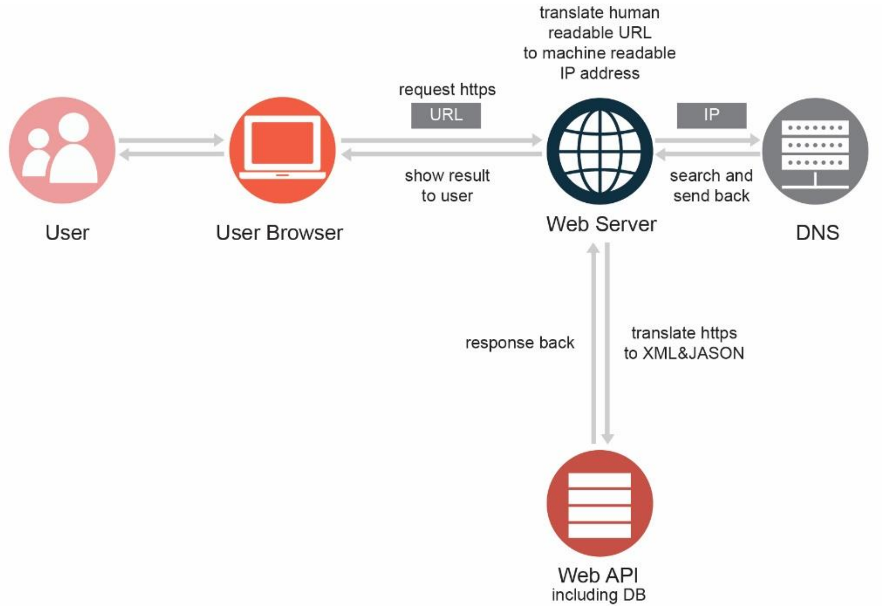


**Figure 23 Web Application Architecture**

When developing a web tool for building performance assessments, the tool´s Application Programming Interface (API) is hosted on such web server and is responsible to answer the request of the user, by sending back HTTP responses. The web server's role is to interpret the HTTP request, make the necessary computations and return a valid responded *(Layman n.d).* An example of such a web tool in the building industry, is the Linked Building Data Server (LBD Server), as introduced in the literature review (**2.3.3 Web-based information exchange**) it intends to establish a decentralised communication platform for the AEC industry. The LBD Server provides the user of the web with the ability to store its data and uses other online-based information in multiple databases for several purposes. In other words, the LBD Server can be understood as a bridge to link building models, with interdisciplinary and building-related data throughout multiple web-based data sources *(Malcolm et al., 2020).* Supporting this idea of data accessibility and transparency this thesis makes use of the LBD Server (version January 2021) and intends to add content functionalities to support design evaluation and decision-making process for refurbishment projects, for Dutch housing.

### 3.3.1 Implementation steps

The iterative and incremental development process is chosen to design and develop the web-based frameworks. The developer can thereby iterate between research and development steps, that allows a test-driven development. The aimed system is divided into parts and subtasks that are executed in repetitive cycles. Functional and design modifications can be added, and thus improve the system while developing *(VisualParadigm n.d*). Multiple cycles can be performed per requirement, that differ in performance depth. In this thesis, we focus on the first cycle that includes the establishment of requirements, analysis and design of the tool and code implementations. The chosen parts and subtask for this thesis are illustrated in **Figure 24**.

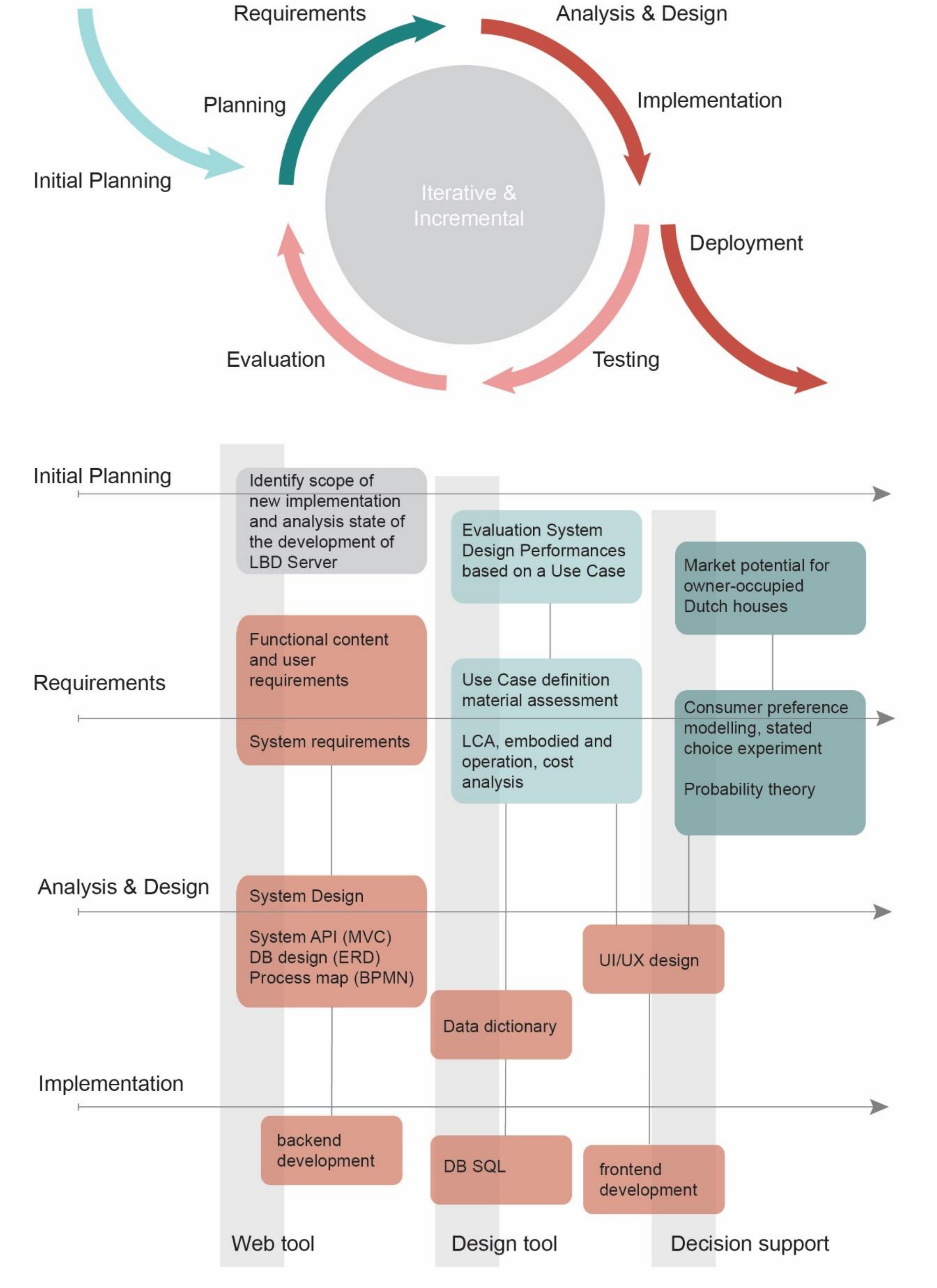


**Figure 24 Iterative and Incremental Development**

Four implementation steps are represented in horizontal direction (Initial Planning, Requirements, Analysis & Design and Implementation). In vertical direction the content sections are illustrated and show relations with each other throughout all four implementation steps.

The initial planning represents the decision support system, as explained in this **Chapter 3 Program of Requirements**. The scope of the new implementation is defined. A new evaluation system to support engineering design with the market potential for homeowners on a Dutch market. The web-based LBD Server is used as the basic framework. The functional user and content requirements for the web tool are divided into two parts. The evaluation system (Section 3.3.2) and the consumer preference model (Section 3.3.3). Ones established, they are included in the analyse & design and implementation stage of the tool (3.3.4).

### 3.3.2 Evaluation System

Firstly, the evaluation system and design performance assessment are performed on a use case**.** A Dutch terrace house is analysed with refurbishment packages, seeking to reduce energy consumption and improve insulation material performances. The multi-objective optimization of material evaluation is derived from the study of Kumar (2020) and Schiavoni (2016). In their study, they define the decision criteria in the framework of sustainable assessment, 1. Energy, 2. Environment, 3. Economy, and 4. Comfort. Decision variables are used to evaluate these criteria. The variables express performance assessment in the form of calculation formulas. The LCA is used as it includes the operational and embodied energy and carbon calculations. Moreover, BIM and manufacturing product cost data are used to assess investment costing and indoor environment quality (IEQ) performance are derived from material properties. It is aimed to analyse materials that are used in the Netherlands, reaching from a fossil fuel, a mineral and a bio-based domain. The methods and results are presented in **Chapter 4 Evaluation System.**

### 3.3.3 Preference Modelling

Secondly, the decision support focuses on the market potential in the form of a consumer preference model. Individuals make decisions daily by comparing options of a choice situation, consciously or subconsciously. Capturing these choices to create a statistical prediction of future demand situations is the subject of quantitative urban economics. Choice tasks can focus on problems to make forecasts and predictions of certain scenarios. The preference modelling of individuals is based upon the Stated Choice Experiment. In this method, the participant is exposed to choose options consisting of multiple attributes (criteria) while each attribute can perform in multiple levels. It is aimed to shape insulation material packages that perform differently in the sustainable criteria, using fossil fuel, mineral and bio-based material applications. These packages are then presented to Dutch homeowners who are a member of energy collectives and face refurbishment. To analyse the results, the logit model is commonly used to analyse and explain discrete choices. Using the probability theory, in the form of the multinomial logit model, the likelihood of choosing refurbishment packages can be analysed. The methods and results are represented in **Chapter 5 Preference Modelling.**

### 3.3.4 Web-based assessment framework

The web-based assessment framework focus on the analysis and design step to translate requirements into a system design. This system design takes the form of an API following the Model-View-Controller (MVC) design pattern. The process maps, such as BPMN Activity Diagram, allows to set tasks into relations, and structures each element towards the frontend's user interface design (UI/UX). The frontend UI design includes definitions of user queries while interacting with the dashboard. Databases in the form of a data dictionary are designed using the Entity Relationship Diagram (ERD), including BIM and LCA, materials and cost data. The final implementation of the above in the form of a code is done using the LBD Server framework, which is developed using React and JavaScript. The system design is already in place using LBD developments. The evaluation system and the preference model are subject to frontend implementation. Therefore, the scope of the frontend implementation is based on implementing hardcoded data first, before making an actual connection to the 3D BIM model. The latter should happen in the second implementation cycle. The methods and results are represented in **Chapter 6 Web-based assessment framework.**

# CHAPTER 4

# Evaluation System

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# 4 Evaluation System

## 4.1 Base model definition

The terrace house (Rijwoning) from the construction period 1965 – 1974 represents 9% of the Dutch housing stock, in 2011. Thereof 47% is owned and maintained by social housing corporations, another 57% is homeowner occupied and the remaining 6% privately owned and rented. With a gross floor area of 120 m², four to five rooms are distributed over three levels (ground floor, first and second floor). According to the Agentschap b NL, 2011, the functional design was increasingly used however, insufficient materials were applied that are not comfortable with current thermal and energy standards. Brick walls, with superior façade made of sandwich panels and floors made of concrete slabs with little to no insulation, had Rc-Values of 0,43 m²K/W and 0,17 m²K/W respectively. Pitched roofs were constructed and insulated with wood and a low-performance Rc-value of 0,86 m²K/W. Window glazing was mainly single and double glazing, with poorly performing U-values of 2,90 m²K/W respectively and Doors with of 3,50 m²K/W.

Similar, to the building elements, the heating systems have been mostly improved due to too poor performances. Central heating HR boilers (HR107 and HR107) provide heating and mostly hot water supply. Although some of the buildings have been insulated, the majority of the Rijwoning remains with an energy index of 2,08 (Label E).

### 4.1.1 Model verification and performance as-is

The use case (Terrace House) has been digitally modelled, using the Building Information Modelling (BIM) software Autodesk Revit. The as-built model represents the base model (BM) of the Terrace House (in between house unit), as highlighted in **Figure 25** The building's geometry and elements were modelled by using sensor measures of a typical Dutch terrace house and RVO archetype definition. The building elements' thermal properties are aligned to the as-built definition according to the Ministry of the Interior and Kingdom Relations *(Agentschap b NL, 2011).* Five elements that impact the overall energy performance are shown in **Table 9** and **Table 10.** The external walls, roof, ground-level floors, windows and external doors. ***Appendix A*** describes in more detail the building element definition. *Note: The total Rc-Value per multi-layer construction was used according to the RVO.*

**Figure 25 Terrace House (Rijwnoning)** ***(Agentschap, 2011)***

| NLSFB | Element | Quantity | Rc-Value * (m²*K)/W | U Value* W/(m²*K) | Thickness* (m) | Area* (m²) | Area total (m²) |
|---|---|---|---|---|---|---|---|
| 41 | Wall | 2 | 0.68 | 1.45 | 0.24 | 24.41 | 48.81 |
| 47 | Roof (pitched) | 1 | 1.12 | 0.89 | 0.20 | 72.78 | 72.78 |
| 43 | Floor | 1 | 0.42 | 2.33 | 0.30 | 40.00 | 120.00 |
| 31 | Windows Type 1 | 2 | 0.34 | 2.9 | - | 1.00 | 2.00 |
| 31 | Window Type 2 | 4 | 0.34 | 2.9 | - | 4.60 | 18.4 |
| 31 | Doors | 2 | 0.27 | 3.7 | - | 1.81 | 3.62 |

**Table 9 Terrace House (Rijwoning) quantity, according to as-built BIM model**

| NLSFB | Element | Quantity | Area total (m²) | Glass Area (m²) | Frame Area(m²) |
|---|---|---|---|---|---|
| 31 | Windows Type 1 | 2 | 2.00 | 1.80 | 0.20 |
| 31 | Window Type 2 | 4 | 18.36 | 16.53 | 1.84 |
| | Total | | 20.36 | 18.33 | 2.04 |

**Table 10 Window quantity take off, according to as-built BIM model**

**per building element*

The base model is validated by the operational energy and carbon performance. The as-built energy label, energy and electricity consumption, expressed in the primary energy and operational carbon is represented in **Table 11** *(Agentschap b NL, 2011)*. The electricity average value for a family house with 3 occupants was used from the energy provider of the use case *(Oxxio.nl)*. To ease further calculations, the gas consumption in m³ was converted to kWh/yrs.

| | As Built (Base Model) |
|---|---|
| Location/Climate | Netherlands/moderate climate |
| Building/ usage type | Residential home, refurbishment |
| Gross Floor Area; Net Floor Area | 120m²; 90m² |
| EI | 2,08 |
| Energy Label | D |
| Space heating (m³/y)] [44] | 1,085.07 |
| DHOW gas (m³/yr) [45] | 262.87 |
| Appliance electricity (kWh/yr) | 4,050.00 |
| Total energy consumption (kWh/yr) | 17,218.00 |
| Primary Energy (MJ/yr) | 84,791.57 |
| Primary Energy (kWh/yr) | 23,500.91 |
| Operational $CO_2$ Emission (kg$CO_2$/yr) | 4,755.38 |
| Energy Costs (excl. BTW) (€/yr) | 2,008.47 |

**Table 11 Terrace House (Rijwoning) Energy and carbon performance As-Built**

### 4.1.2 Refurbishment Package definition

Based on the knowledge gained from the literature review, two improvement packages were created, see **Figure 26**. Those are influenced by Milieu Centraal[46], thermal resistance values, available space and financial support[47] measures (see literature study). Package 1 (P1) aims to achieve with low

44 https://www.energieconsultant.nl/energiemarkt/energie-berekeningen-uit-de-praktijk/omrekening-van-m3-n-naar-kwh/
45 https://www.energieconsultant.nl/energiemarkt/energie-berekeningen-uit-de-praktijk/omrekening-van-m3-n-naar-kwh/
46 https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/alles-over-isoleren/
47 https://www.rvo.nl/subsidie-en-financieringswijzer/isde/woningeigenaren

measures an Energy Label C, Package 2 (P2) aims to achieve with medium measures Energy Label B. Additionally, material studies are applied to each of the energy packages. These are fossil fuel-based materials (M1), mineral-based materials (M2) and bio-based materials (M3). A comparative analysis of embodied energy and carbon use, as well as costing can be conducted.

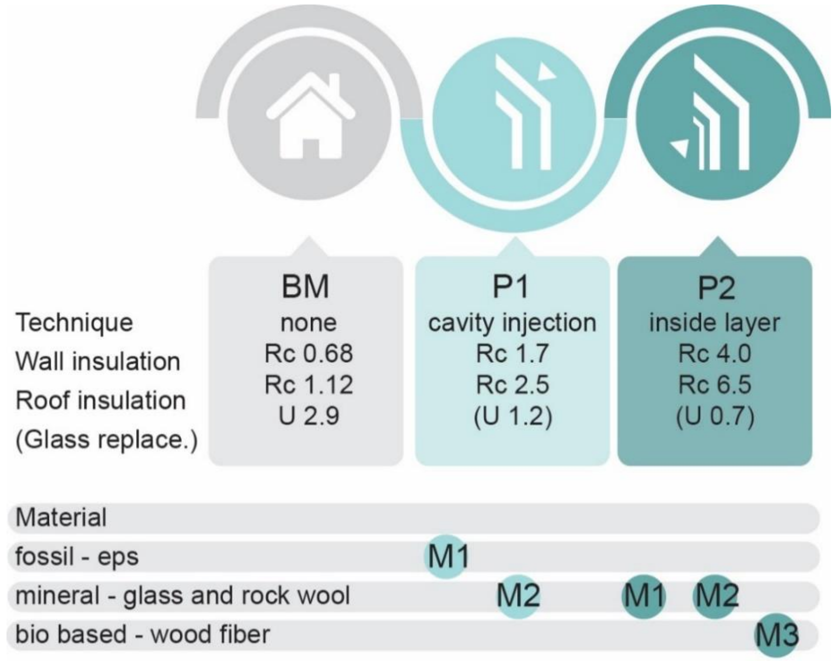



**Figure 26 Refurbishment Package**

### P1 Low measure

Low refurbishment measures of existing constructions can be done via injecting the insulation material with high pressure in the hollow layer of a cavity wall. The cavity walls have a limited thickness to insulate, which lies between 6 and 8 cm, that can achieve an Rc-Value of approx. 1.7 (K·m²)/W *(Agentschap b NL, 2011)*. Existing roof structures can be access from the outside and the hollow layer can be filled in the mostly wooden structure with a thickness between 8 and 14 cm to achieve an Rc-value around 2.5 (K·m²)/W. Windows in the façade will be replaced with an HR++ with a U Value of 1.2 W/(m²·K). Even though rather low insulation values can be applied, Milieu Centraal classifies this level as a medium to good insulation (matige insolatie) that can reach a reduction of up to 30% of the current annual energy consumption. The quantity and element definition for injection can be seen in **Table 12**.

| Quantity when injection | Property | Area |
|---|---|---|
| Wall insulation | Rc 1.7 | 48.81 m² |
| | | |
| Roof insulation | Rc 2.5 | 72.78 m² |
| | | |
| HR ++ | U 1.2 | 20.36 m² |

**Table 12 Package 1 - Injection Quantity**

### P2 Medium measure

Secondly, a medium refurbishment measure was identified with a second insulation layer inside of the wall and roof. It is often considered in practice since it’s easy to apply and offers more space, thus higher insulation values. With a thickness up to 15 cm for the walls an Rc-Value of 4.0 (K·m²)/W can be achieved.[48] The inside roof layer was assumed with a thickness of max 25 cm and achieves an Rc-Value of 6.5 (K·m²)/W. The Windows were used with a triple glassing and U Value of 0.7 W/(m²·K). With this method, there is a secondary support construction to be considered. Wooden framing for wall and roof plus a plasterboard gladding. The quantity and element definition for the inside surface was derived from the 3D BIM model and can be seen in the **Table 13**. Attention must be given regarding a shifting dew point. Thus, a vapour diffusions barrier (PE foil) must be added between the wall and the insulation material.

| Quantity when second layer inside | Property | Area, Length |
|---|---|---|
| Wall insulation | Rc 4.0 | 34.38 m² |
| Wood sub construction | 0.07 x 0.15 m | Length: 62.5 m |
| Wall Gypsum board | 1.25 cm | 34.38 m² |
| | | |
| Roof insulation | Rc 6.5 | 64.67 m² |
| Roof sub construction | 0.075 x 0.25 m | Length: 61.54 m |
| Roof Gypsum board | 1.25 cm | 64.67 m² |
| | | |
| Triple | U 1.2 | 20.36 m² |

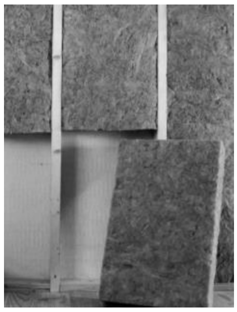


**Table 13 Package 2 - Inside Quantity**

### *(P3 High measure)*

A third package has been formulated to represent possible extension of the suggested refurbishment packages that combines the strong focus of insulation material with gas free solutions of energy production. Note, that this package is defined, however is not further elaborate in the calculation performances. A common trend in the Netherlands is to keep the existing facade and wrapping around the external surface in the form of an additional façade and roof layer. Thereby, prefabricated building elements as a new façade are mounted on top of the old façade. It allows a higher level of insulation and can reduce the initial energy performance by up to 50%. Building element thicknesses up to 35 cm allow a Rc-Value from 6.0 (K·m²)/W up to 7.0 (K·m²)/W *(INDU ZERO, 2021; Milieu Centraal, 2020[49])*. As advantage windows and external doors can be premanufactured and placed within the installed makeover faced[50] *(VolkerWessels, 2015).*

**Figure 27 External insulation (wrap-it)** ***(by VolkerWessels, 2015)***

The goal in this package is to step away from gas entirely. An air-air heat pump is chosen, due to common practice in the Netherlands. To be self-sufficient in terms of electricity consumption, a PV system is proposed. 10 panels are chosen

[48] https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/buitenmuur-isoleren-met-voorzetwand/

[49] https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/isoleren-en-besparen/buitenmuur-isoleren-aan-de-buitenkant/

[50] https://www.youtube.com/watch?v=I3WBT2eAArI&t=1s

To summarize, the packages are defined as shown in the **Table 14.**

| | Base Model | P1 Injection | P2 make over | (P3 energy neutral) |
|---|---|---|---|---|
| Wall | Rc 0.68 | Rc 1.7 | Rc 4.0 | Rc 4.0 |
| Roof | Rc 1.12 | Rc 2.5 | Rc 6.5 | Rc 6.5 |
| Window | Single U 4.05 | HR ++ U 1.2 | Triple 0.7 | Triple 0.7 |
| Heat pump | no | no | no | Air-Air |
| PV panels | no | no | no | 10 panels |

**Table 14 Refurbishment package for energy refurbishments**

### M1-M3

The conducted literature study shows that depending on the sourcing material of the insulation building elements the thermal, environmental and cost performances differ. Furthermore, depending on the installation's method (within, in and outside of the load bearing structure) also the comfort attributes differ. Thus, package 1 and 2 will be analysed with a set of different insulation materials. Staying in the framework of the three material classifications (fossil-, mineral-, bio-based), **Table 15** shows M1, M2 and M3 for wall, roof and windows.

| | P1.M1 Fossil-based | P1.M2 Mineral-based | P2.M2 Mineral-based | P2.M3 Bio-based |
|---|---|---|---|---|
| Wall insulation | EPS | Glass wool | Rock wool | Wood Fibre |
| Roof (pitched) insulation | EPS | Glass wool | Rock wool | Wood Fibre |
| Window | PVC Frame | Aluminium Frame | Aluminium Frame | Wood Frame |

**Table 15 Material Selection**

With the application of those material scenarios on the refurbishment package the trade-offs between the three key criteria of sustainable developments should be analysed. Energy refurbishments with a strong focus on carbon emission reduction, as well as costing and societal concerns, such as the indoor living quality.

## 4.2 Material Evaluation Method

*The following section will introduce the evaluation system that is introduced in **Chapter 3 Program of Requirements**. Firstly, the material evaluation method is shown, and a comparative analysis is established.*

Thermal characteristics are the main parameters that express the thermal performance and thus contribute significantly to the operational energy use and carbon reductions. Furthermore, an implicit relation of the Indoor Environment Quality (IEQ) and Safety variables and the thermal properties are established. Moreover, an increasing number environmental and economic concerns occur when choosing suitable insulations material. The correlation of thermal, environmental and economic parameters stands in a linear relationship. Meaning, the higher the thermal requirements, the higher material thickness and density, the higher the embodied emission and related costs. Beyond the material level, additional investment cots are to consider depending on materials' application possibilities, see **Figure 28** *(Spithoven, 2020; Kumar et al., 2020; Schiavoni et al., 2016).*

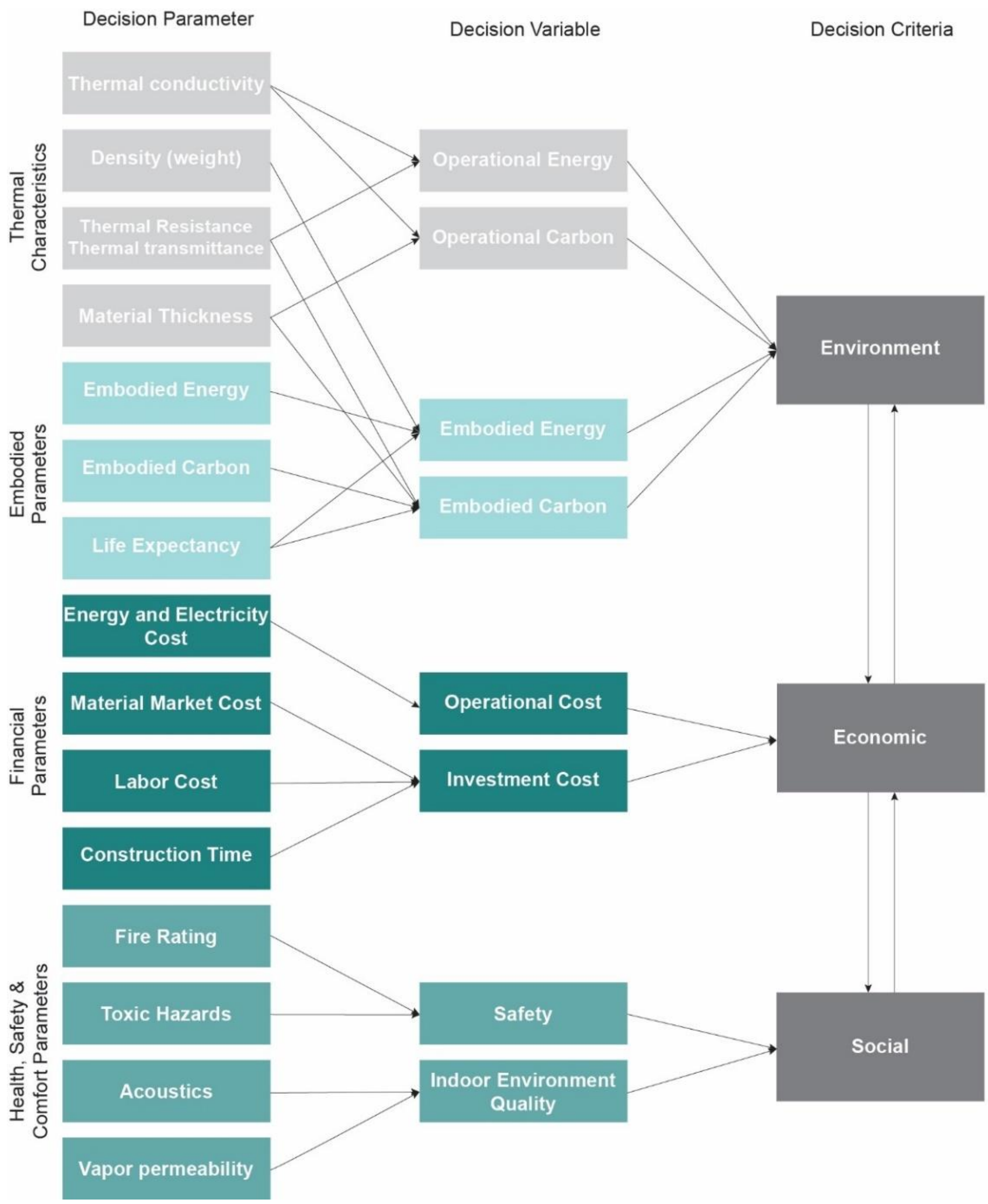



**Figure 28 Framework to select optimum building insulation material**

### 4.2.1 Thermal Characteristics

*Thermal conductivity (λ)* defines the heat flow that penetrates through a homogenous material through a temperature gradient of 1Kelvin and is expressed in W/mK *(Schiavoni et al., 2016)*. Due to low thermal conductivities only limited heat flows through the materials. This means that the lower the value the higher the thermal isolation to keep warmth inside. The values of the materials were gathered from the Dutch Kennisbank [51] and have been integrated in the materialisation of the digital building model.

*Thermal resistance (Rc)* represents next to the material thickness the most considered parameter in refurbishment projects. The Rc-Value, expressed in (K·m²)/W, is defined by the quotient of the thickness in m *(d)* and the thermal conductivity Lambda *(λ)* of the material, see **Formula 1**. The Rc-Value is commonly used to evaluate insulation material thermal performances. It is assumed that the higher the thermal resistance the better the insulation performance. Attention must be given to potential room overheating due to too high Rc-Values and too little (natural or mechanical) ventilation of rooms.

*(1)*

$$Rc = \frac{d}{\lambda}$$

*Thickness (d)* represents the most important decision parameter in refurbishment projects and can be derived from the **Formula 1**. The thickness *(d)* is measured in meters. Limitations arise when limited space is available for insulation refurbishment and high Rc-Values are required simultaneously.

*Density (ρ)* measures the weight of a material in kg/m³. The density is used to calculate *the weight per unit measures,* so the kg/m² with a defined thickness *(d)* per 1 m² material. It was calculated by multiplying the density *(ρ)* with the material thickness *(d),* see **Formula 2**. The density values were gathered from the Dutch Kennisbank [52].

*(2)*

$$\rho\left(\frac{kg}{\mathrm{m}^2}\right) = \rho\left(\frac{kg}{\mathrm{m}^3}\right) * d(m)$$

### 4.2.2 Embodied parameter

The embodied impacts of materials perform a crucial part of this thesis. The performance and comparison of various materials stand in focus to test the hypothesis of the decisive role to find low carbon materials to stay within climate and carbon budgets. The data used were derived from the GPR Gebouw tool, with the national milieu database (NMD) version 2.3 as underlying source. The tool allows the user to retrieve 11 impact categories of varies materials per Rc-Value per $m^2$. *Note, in contrary, many times embodied impacts are stated per m³ and kg, which is translated to the impact per the weight for 1 m² (Mass Per Unit Area). This can be performed via the product of density and thickness of the material.*

[51] Kennisbank https://kennisbank.isso.nl/publicatie/energievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen/2017/bijlage-3

[52] Kennisbank https://kennisbank.isso.nl/publicatie/energievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen/2017/bijlage-3

#### 4.2.2.1 National Milieu Database

The NMD is a database in the form of tables that contains environmental data based on building elements and construction products. The LCA of these products/materials are based on so called product cards with an expiry date of 5 years[53]. These product cards are performed either based on the Environmental Product Declarations (EPDs) from the manufacturers and suppliers (Category 1 and 2) or third parties (Category 3) such as groups of manufacturers and clients who develop the LCA of products and materials. Category 3 is brand-independent data that is not tested according to Stichting Bouwkwaliteit in Rijswijk (SBK). Yet, these data are freely accessible and can be used within this thesis *(SBK, 2014)*.

The following will explain the data structure including the life cycle stages of a product or material within the NMD version 2.3, see the schema in **Figure 29**. Materials listed in this database have an element code and name that stays in line with the NL-Sfb. Every element classification includes multiple products, represented in product code and name. For instance, element name*: Façade wall systems not load-bearing (Bekledingen systeemwanden niet dragend)* has the element code: *22.04*. This element includes a set of products, such as *multiplex, gypsum, aluminium, etc.* all indicated with an auto-incrementing number suffix for instance *22.04.01, 22.04.02, etc*[54]. Every product contains a set of environmental information. Eleven environmental impact categories are for example the Global Warming Potential (kg$CO_2$eq), total non-renewable, total renewable and the total energy (MJ), acidification (kg$SO_2$), etc.[55], as well as the emissions due to transportation[56]. The LCA data and the emissions due to transportation and background processes are retrieved from Ecoinvent 2.2 (*SBK,* 2014).

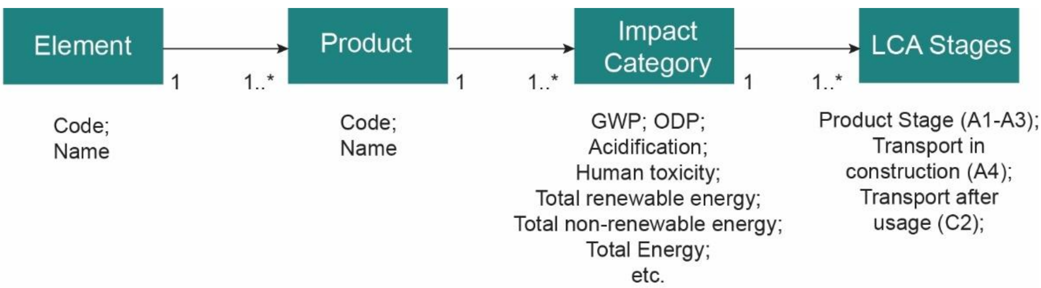



**Figure 29 NMD Data structure**

#### 4.2.2.2 Embodied Life Cycle Stages

The previous paragraph explained that the NMD data category 3 contains environmental impact categories. Each category holds information about the processing of the product, ideally in every life cycle stage (A1-A5, B1-B7, C1-C4, D). It could be identified that the insulation materials within the same category 3 hold different information considering the life cycle stages. Inconsistency is cause due to human error while performing LCA and the uncertified and unverified nature of the data itself *(Boer,*

[53] https://milieudatabase.nl/milieudata/database/
[54] https://www.milieudatabase.nl/viewNMD/
[55] https://www.milieudatabase.nl/viewNMD/view_materiaal_new.php?numCode=166
[56] https://www.milieudatabase.nl/viewNMD/view_transport_new.php?transportcode=1

*2021).* **Table 16** illustrates the included life cycle modules throughout the attempted harmonized insulation materials.

| | Product Stage | | | Construction Process Stage | | Use Stage | | | | | | | End of Life Stage | | | | Potential Benefit and Loads |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| | Raw material supply | Transport | Manufacturing | Transport | Construction installation process | Use installed products | Maintenance | Repair | Replacement | Refurbishment | Operational energy use | Operational water use | Deconstruction | Transport | Waste processing | Disposal | Recovery, reuse, recycling potential |
| EPS | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | ✓ | ✓ | ✓ |
| Glass wool | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | ✓ | |
| Rock wool | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | ✓ | |
| Flax wool | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | ✓ | |
| Wood fibres | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | ✓ | |
| Cellulose | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | ✓ | |
| PUR foam | ✓ | ✓ | ✓ | ✓ | | | | | | | | | | | | ✓ | |

**Table 16 Embodied Life Cycle Stages**

For the in this thesis two impact categories (the Total Energy in MJ and the GWP in kgCO2eq) are considered. Embodied energy (EE) refers to the energy consumption in MJ/m². Embodied Carbon emission (EC) refers to the Global Warming Potential (GWP100) and is expressed in kgCO2eq/$m^2$ of a material. Both values stand in a linear relation to the Rc-Value, and therefore also to the material thickness. It could be identified that the higher the thermal resistance, the higher the thickness, hence the higher the embodied energy and carbon emission.

*Life Expectancy (years)* of material is relevant to mention when evaluating materials life cycle performance. The SBR kennisplatform voor de bouw (2011), was chosen as source, as it represents the expected service lifetime of materials according to the ISO 15686. As the name indicates, the service lifetime represents the guaranteed lifetime of the material and does not indicate date of decay. In the event that the material lifetime is short or longer than the building service lifetime, maintenance efforts and recyclability/reusability can be discussed. In this thesis the material lifetime is not included in any additional data processing.

### 4.2.3 Financial parameter

To identify financially attractive solutions, the acquisition costs are fundamental part of this study. Refurbishment packages as well as the chosen materials must stay in an attractive payback time and in a significant relation towards the energy savings. For a cost benefit analyse the initial costs are defined by the material market cost, the labour cost, and the construction time (depending by refurbishment method).

*Material market costs (MC) (€/m²)* is primarily derived from manufactures product sheet. Pricing lists are exclusive BTW and per m². The price depends on thermal performance (Rc and U Value) and the application method (injectable, roles, plates, etc).

*Labour costs (h/m²)*

A full-time labour is considered with the working-class C to E. The value is at 30€/hour (Bouw, et al., 2020; According to CAO[57])

*Construction Time (h/building element)*

Wall injection: 8 min/m² -> 390.48 min (6.5h) for total wall injection.

Wall inside: 25min/m² -> 859.5min (14.3h) for total wall inside.

Roof injection 40 min/m² -> 2,911.20 min (48.52h) for total roof injection.

Roof inside: 40 min/m² -> 2,586.8 min (43.11h) for total roof inside.

*Construction time was derived from Van der Ven, 2018; Rovers, 2020; 040Energie, 2020.*

### 4.2.4 Health, Safety and Comfort parameter

#### 4.2.4.1 Fire Rating

The material contribution to the acceleration of fire is amongst other effects measured in the ignition temperature and the smoke development *(Fire Safety in Buildings, 2020)*. In fact, the flammability and the toxic extraction from fired materials can cause harmful damage for humans *(Schiavoni et al., 2016)*. Therefore, every material must be rated according to the European standard EN13501-1 fire classification. Fire ratings are performed with a ranking system A1, A2, B, C, D, E & F, see **Table 17**. Where A1 and A2 is limited combustible and does not contribute to fire. Whereas B to F is combustible and is limited to highly flammable. Additionally, the fire flashover to adjacent rooms can be measures per fire rating in minutes. Further, classifications are the smoke development and dropping of the material while being exposed to fire. They are rated with the s1, s2 or s3 and d0, d1 or d2. The fire rating for the chosen materials shown in **Table 18** has been collected from product data sheets and from the study by Schiavoni (2016).

| Classification | Definition | Description | Flashover in adjacent rooms |
|---|---|---|---|
| A1 | Non-combustible | No contribution to fire | No |
| A2 | Limited combustibility | Very limited contribution to fire | No |
| B | Combustible | Limited contribution to fire | No |
| C | | Minor contribution to fire | Flashover after 10 min |
| D | | Medium contribution to fire | Flashover between 2 and 10 min |
| E | | High contribution to fire | Flashover before 2 min |
| F | | Easily flammable | No performance determined |

**Table 17 Material fire rating classification, according to EN 13501-1**

#### 4.2.4.2 Toxic Hazards (FED in g/m³)

Even though the consideration of smoke exhaust of burning materials is crucial when considering human health *(European Commission, 2017)*, manufactures do only rarely represent the smoke related toxic exhaust. Toxic hazard is measure on various stages of the materials burning under consideration of various ventilation scenarios. In this thesis the assessment practice of materials that were exposed to under-ventilated fire stages was adopted, based on the aim of preventing injury or long-term damage to human health *(Stec et al., 2011)*.[58] The Fractional Effective Dose (FED) expresses the sum of exhausted gases such as $CO_2$, hydrogen cyanide, nitrogen dioxide, hydrogen chloride, and hydrogen bromide, measured based on ISO 13344. The higher the FED, the higher the toxic impact of the

[57] https://www.scabadvies.nl/wp-content/uploads/2020/03/SCAB-Loon-en-loonkostenvergelijking-Bouw-2020-01-01.pdf

[58] *https://www.iso.org/obp/ui#iso:std:iso:13571:-1:dis:ed-1:v1:en*

material towards the human health. **Figure 30** illustrates among others a set of materials, like Glass wool, Rock wool, EPS and PUR, and demonstrated the normalized FED and the including toxicities. To quantify the FED factor for a specific testing circumstance (under-ventilated), the variable $LC_{50}$ in g/m$^3$, is used to explain the volume material in grams needed to generate 1m$^3$ of toxic hazard. Thus, the lower the value the less material is needed, ergo the greater the toxic exhaust *(Stec et al., 2011).* The data, shown in **Figure 30**, for organic and inorganic material has been collected from the study of Stec (2011) and for bio-based materials has been retrieved from Maskell (2020) and interviews with Gauvin, (2020).

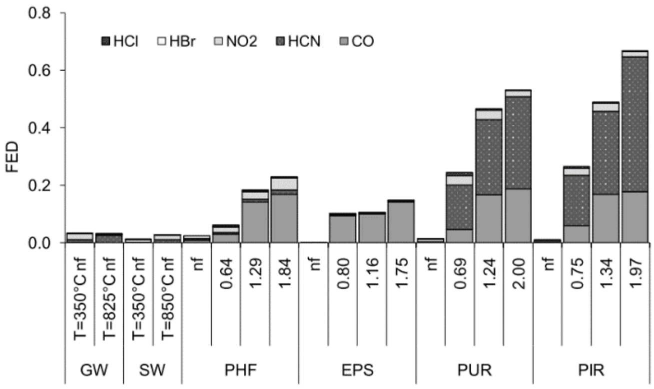



**Figure 30 Fractional Effective Dose of insulation materials *(Stec at al., 2011)***

### 4.2.4.3 Acoustic Characteristics (NRC and dB)

Increasingly important role play acoustics improvements of indoor environment quality (IEQ). Limiting sound traveling from exterior to interior and between adjacent rooms contribute highly towards the human health impact and can be delegated by evaluating sound absorption behaviour of materials *(Alonso et al., 2020)*.

The sound absorption coefficient *(α)* measures the sound absorption regarding the material´s density and structure. It reaches between 0.0 to 1.0, where 1 is 100% sound absorption *(Book Heat-insulating Materials and Sound-absorbing Materials, Chapter 12; [59]).* The efficient sound absorption level of a materials is between 0.7 and 0.9 α when being exposed to an optimum room acoustics of a frequency range of 500 to 2000 Hz *(Kuijpers-Van Gaalen et al., 2017).* The data chosen in this thesis was collected from the study of Kumar (2020). Whereas *α* is defined per material for a range of material´s density and thickness. This density stays in line with the in this thesis chosen density. In order to quantify the sound absorption coefficient *(α)*, the Noise Reduction Coefficient *(NRC)* is introduced. The NRC defines the consecutive average[60] of *α* at a frequency range of 250, 500, 1000 and 2000 Hz, and allows thereby to compare various materials with each other *(Kumar et al., 2020)*. To express impact of the NRC between outdoor and indoor noise levels the Decibel Drop *(db)* is calculated with the **Formula 3.**[61] *(Locher et al., 2018).*

*(3)*

$$db = -20 * \log_{10}(1 - \mathrm{NRC})$$

[59] https://www.theinsulationguy.com/how-nrc-numbers-work

[60] consecutive average = (minimum+maximum)/2

[61] https://www.thermaxxjackets.com/noise-reduction-coefficients-and-decibel-drop/

Where:
*db* is the decibel drop
*NRC* is the coefficient consecutive average of the sound absorption coefficient ($\alpha$).

#### 4.3.4.4 Vapour permeability (MNs/g)

The vapour permeability expresses the vapour resistance of a material and is measured with the level of moister permeability of the material, the vapour diffusion resistance *(μ-value).* The higher the μ-value the lower the moister permeability *(Schiavoni et al., 2016)*. Building refurbishments have a high demand for thermal insulation, which requires air-tight constructions with high thermal resistance. Airtight materials with fine-grained structures are vapour closed and can lead to water condensation between material layers. Due to moister permeability in so-called breathable materials, the moisture content in the air can be regulated. In refurbishment projects, the likelihood of a shifting dew point due to the layering of new materials is rather high, which can lead to structural damages, cold bridges or mould formation. Consequences of closed materials and too little air exchange cause airborne pollutants that lead to the harmful impact of human health (*Maskell et al., 2020).* According to Visser (2015) bio-based materials are capable of absorbing moister up to 30% of their own weight. Whereas fossil or mineral-based materials accumulate only fractions. For instance, hempcrete has the unique capability to accumulate moister if the relative humidity increases.

The μ-values per material was collected from the study of Schiavoni (2016). To evaluate the effect of the μ-value per chosen material thickness *(d),* the vapour diffusion vapor resistance factor *(VDRF)* is commonly used in practice and also collected for this study *(Schiavoni et al., 2016; BademliOğlu et al., 2018).* The *VDRF* is explained with the *sd* value per material *(Msd)* and was established with **Formula 4**. It represents the equivalent thickness of air, with the same vapour transfer resistance as of the analysed material. Materials acting as vapour barriers are considered with a *sd* ≥ 1000–1500 m and vapour retarder with a sd≤10 m *(Schiavoni et al., 2016)*. To convert the *Msd* further to vapour resistance of the material *(MNs/g),* we divide the *Msd* by the 0.2g.m/MNs, which is the vapour permeability of still air, see **Formula 5** *(Build Desk, 2002).*

*(4)* $$Msd = d(m) * \mu - \text{value}$$

*(5)* $$MNs/g = Msd : (0.2\ g.m/MNs)$$

To conclude, in this Section it was aimed to describe the methodological baseline to collect material related information that allows to evaluate its performances in sustainable refurbishment projects. Thereby, thermal properties, environmental footprint, cost, comfort, health, and safety related properties were investigating. **Table 18** illustrates the results of the analysed materials in this case for Rc-Value 1.7 - Rc 6.5. Find all other Rc-Value (1.7, 2.5, 4.0, 6.5) in the **Appendix B.**

## 4.3 Comparative Material Analysis

In the previous Section, decision parameters to evaluate materials are studied. Various insulation materials were analysed to create a comparative study. The material classification was divided according to the sourcing materials. These are non-renewables such as fossil fuel-based materials, mineral-based and bio-based materials, see **Table 18**. Find the comparative analysis per Rc-Value in the **Appendix B.**

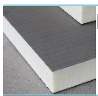
| | **Name** | **Lambda (λ)** | **Density (ρ)** | **Weight** | **EE** | **EC** | **Costing** | **Lifetime** | **Fire rating** | **Toxic Hazards** | **dB drop** | **VDRF** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *W/mK* | *kg/$m^3$* | *kg/$m^2$* | *MJ/$m^2$* | *(kg$CO_2$e q/$m^2$)* | *€/m2* | *years* | *A-F* | *g/$m^3$* | *dB* | *μ-value* |
| **Mineral-based** | | | | | | | | | | | | |
|  | Glass Wool | 0.034 | 18.4 | 1.06 - 4.07 | 51.50 - 196.91 | 1.60 - 6.12 | 6.80 - 20.00 | 75 | A2 | 129.5 | 8.52 | 0.29 - 1.11 |
|  | Rock Wool | 0.035 | 45 | 2.68 – 10.24 | 48.90 - 186.97 | 2.90 - 11.09 | 7.40 - 26.00 | 75 | A1 | 172.1 | 7.85 | 0.36 - 1.37 |
| **Fossil-based** | | | | | | | | | | | | |
|  | PUR | 0.026 | 33 | 1.44 - 5.49 | 179.30 - 680.70 | 11.60 - 43.90 | 7.86 - 23.00 | 75 | E | 11.4 | 11.54 | 22.10 - 84.50 |
|  | EPS | 0.0325 | 23 | 1.24 - 4.75 | 117.50 - 449.26 | 8.70 - 33.26 | 5.85 - 21.00 | 75 | E | 27.6 | 2.16 | 15.19 - 58.09 |
|  | XPS | 0.027 | 35 | 1.61 - 6.14 | 178.20 - 681.35 | 24.80 - 94.82 | 8.11 - 39.92 | 75 | E | ≤ 27.6 | 4.81 | 26.39 - 100.91 |
| **Bio-based** | | | | | | | | | | | | |
|  | Flax wool | 0.041 | 31 | 2.16 - 8.26 | 86.30 - 329.97 | 2.60 - 9.94 | 24.08 - 67.25 | 40 | C | ≥ 129.5 | 10.17 | 0.52 - 2.00 |
|  | Wood Fibre | 0.038 | 45 | 21.96 - 83.98 | 23.50 - 89.40 | 0.62 – 2.35 | 6.91 - 30.17 | 100 | C-D | ≥ 129.5 | 21.00 | 0.97 - 3.71 |
|  | Cellulose | 0.04 | 70 | 4.76 - 18.20 | 8.80 - 33.30 | 0.29 - 1.11 | 55.50 - 90.00 | 30 | C | ≥ 129.5 | 10.90 | 0.85 - 3.25 |
|  | Sheep Wool | 0.0412 | 25 | 1.75 - 6.70 | 21.54 82.35 | -2.10 - -8.03 | 13.48 - 51.55 | 100 | E | ≥ 129.5 | 6.52 | 0.70 - 2.68 |
|  | Hemp Lime | 0.067 | 340 | 38.73 - 148.07 | 152.63 - 583.57 | -8.59 - -32.84 | 23.92 - 91.46 | 100 | B | ≥ 129.5 | 16.48 | 1.59 - 6.10 |

**Table 18 Material Comparative Analysis Rc 1.7 - 6.5**

Striving towards a more sustainable built environment requires more than reducing operational energy. Among other impact categories, the global warming potential in the form of embodied carbon emissions represents 11% of the total building industry´s carbon footprint. In this context, bio-based materials offer an alternative to the commercial organic and inorganic materials. However, when making the decision for the best suitable insulation materials, thermal and economic performance stand primarily in focus, followed by IEQ criteria. **Table 19** summarizes the performances of each material group in six parameters. The relative performances are evaluated with **++** is best performing, **+-** and **-+**average good and **--** poor performing.

| | Thermal | Environment | Economic | Fire & Toxic Hazard | Acoustics | Humidity |
|---|---|---|---|---|---|---|
| Fossil-based materials | ++ | -- | +- | -- | +- | -- |
| Mineral-based materials | +- | +- | ++ | +- | +- | +- |
| Bio-based materials | -+ | ++ | -+ | -+ | ++ | ++ |

**Table 19 Comparative analysis of decision parameter**

Fossil-based materials have a dense structure, that positively contributions to an airtight construction. Little thickness has already high thermal performances while low weights make the installation easy. Because fossil fuel-based materials are most often used on the market, they have relatively low costs. Acoustically, they perform better than others as they can reduce noise disturbance. However, low fire rating and a high share of chemical additives cause harmful consequences to the human health. Little material is needed to be in flames to extract a great number of toxic hazards. Similar, the fossil-based materials are vapour closed and do not regulate air humidity. In fact, special attention must be given to a correct installation to avoid mould formations. The most negative property however is the poor environmental performance. Because the material relies heavily on fossil-fuel and chemical productions, much energy is used, and a high carbon emission exhaust is produced. Taking as example an 8cm PUR insulation and applying it into a cavity wall (area 65m²) consumes 882 kg$CO_2$eq and 11,189 MJ of energy. In other words, someone would need to plant 40 trees to capture this amount of carbon within.[62]

Mineral-based materials have a slightly lower thermal properties (higher lambda values) than organic materials. As second biggest commercial material[63] on the market, wool insulation is easy to install. Mineral based wool certainly performs best in fire rating classifications. Consequently, this requires toxic additives in the production. This in return can lead to irritations of skin, throat and eyes in fire situation. In this context also care should be taken when working with the material. Wool generally performs well in sound insulation as it has a porous structure. This also allows to be vapour open however does not act as breathable and humidity regulating material. The environmental footprint is much better than for organic materials within a similar price range.

Alternative sustainable materials are based on re-growable source materials. In fact, because of its natural and local sourced materials the embodied carbon and energy remains low until negative. Further, bio-based materials outperform others in terms of toxic hazards. Low to nontoxic additives are added that leads to no threat for human health in fire situation. Due of little additives, the fire resistance remains in a medium range. In combination with their porous structure, it allows the

[62] https://www.carbonpirates.com/blog/how-much-carbon-do-trees-absorb/
[63] https://www.grandviewresearch.com/industry-analysis/insulation-market

material to breath and regulate indoor temperature and humidity. For instance, an extraordinary quality of hemp lime is the adoption of the lambda value when temperature difference between in and outdoor increases. This means the colder it becomes outside the better the material insulates. Also, in terms of sound absorption, bio-based material performs best as they are capable to drop the highest dB difference between the out- and indoor environment. In terms of the thermal properties, bio-based materials are outperformed by the commercial materials. Additionally, higher thicknesses and weights are required which leads to much higher market costs. Little knowledge is shared due to too little investment for research and development, and it causes a poor market reputation.

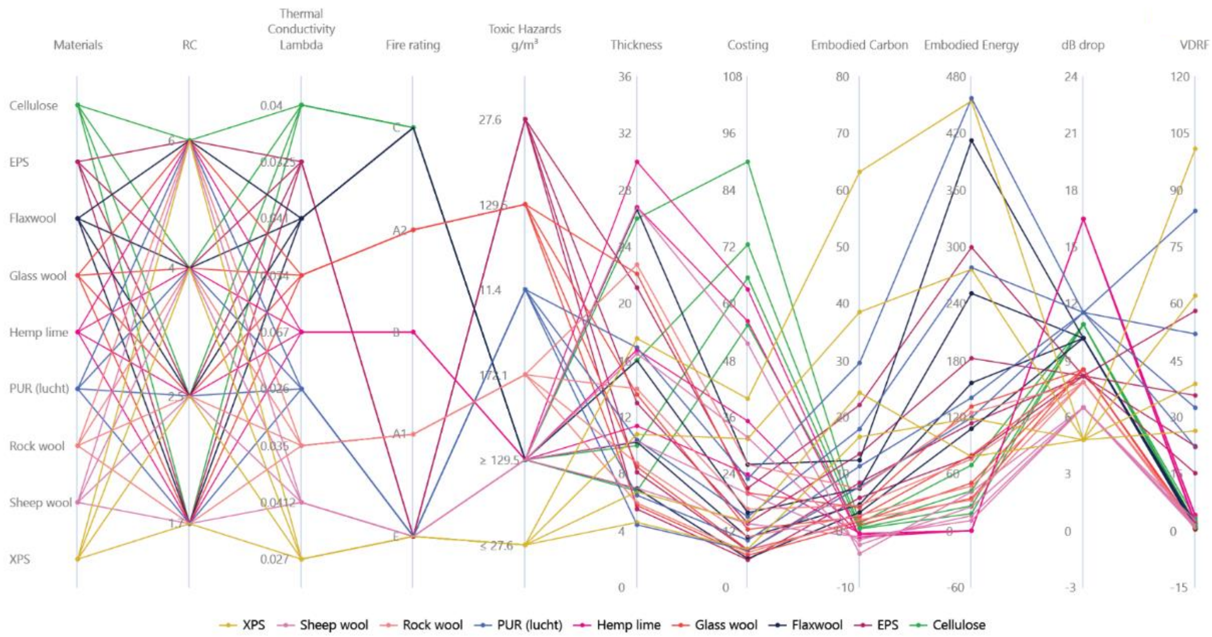



**Figure 31 Material Comparative Analysis**

## 4.4 Performance assessments

The building and refurbishment evaluation builds upon the knowledge of **Section 4.2 Material Evaluation Method**. The logic is as follows. The thermal characteristics influence the buildings operational energy performance for the as-is and each refurbishment package. The embodied and the financial parameter are used to calculate the total impact of every material scenario, per refurbishment package. This results in the environmental and economic performance evaluation, respectively. Finally, the health, safety and comfort related parameter are discussed to evaluate the Indoor Environment Quality (IEQ).

### 4.4.1 LCA Scope and System Boundaries

The following will present the inventory of the building and the system boundaries. This includes a listing of included building elements of the case study. Further, the life cycle stages of the elements, the functional unit and the reference study period.

#### 4.4.1.1 Functional Equivalent

To benchmark energy refurbishment scenarios in regard to the LCA performances, the functional unit for this use case refers to the thermal improvement per refurbishment measure. The Rc-Value yields as common attribute between all chosen refurbishment measures, see *Table 20*.

| Functional Equivalent | P1 | P2 |
|---|---|---|
| What? | Low measure and no regret scenario. Includes the minimum thermal improvement.<br>- EPS<br>- Glass wool | Includes medium to high thermal improvement.<br>- Glass wool<br>- Rock wool<br>- Wood fibre |
| How much? | Includes wall and roof insulation into existing construction. Wall insulation thickness 6 to 8 cm, Roof insulation thickness 8 to 16cm. | Includes wall and roof insulation added as second layer inside. Wall insulation thickness 14 to 16 cm, Roof insulation thickness 22 to 26cm. |
| How well? | Energy Label C-B.<br>Wall Rc 1,7; Roof Rc 2,5<br>(opt. Window U 1.2) | Energy Label B-A.<br>P2: Wall Rc 4,0; Roof Rc 6,5,<br>(opt. Window U 0.7) |
| How long? | 10 years. | 10 years. |

**Table 20 Functional Equivalent**

#### 4.4.1.2 Building Elements and System boundaries

The included elements to be assessed are constrained to those which are added during the refurbishment process. Existing elements are not taken into consideration (according to EN 15978).

- External wall insulation layer.
- External and internal wall sub structures and claddings.
- Roof insulation.
- External and internal roof sub structures and cladding.
- *Optional: Window framing and glass.*
- *Optional: Heating pump and boiler systems.*
- *Optional: PV panels and solar boilers.*

A more elaborate table that differentiates between the shell and the core structure of the building can be found in the **Appendix C.**

#### 4.4.1.3 Reference Study Period

The reference study period refers to the period for study and not to the actual extended building lifetime. To allow a comparative benchmarking a reference study period of 10 years was chosen.

### 4.4.2 Operational Energy and Carbon

The operational energy and carbon performance is defined by the heat load demand, the primary energy and the operational $CO_2$ performance.

#### 4.4.2.1 Heat load demand

The Space heating demand (kWh/m²/yr) derives from the energy simulation model from the software VABI and Design Builder. The former is based on the Dutch energy standard NTA8800 and the latter is used to verify the result, see **Appendix D**. The use case was entered and simulated according to the thermal properties (Rc and U Values) of varies building elements, as explained in the refurbishment packages above. The results, representing the space heating demand, must be further expressed via the gas consumption with the factor of 9.769 kWh as being 1 m³ gas. *This needs to be done in order to calculate the gas cost separately form the electricity cost.* Additionally, the Domestic Host Water demand (DHOW) (m³/yr) must be considered with 856 kWh/person/yr according to the Dutch guideline, NTA8800 page 501. The total electricity demand was derived by the energy provider Oxxio for a three-person household with 4,050 kWh/yr.

The operational energy $OE$ consumption in kWh/yr for heating, water and electricity per refurbishment package as well as the operational energy saving potential $\Delta OE$ can be established, see **Formula 6.**

$$(6) \qquad OE[kWh/yr] = Space\ Heating\ \left(\frac{m^3}{yr}\right) + DHOW\ \left(\frac{m^3}{yr}\right) + Electricity\ \left(\frac{kWh}{yr}\right)$$

#### 4.4.2.2 Primary Energy

The Energy Index, on the basis of the primary energy, is used when performing energy refurbishments. Majcen (2016) explains the operational energy consumption per year with the primary energy calculation represented in **Formula 7** (Total Primary Energy in MJ). The calculation derives from the original consumption of gas [m3] and electricity [kWh] to cover a dwelling type and floor area *(Majcen, 2016).*

$$(7) \qquad Qtotal[MJ] = Q_{total\ gas}\ [m^3] * 35.17\ \left[\frac{MJ}{m^3}\right] + (Q_{total\ el.}\ [kWh] * 3.6\ \left[\frac{MJ}{kWh}\right]): 0.39$$

The primary energy is defined as the pure form of energy source found in nature; thus, the energy transformation factor must be considered. The assumed conversion factors are 35.17 MJ/m³ for gas based on North Sea gas, and a factor of 0.39 for electricity (39% efficiency of energy transferee for electricity as consumed from the end user) *(Majcen, 2016)*. The energy consumed by the end user depends heavily on the user's occupation degree and the efficiency of the space heating/cooling system and DHW system *(Majcen et al., 2013)*.

#### 4.4.2.3 Operational Carbon

To know the respective operational carbon footprint, the $CO_2$ emission conversion factor is used as a fuel specific coefficient factor. It is generally expressed in $kgCO_2e$/KWh that are usually published on a national administration level to monitor consistency GHG in geographical boundaries (CREEM 2020). Regarding the TNO report 2002, the $CO_2$ emission factors for natural gas (aardgas) in the Netherlands are stated with 56.1 $tCO_2/TJ$, which are 0,2019 $kgCO_2/kWh$ *(Harmelen & Koch, 2002)*. In the contrary the electricity variable for carbon intensity factor is expressed depending on the fuel mix used to generate the electricity. According to the European Environment Agency[64] the electrical carbon factor in the Netherlands is 0.441 $kgCO_2/kWh$.

Due to simplicity reasons the carbon emission factor is going to be derived from the primary energy consumption per refurbishment measures, as defined in CREEM (2020). The primary energy in MJ is going to be translate to kWh and then multiplied by the emission factor 0,2019 $kgCO_2/kWh$. This ensures the inclusion of all energy sources in its original form and stands in line to national repots (such as TNO).

### 4.4.3 Embodied Energy and Carbon

In this step it is explained how to upscale the gathered embodied impact (NMD) from material unit towards the building levels. The procedure is shown in **Figure 32.** The embodied data is available per construction materials (per $m^2$), as described in the **Section 4.2.2 Embodied parameter.** This must be relational quantified to the sub-element and the building element (BE). Eventually, the sum of all improved building elements expresses the environmental impact per package (according to EN 15978). Finally, to start comparison towards the operational energy consumption and carbon emission, the embodied impact is expressed per $m^2$ of the total GFA.

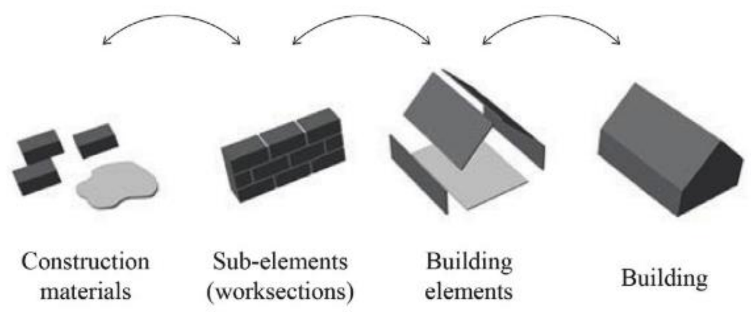



**Figure 32 From material level to building element *(Röck et al., 2018)***

Starting with the data processing from material to building level. Per definition, the embodied energy (EE) consumption and related embodied carbon (EC) emission is expressed in $MJ/m^2$ and $kgCO_2eq/m^2$ respectively. It states how much energy and carbon is needed to produce and construct $1m^2$ material *(Röck et al., 2020)*. Röck (2020) showcases in his study the harmonized unit to perform embodied impacts per square meter ($m^2$) of the building material *(Röck et al., 2020)*. This means that the embodied unit value is multiplied with the sum of material used which further is added up with all materials within one building element - to achieve the impact value EE and EC per building element (BE).

Aligned to this definition, the **Formulae 8 and 9** explains the embodied energy and carbon per building element

[64] https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment

$$EE_{BE}(MJ) = \sum(EE\left(\frac{MJ}{m^2}\right) * Area(m^2)) \quad (8)$$

Where:

$EE_{BE}$ = Total energy emitted per building element (MJ).

$EE$ = Embodied Energy (Embodied Energy impact value) per $m^2$ of a building material.

$Area$ = Building material quantity in $m^2$.

Taking the sum $\sum(EE * Area)$ allows to use multiple materials within one Building Element (BE).

$$EC_{BE}(kgCO2eq) = \sum(GWP\left(\frac{kgCO2eq}{m^2}\right) * Area\ (m^2)) \quad (9)$$

Where:

$EC_{BE}$= Carbon emissions emitted per building element ($kgCO_2eq$).

$GWP$ = Global Warming Potential (Embodied Carbon impact value) per $m^2$ of a building material.

$Area$ = Building element total quantity in $m^2$.

Taking the sum $\sum(GWP * Area)$ allows to use multiple materials within one Building Element (BE).

These two formulas are defined to allow a flexible definition of multiple material layers per refurbishment scenario. As for this thesis, the defined package P1 is a simple multiplication of the embodied impact by the injected insulation area, for windows and roofs. While the refurbishment packages P2 requires sub constructions, in the form of wooden beams and gypsum boards. Adding up all newly applied building elements, the Total $EE$ and $EC$ of refurbishment scenario can be established that stays in line with the LCA definition according to the EN 15978. To evaluate the overall building embodied performance for the respective refurbishment measure, the payback is used and further elaborated.

#### 4.4.3.1 Environmental Payback Time

The goal is to evaluate the total operational and embodied impacts of buildings compared to the saving potential of a performed measure. A well-known concept therefore is the carbon budget. For instance, the study of Brejnrod (2017) defines the environmental budget per person for housing is set with a maximum value of 110 $kgCO_2eq$ per year. Another definition would be from Habert (2020) as he refers to the carbon budget per $m^2$ of a building user surface. Thereby, a total of 5.8 $kgCO_2eq/m^2year$ results *(Brejnrod et al., 2017; Habert et al., 2020).*

In this thesis neither of both budgets could be achieved with any of the performed refurbishment packages. Therefore, this thesis relies on evaluating the packages with the so called energy and carbon payback time EPT and CPT respectively. Based on the study of Berggren (2013) and Passer (2016) the **Formulae 10 and 11** are used *(Berggren et al., 2013; Passer et al., 2016).*

$$EPT = \frac{EE}{\Delta OE} \quad (10)$$

$$CPT = \frac{EC}{\Delta OC} \quad (11)$$

Where:
$EPT$ and $CPT$ is the energy and carbon payback time, respectively, for a specific measure.
$EE$ and $EC$ is the total embodied energy and related carbon impact due to a specific measure.
$\Delta OE$ and $\Delta OC$ represents the difference (savings) of the operational performance after applying a specific measure.

### 4.4.4 Operational Cost and Investment Cost

This section introduces the cost analysis divided in operational cost and investment cost. Note that no maintenance cost over the study period is included but return of investment (ROI) and subsidy costs are included as well. For the investment cost the material cost, labour cost and fabrication cost are established.

#### 4.4.4.1 Operational Cost

Due to the operational energy demand calculation in **Section 4.4.2 Operational Energy and Carbon** the gas (for space heating and DHOW) and electricity could be used to determine the operational cost (€/yr). The total annual energy cost can be derived from the total gas and electricity consumption and multiplied with the gas price of 0.814 €/m³ and for electricity with 0.225 €/kWh *(Milieu Central b, 2020).* The operational cost $OC$ in €/yr per refurbishment package can be determined as well as the operational cost saving potential $\Delta OC$. See **Formula 12** for the operational cost.

$$(12)\ OC\left(\frac{€}{yr}\right) = \left(Space\ Heating\ \left(\frac{m^3}{yr}\right) + DHOW\ \left(\frac{m^3}{yr}\right)\right) * 0.814\ \left(\frac{€}{m^3}\right) + \left(Electricity\ \left(\frac{kWh}{yr}\right) * 0.225\ \left(\frac{€}{kWh}\right)\right)$$

#### 4.4.4.2 Investment Cost

The investment costs are crucial to perform a cost benefit analysis and to determine the payback time, see **Formula 13**.

*Investment Cost (IC) (€)*

$$(13)\qquad IC_{BE}(€) = \sum\left(MC\left(\frac{€}{m^2}\right) * Area(m^2)\right) + CC_{Pn}$$

Where:
$IC_{BE}$ Total investment costed per building element (€)
$MC$ Material Cost in € per $m^2$ of a building material.
$Area$ = Building element total quantity in $m^2$.
Taking the sum $\sum(MC * Area)$ allows to use multiple materials within one Building Element (BE)
$CC_{Pn}$ The construction cost per package and chosen specific measure.

Every refurbishment measure, so the cost per building element (BE), is added up in order to know the total invested cost per package. In the same way as the embodied impact is defined, also **Formula 13**, allows to consider various numbers of material layers and application methods within a particular package. Thus, P1 with easy injection and P2 considers sub constructions and additional construction time is guaranteed.

#### 4.4.4.2 Construction Cost

*Construction Cost (CC) (€)*

The construction cost exists out of construction time and labour cost, see **Formula 14**. The construction and assembly cost are highly influenced by the required thermal improvement. For instance, cavity wall injection can be performed relatively quick and requires less labour cost. While a second wall inside or a full make over asks for prefabrication processes and extra materials. Note: Additional pre works like examen a building with a thermal image camera and material spare is not included in this thesis.

*(14)* $$CC_{Pn} = \text{Labour Cost} * \text{Construction Time}$$

#### 4.4.4.3 Economic Payback Time

The economic payback time refers to the time needed to recover from an investment, see **Formula 15**. In this thesis the investment is the refurbishment package expressed as IC and the recovery time is derived from the operational cost saving potential $\Delta OFC$.

*(15)* $$FPT = \frac{IC}{\Delta OFC}$$

## 4.5 Performance Results

### 4.5.1 Operational Performance

For both packages the operational energy and cost performance is analysed and presented in **Table 21**. Results show that both packages decrease the gas consumption. The gas saving for Package 1 (P1) is 17% and for package 2 (P2) is 27%. Due to lower gas consumption also lower $CO_2$ emission are emitted. The $CO_2$ saving are at 10% and 15%. Finally. The gas cost is reduced by 200€/yr and 300€/yr. This is a cost saving potential of 17% and 27%.

| | | BM | P1 | P2 |
|---|---|---|---|---|
| Space heating demand | kWh/yr | 10,600.00 | 8,300.00 | 7,100.00 |
| Space heating Gas | m³/yr | 1,085.07 | 849.63 | 726.79 |
| DHOW Gas | m³/yr | 262.87 | 262.87 | 262.87 |
| Total Gas consumption | m³/yr | 1,347.94 | 1,112.50 | 989.66 |
| ΔOE-Gas saving | m³/yr | 0.00 | 235.44 | 358.28 |
| ΔOE-Gas saving | % | 0.00 | 17.47% | 26.58% |
| Operational CO2 emission | kgCO2/yr | 4,755.38 | 4,290.99 | 4,048.70 |
| ΔOC (CO2 saving) | kgCO2/yr | 0.00 | 464.39 | 706.68 |
| CO2 saving | % | 0.00% | 9.77% | 14.86% |
| Gas costs | €/yr | 1,097.22 | 905.57 | 805.58 |
| ΔOFC- Gas Cost Savings | €/yr | 0.00 | 191.65 | 291.64 |
| Cost Savings | % | 0.00% | 17.47% | 26.58% |

**Table 21 Operational Energy Performance**

### 4.5.2 Material Performance

The above mentioned energy performances represent two potential operational energy reductions measures. Within this thesis multiple materials were analysed based on the use case. The following could be identified as the key materials, that offer comparable data in sustainable aspects (energy-carbon-costing-health, comfort and safety).

Results are represented in **Table 22**. It introduces the materials for P1.M1 EPS and P1.M2 Glass wool, and for P2.M1 Glass wool, P2.M2 Rock wool and P2.M3 Wood fibre. The package P1 and P2 differ in the installation methods. EPS and Glass wool are injectable while Rock wool and Wood fibre can only be place as second layer inside. Bio-based and mineral based materials perform best in embodied impact and health criteria, however, are yet more expensive. Fossil fuel-based materials, such as EPS, yields poor fire resistance, has however the highest life expectancy and is relatively cheap.

| | P1 | | P2 | | |
|---|---|---|---|---|---|
| Wall + Roof | M1<br>EPS (cavity) | M2<br>Glass Wool (cavity) | M1<br>Glass Wool (roles) | M2<br>Rock Wool (Plates) | M3<br>Wood Fiber (Plates) |
| Installation method | Injection | Injection | Second layer inside | Second layer inside | Second layer inside |
| Rc-Value (Wall, Roof) | 1.7, 2.5 | 1.7, 2.5 | 4.0, 6.5 | 4.0, 6.5 | 4.0, 6.5 |
| Thickness (Wall, Roof) | 6 cm, 8 cm | 6 cm, 9 cm | 14 cm, 22 cm | 14 cm, 23 cm | 15 cm, 25 cm |
| Investment Cost (IC) | € 2,693.32 | € 2,626.65 | € 2,901.16 | € 3,435.29 | € 3,730.06 |
| Financial Payback time (FPT) | 14 years | 14 years | 10 years | 12 years | 13 years |
| $CO_2$ footprint in manufacturing | 1,348.94 kg$CO_2$eq | 249 kg$CO_2$eq | 1,349.77 kg$CO_2$eq | 1,774.32 kg$CO_2$eq | 1,028.61 kg$CO_2$eq |
| $CO_2$ payback time (CPT) | 2.9 years | 0.5 years | 1.9 years | 2.5 years | 1.4 years |
| Street noise reduction | 25% | 50% | 50% | 50% | >50% |
| Humidity regul. | NO | NO | NO | NO | YES |
| Life expectancy | 75yr | 50yr | 50yr | 50yr | 40yr |
| Fire resistance | Flashover before 2 min (E) | No flashover (A) | No flashover (A) | No flashover (A) | Flashover after 10min (C/D) |

**Table 22 Material Performances Scenarios**

### 4.5.2.1 Investment Cost

The Investment cost is calculated according to the **Section 4.4.4 Operational Cost and Investment Cost** and interviews held with the energy collective 040Energie. For P1, solely insulating materials and for P2 also sub construction materials are included. The calculation tables can be found in the **Appendix E.**

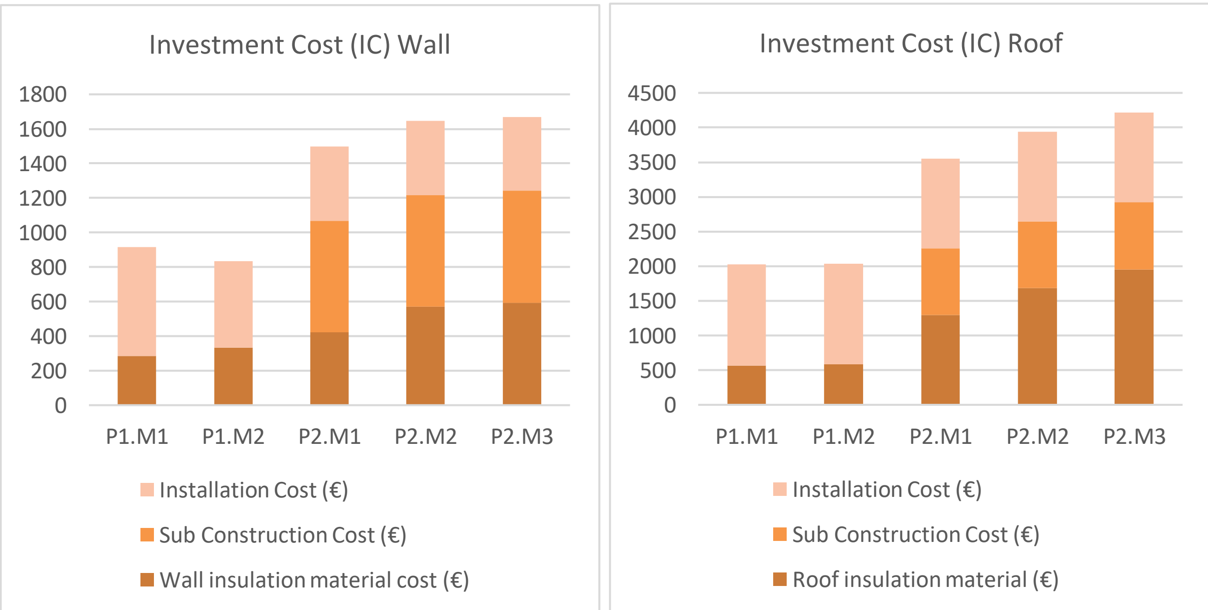



**Figure 33 IC Wall and Roof**

The final IC per package is the sum of the wall and roof insulation investment minus the subsidy gain, see **Figure 34** and **Table 23**. Results show that the higher the energy reduction measure the higher the IC. Especially noticeable is the high prices of bio-based insulation measure (P2.M3). Glass wool seems to be the cheapest solution in both packages, comparing P1.M2 and P2.M1. The subsidy remains within one package definition the same. The P1 does not receive subsidy for the roof insulation, due to too low Rc-Value. Nevertheless, the wall insulation receives subsidy, because two measures are applied. The P2, receives subsidy for both improvements. The full calculation and subsidy regulation can be found in the **Appendix E.**

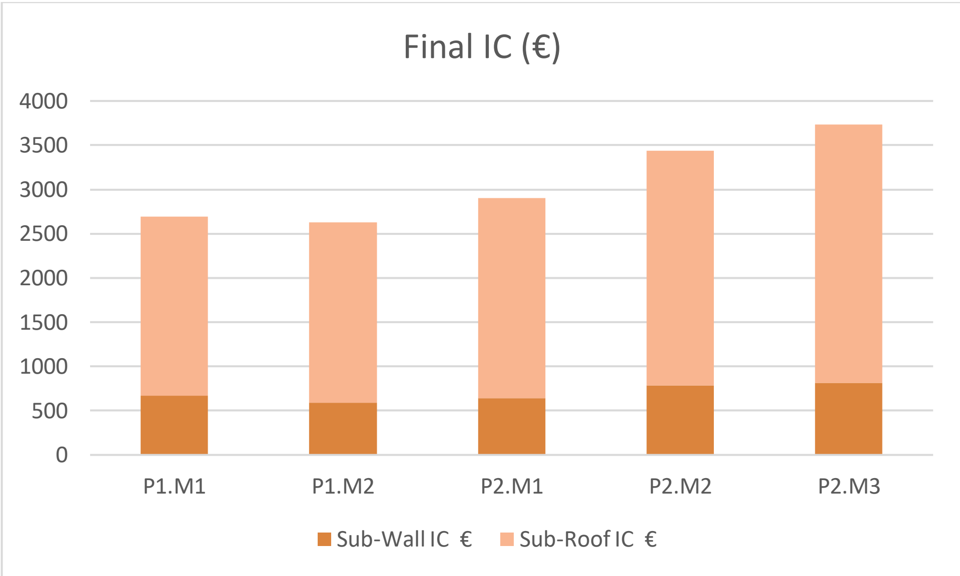



**Figure 34 Final IC per refurbishment package**

| | | **P1** | | **P2** | | |
|---|---|---|---|---|---|---|
| | | M1<br>EPS (cavity) | M2<br>Glass Wool (cavity) | M1<br>Glass Wool (roles) | M2<br>Rock Wool (Plates) | M3<br>Wood Fiber (Plates) |
| Sub-Wall IC | € | 914.09 | 832.86 | 1,499.07 | 1,645.19 | 1,670.29 |
| Subsidy Wall | € | 244.05 | 244.05 | 859.50 | 859.50 | 859.50 |
| Sub-Roof IC | € | 2,023.28 | 2,037.84 | 3,554.98 | 3,943.00 | 4,212.68 |
| Subsidy Roof | € | 0.00 | 0.00 | 1,293.40 | 1,293.40 | 1,293.40 |
| Final IC | € | 2,693.32 | 2,626.65 | 2,901.16 | 3,435.29 | 3,730.06 |
| ΔOFC | €/yr | 191.65 | 191.65 | 291.64 | 291.64 | 291.64 |
| FPT with subsidy | yr | 14.05 | 13.71 | 9.95 | 11.78 | 12.79 |

**Table 23 IC Wall and Roof (with Subsidy)**

### 4.5.2.2 $CO_2$ footprint

The embodied impact per materials scenario is presented for wall, roof and total. The sub construction is included in the second package, find the calculation in **Appendix D.** The saving potential is shown in the Carbon Payback Time (CPT) and in the effect of trees to be planted, see **Table 24**.

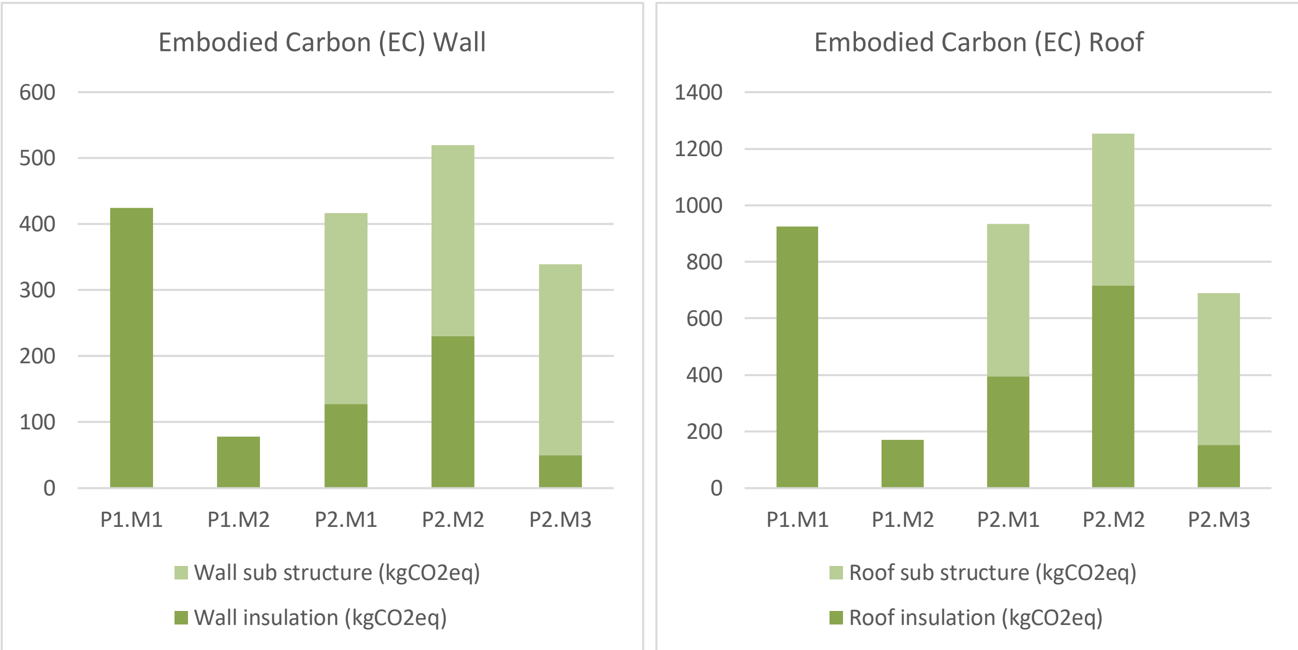



**Figure 35 EC Wall and Roof**

P1.M1 and P1.M2 is simple injection of materials and does not require any more additional materials. P2 requires extra material and yield generally higher embodied carbon emissions. Nevertheless, comparing the P1.M1 EPS and P2.M1 glass wool show equal embodied impact while performing differently in the operational carbon. In fact, P2.M1 performs the lowest embodied carbon impact and yields a CPT of 0.56 years. This is closely followed by P2.M3, with a CPT of 1.7. EPS in the package P1.M1 performs very poorly with a CPT of 4.09.

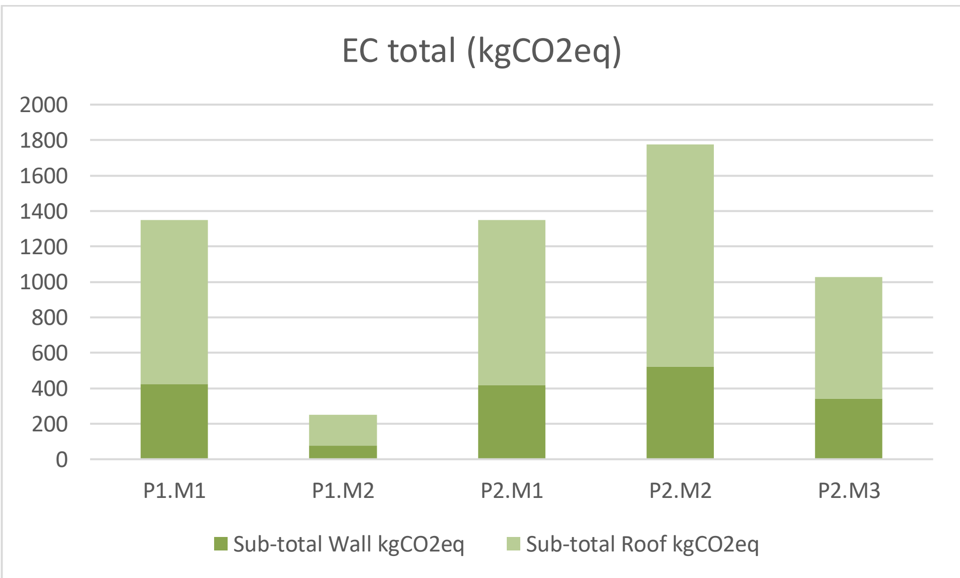



**Figure 36 Final EC per refurbishment package**

| | | P1 | | P2 | | |
|---|---|---|---|---|---|---|
| | | M1<br>EPS (cavity) | M2<br>Glass Wool (cavity) | M1<br>Glass Wool (roles) | M2<br>Rock Wool (Plates) | M3<br>Wood Fiber (Plates) |
| Sub-total Wall | kgCO2eq | 424.64 | 78.09 | 416.85 | 519.99 | 339.5 |
| Sub-total Roof | kgCO2eq | 924.30 | 171.03 | 932.92 | 1,254.33 | 689.11 |
| EC one-time | kgCO2eq | 1,348.95 | 249.34 | 1,350.03 | 1,774.62 | 1,029.02 |
| EC/10 years | kgCO2eq | 134.90 | 24.93 | 135.00 | 177.46 | 102.90 |
| ΔOC | kgCO2/yr | 464.39 | 464.39 | 706.68 | 706.68 | 706.68 |
| Total CO2 saving (ΔOC - EC/10 years)[65] | kgCO2/yr | 329.49 | 439.46 | 571.68 | 529.22 | 603.78 |
| CPT | yr | 4.09 | 0.56 | 2.36 | 3.35 | 1.7 |
| Effect of trees | | 16.47 | 21.97 | 28.58 | 26.46 | 30.19 |

**Table 24 Total $CO_2$ footprint and effect of trees**

#### 4.5.2.3 Noise reduction and comfort improvement

The noise reduction potential is explained by a decrease of 25% and 50 % noise reduction. This is derived from the comparative material study of **Section 4.3 Comparative Material Analysis** in accordance with **Table 25** and **Table 26**. The comfort improvement is assumed with a dichotomous value, yes and no. Interviews and in field expert knowledge recommends using no comfort improvement when injecting in existing cavity walls, and comfort improvement when a second insulation wall is installed.

| NRC | EPS | XPS | Glass wool | Rock wool | Flax wool | Cellulose | Wood fibre |
|---|---|---|---|---|---|---|---|
| NRC (%) | 20% | 40% | 60% | 60% | 70% | 70% | 90% |
| dB drop | - dB | 5 dB | 9 dB | 8 dB | 10 dB | 11 dB | 21 dB |
| Noise reduction | < 25% | ≤ 25% | ≤ 50% | ≤ 50% | ≥ 50 % | ≥ 50% | 100 % |

**Table 25 Noise reduction**

| Change in dB | Physical Difference | Perceived Difference |
|---|---|---|
| 3 dB | Doubling or halving | Barely noticeable |
| 5 to 6 dB | 3 to 4 times increase or 67-75 % decrease | Clearly noticeable |
| 10 dB | 10 times increase or 90 % decrease | Half or twice as loud |
| 20 dB | 100 times increase or 99 % decrease | Very dramatic change |

**Table 26 DB interpretation**

[65] *1 Tree absorbs 20 kgCO2 per year, so we divide the savings per year by 20 to know the effect.*

# CHAPTER 5

# Preference Modelling

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# 5 Preference Modelling

*In this Chapter, the preference modelling is discussed that eventually will be used inside the tool to determine the market potential of the packages. Firstly, the conceptual framework based on random utility is introduced in Section 5.1. In Section 5.2 the experiment design is explained, and the attributes and levels used for the experiment are dealt with. The data collection and the analysis of the data sample is explained in Section 5.3. Section 5.4 presents the results of the experiment and the estimated coefficients. Section 5.5 discusses sensitivity analysis and derives the willingness to pay. Section 5.6 presents the results of the use case.*

## 5.1 Conceptual framework

Discrete choice modelling is usually performed using stated or revealed choice data. The former gains new data by examining the preferences of the participants in a selection process. The latter builds on existing data and derives correlations that determine the likelihood of accepting one over the other. The advantage of a stated choice model over the revealed method is that participants make choices after making a trade-off assessment of the choices they have seen. It makes it possible to understand the actual decision-making process of the participants *(Chau et al., 2010).*

### 5.1.1 Random utility model

The random utility theory is applied to model the homeowner's decision-making process when facing sustainable refurbishments. The utility of homeowners to choose insulation material packages is defined in a function containing the chosen attributes plus a random component as the unobserved factor. The utility of no refurbishment is defined with a constant plus the random component. In the decision-making process, the homeowners compare alternatives with each other, that represent insulation material packages and the option not to refurbish. The chosen alternative reveals the highest utility. The choices that homeowners make are defined as vectors $\{m = 0\}$ and $\{m = 1, j\}$, where $m = 0$ means no refurbishment, $m = 1$ is refurbishment and $j$ indicates the alternative, from the possible refurbishment packages. The base model for a stated choice experiment is defined as standard multinomial logit (MNL) model *(Ossokina et al., 2021; Ossokina et al., 2019)*. The multinomial logit model is used as the workhorse in this thesis *(Hensher et al., 2015).*

When no refurbishment is chosen ($m = 0$) **Formula 16** will be applied and when a refurbishment alternative $j$ is chosen ($m = 1$) then **Formula 17** will be applied.

*(16)* $$U_{m=0} = V_{m=0} + \varepsilon_{m=0} = \rho + \varepsilon_{m=0}$$

Where:
$U_{m=0}$ is the Utility for no alternative, so no refurbishment.
$V_{m=0}$ = $\rho$ is the Structural Utility when no refurbishment is chosen.

*(17)* $$U_{m=1,j} = V_{m=1,j} + \varepsilon_{m=1,j} = \sum_i (\beta_i * X_{i,j}) + \varepsilon_{m=1,j}$$

Where:
$U_{m=1,j}$ is the Utility for an alternative $j$.
$V_{m=1,j}$ is the Structural Utility when choosing an alternative $j$.
$\beta_i$ is the parameter weight for $X_{i,j}$
$X_{i,j}$ is the value of the attribute $i$ of alternative $j$.

$\varepsilon$ is the Error component for the overall model, that is assumed to be a standard Gumbel distribution.

The Stated Choice Experiment will present choice tasks to the homeowners and will let him/her choose their personal preference. The experiment offers alternative packages including a set of attributes that are expressed in levels ($X_{i,j}$) and the alternative not to refurbish ($\rho$). With the stated choice model, the parameter weights ($\beta_i$) for the attribute levels ($X_{i,j}$) and ($\rho$) can be estimated. Levels define the possible performances per attribute. A reference level is chosen (L0) to determine the parameter weights of the other attributes' levels in relation to L0. The sum of the attributes and the parameter weights explains the gained utility of an alternative $j$. Collecting a high number of choices (+200), the estimated results yield statistically significant weighting factors of attributes.

### 5.1.2 Probability of choosing a package

The probability of choosing a solution, whether $m = 0$ or $m = 1$, can be determined using the probability **Formulae 18 and 19**, respectively. To evaluate the alternative probability, the structural utility $V_{m=1,j}$ from the decision made for alternative $j$, can be applied in the probability **Formula 19**. The exponent utility of the observed alternative is placed in the numerator. The sum of the exponent utilities of all alternatives are in the denominator.

*(18)* $$P_{m=0} = \frac{exp^{\rho}}{exp^{\rho}+\sum_j exp^{V_{m=1,j}}}$$

Where:

*(19)* $$P_{m=1,j} = \frac{exp^{V_{m=1,j}}}{exp^{\rho}+\sum_j exp^{V_{m=1,j}}}$$

Where:

$P_{m=1,j}$ is the probability that the analysed alternative $j$ is preferred over all alternatives (including no refurbishment option).

$exp^{V_{m=1,j}}$ is the exponent of the structural utility of the observed alternative $j$.

$exp^{\rho}$ is the exponent of the structural utility of no refurbishment $\rho$.

### 5.1.3 Model performance

The model estimation is performed in R-Studio. The model performance is calculated with McFadden´s rho square, see **Formula 20**. The multinomial package in R estimates the log likelihood $log\ (L_c)$ of the performed attributes. The log likelihood of the null model $log\ (L_{null})$ explains the model at L0. The $Rho^2$ yields a value between 0 and 1, where 0 shows no predictability of the estimates and 1 shows full predictability. In order to achieve a good probability with the model, a minimum value of 0.2 must be reached *(McFadden et al., n.d).*

*(20)* $$Rho^2 = 1 - \left(\frac{log\ (L_c)}{log\ (L_{null})}\right)$$

Where:

$Rho^2$ is the goodness of fit of the model

$\log\ (L_c)$ is the log likelihood of the estimated model

$\log\ (L_{null})$ is the log likelihood of the null model

## 5.2 Experiment design

### 5.2.1 Refurbishment Packages

The refurbishment scenarios, that are used within the stated choice experiment, are based on the calculations from **Chapter 4 Evaluation System.** With the goal to achieve no-regret scenarios, the experiment design offers homeowners to choose from realistic packages. The informative aspects regarding the operational and material related performances plays an important role in this design. Letting homeowners choose from alternatives leads to new insights regarding the willingness to make compromises and certain trade-offs between the three key aspects of sustainability.

The refurbishment package 1 and 2 (P1 and P2), as illustrated in **Table 27**, include insulation improvements for wall and roof. The minimum of two refurbishment measures per package are taken to guarantee financial subsidy. Further, taking two material-based measures, ensures an immediate decrease of energy consumption, with low investment cost, when comparing to window replacement and technical upgrading for heating systems. The package 1 is realised via injecting insulation material inside the cavity space of wall and roof, the package 2 is made via a second wall inside the house. Each package has been assigned with material scenarios (P1 M1-M2, and P2 M1-M3). Depending on the thermal improvement per package, and the used material, the energy reduction potential, the $CO_2$ reduction and the comfort improves, see **Table 28**.

| **Insulation Package** | **Unit** | **P1** | | **P2** | | |
|---|---|---|---|---|---|---|
| | | M1 | M2 | M1 | M2 | M3 |
| Installation method | | Injection | Injection | Second layer inside | Second layer inside | Second layer inside |
| Rc-Value (Wall, Roof) | (K·m²)/W | 1.7, 2.5 | 1.7, 2.5 | 4.0, 6.5 | 4.0, 6.5 | 4.0, 6.5 |
| Thickness (Wall, Roof) | cm | 6 cm, 8 cm | 6 cm, 9 cm | 14 cm, 22 cm | 14 cm, 23 cm | 15 cm, 25 cm |
| Material | | EPS | Glass Wool | Glass Wool | Rock Wool | Wood Fibre |

**Table 27 Package definition**

| **Package Performance** | **Unit** | **P1** | | **P2** | | |
|---|---|---|---|---|---|---|
| | | M1 | M2 | M1 | M2 | M3 |
| Investment cost (with subsidy) | € | 2700 | 2630 | 2900 | 3500 | 3730 |
| Gas savings | m³/yr | 230 | 230 | 360 | 360 | 360 |
| Gas cost savings | €/yr | 200 | 200 | 300 | 300 | 300 |
| $CO_2$ savings | $kgCO_2$/yr | 330 | 440 | 572 | 530 | 605 |
| Street noise reduction | % | 25% | 50% | 50% | 50% | 70% |
| Comfort improves | No/Yes | No | No | Yes | Yes | Yes |

**Table 28 Package Performance**

Taking the package performance as reference, the experiment is designed, and the following attributes and levels are created.

### 5.2.2 Attributes and Levels

The experiment will give the respondent a choice out of two packages, which repeatedly represents six attributes, see **Table 29**. It presents a combined knowledge of application method, one-time investment cost, operational energy saving juxtaposed to payback time in years, as well as includes the operational and embodied carbon footprint. Moreover, comfort aspects are represented in the form of noise disturbance and draft through the attic. Two levels are defined per attribute. For the experiment an orthogonal and a simple fractional factorial design is used *(Hensher et al., 2015).*

| **Attribute** | **L0** | **L1** |
|---|---|---|
| In which way will insulation be installed? | Injected into the existing wall and roof, from the outside | Extra inside wall and inside roof (15 cm thick) with insulation plate behind it |
| What does it cost? | One-time 2500 euro | One-time 3500 euro |
| How much energy can be saved? | Annually 300 euro (this makes 1800 euro after 6 years and 3600 euro after 12 years) | Annually 500 euro (this makes 3000 euro after 6 years and 6000 euro after 12 years) |
| How much CO2 can be saved yearly? | 400 kg (equivalent to the effect of planting 20 trees) | 800 kg (equivalent to the effect of planting 40 trees) |
| How well does insulation reduce street noise? | Fair (25% less) | Good (50% less) |
| Does insulation improve comfort? | NO, only energy reduction. | YES, the draught in the house disappears. |

**Table 29 Attributes and Levels**

Homeowners will each time make their choices based on comparing insulation package 1 and 2. Repeating this decision-making process five times per person allows to analyse which attributes at which level is preferred by the participant and yields thus a higher probability to be chosen in future refurbishment projects. On one hand the participating homeowners will gain insight in a multi objective selection process that stays in line with sustainable development goals. On the other hand, energy collectives gain new insight in an efficient decision-making process when purchasing materials collectively in refurbishment projects.

### 5.2.3 Choice experiment

In order to guarantee random combination of provided packages a simple fractional factorial design was applied. Factorial design with 6 attributes and 2 levels (2^6) equals to 64 possible combination, where 8 profiles were created and used. Out of 8 profiles someone can choose 8*7/2 = 28 possible pairs, choice tasks. To offer people pairs of the profiles to choose from, the packages can be combined in order AB and BA (56 package combinations). Out of these 28 pairs, groups of five choice tasks were presented towards the participants. One choice task can be seen in **Figure 37**. It shows three options to select, “Insulation Package 1” “Insulation Package 2” and “None of these”. The HTML code for each choice task was coded. Find the 28 choice tasks and the full html code in **Appendix F.**

The online platform Lime Survey[66] is used as online environment to execute the data collection. A PIN code was used that selects predefined sets of 5 choice situation for every user individually. 30 x 5 choice sets were pre coded in Lime Survey. This guarantees a random presentation from the initially 28 choice tasks per user.

[66] https://www.limesurvey.org/

| Attribute | Insulation package 1 | Insulation package 2 |
|---|---|---|
| In which way will insulation be installed? | Injected into the existing wall and roof from the outside | Extra inside wall and inside roof (15 cm thick) with insula-tion plate behind it |
| What does it cost me? | One-time 2500 euro | One-time 3500 euro |
| How much energy can be saved? | Annually 300 euro<br>(this makes 1800 euro after 6 years and 3600 euro after 12 years) | Annually 500 euro<br>(this makes 3000 euro after 6 years and 6000 euro after 12 years) |
| How much CO2 can be saved yearly? | 400kg (equivalent to the effect of 20 trees) | 800kg (equivalent to the effect of planting 40 trees) |
| How well does insulation reduce street noise? | Fair (25% less) | Good (50% less) |
| Does insulation improve comfort? | YES the draught in the house disappears | NO only energy reduction |

Insulation package 1 | Insulation package 2 | None of these

**Figure 37 Attribute and Level in the form of Insulation package 1 and 2**

## 5.3 Data

### 5.3.1 Data collection and data cleaning

The target group for the data collection in this thesis are energy collectives' members, mainly homeowners. Multiple interviews and presentation of the experiment towards four energy collectives were performed. HIER Opgewekt, a branch organisation which maintains information about all executing collectives throughout the Netherlands prompted the experiment in their newsletter. 040energie in Eindhoven, Best Duurzaam from Best and AlexEnergie from Rotterdam were partners who offered support by distributing dedicated survey links amongst their members.

In particular 040energie supported this research in the form of interviews and ongoing online calls to adapt the experiment (calculation) to the demands of the collectives. To stimulate the homeowner to participate, 040energy offered a lottery to win a free of charge home visit and consultancy for building refurbishments. 10 lotteries for each 100€ value were to win. The promotion of the survey via newsletter and personal email invitations happened in the end of April 2020, the actual survey was conducted over May 2020.

The data was cleaned by removing the testing phase and participants who did not finish the questionnaire. Furthermore, a time constraint was assigned to people who spent too long or too little time. A time distribution cut by 2,0 % from both sides includes people who spent between 4.9min and 49min. In total, 478 participants, throughout three collectives and other individuals were counted, see **Table 30**.

| Collective | Male | Female | Others | Total | % |
|---|---|---|---|---|---|
| 040energie | 319 | 63 | 7 | 389 | 81% |
| Best Duurzaam | 55 | 4 | 0 | 59 | 12% |
| AlexEnergie | 3 | 0 | 0 | 3 | 1% |
| Individuals | 20 | 7 | 0 | 27 | 6% |
| Total | 397 | 74 | 7 | 478 | 100% |

**Table 30 Experiment Participants**

### 5.3.2 Respondents characteristics

Before and after the choice experiment, personal and building related questions are asked. Socio demographics, such as gender, age, income and education level in combination with the experiment result are meant to create conclusion per target group and future potential to invest in refurbishments. Building typologies and households constellation bring insights into energy consumption distribution and will be juxtaposed towards assumptions made in literature. For instance, buildings constructed between 60s and 90s need most attention for refurbishment concept.

#### Age and gender

Commonly asked are gender and age. It gives information whether different age and gender groups find different sustainable criteria relevant. For instance, if elderly homeowners are keener to financially invest higher in order to reduce $CO_2$ footprints, while younger people find comfort and indoor environment more important. Age groups from 18-30, 31-50, 51-65, 66-75 and >75 were stated.

#### Educational level

The educational level was asked in the form of the highest finished education level, according to Dutch standards. Firstly, lower education as VMBO, MAVO, MBO 1 and HAVO, VWO, MBO 2-4, and higher education as HBO, WO Bachelor, WO masters, PhD.[67]

#### Gross income per household per year

The gross income per year for owner occupation is generally higher than for social housing tenants. The categories are presented in six steps, reaching from less than 10,000€, 10,000€-30,000€, 30,000€-50,000€, 50,000€-75,000€, 75,000€-100,000€ and more than 100,000€ gross income per year per household. The data were retrieved from the CBS data[68].

#### Gas consumption per month

This gas consumption per household is relevant to understand if homeowners do rely on gas as a resource and to what extent. Five levels are introduced, <50€/m, 500-100€/m, 100-150€/m, >150€/m and "I don´t know". In particular interesting is the correlation of gas consumption towards the construction year. The assumption yields, the older the building the higher the chances of using gas instead of electricity. It has to be noted, that for future research another category, namely "no gas" should be added. It is possible that homeowners step away from gas sooner.

#### Construction Year and Building Typology

The construction year and building typology are a crucial information to understand the chosen packages by the experiment's participants. As mentioned earlier, the assumption from the literature review is that the older the building the more energy is consumed, thus the more likely the occupant chooses to refurbish. This statement could be analysed in combination of building typology, construction year and the gas consumption, remains however out of scope for this thesis.

#### Household composition

The household constellation can have directly influence towards the decision made regarding refurbishments. The survey distinguishes between single with and without children as well as a couple with and without children.

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[67] https://longreads.cbs.nl/trends18-eng/society/figures/education/

[68] https://www.cbs.nl/nl-nl/maatwerk/2020/45/huishoudens-naar-inkomensklassen-regionaal-2018-2019

### 5.3.3 Analysis of sample

The above explained characteristics of respondents are further elaborate, starting with the personal questions. **Table 31** shows the descriptive characteristics for socio demographics and household compositions. The primary respondents are male with 83% share followed by female with 17%. Furthermore, the participant age ranges from dominating 51-65 (40%), followed by 66-75+ (38%) and 18-50 (22%). This number respectively correlates with the household composition, that shows that mainly couples without children (50%) and couple with children living at home (30%). Highly educated with high income level are predominant in the sample. The majority building typology are terrace houses, single family and detached houses constructed between 1946-2005. This assessment stands in line with the literature review conducted on building typologies. Finally, the gas consumption is relatively high in the sample and is on average 100€/month. The samples where primarily take in Eindhoven area.

| **Socio-economic characteristics** | | **Housing characteristics** | |
|---|---|---|---|
| Man | 83% | Single | 16% |
| Woman | 17% | Single with children | 4% |
| Age 18-50 | 22% | Couple with children | 30% |
| Age 51-65 | 40% | Couple without children | 50% |
| Age 66-75+ | 38% | Terrasse House (Rijwoning) | 39% |
| Low educated | 21% | Detach house (2 onder 1 kap woning) | 27% |
| High educated | 78% | Single-family (Vrijstaande woning) | 25% |
| Household yearly gross income, less than 50.000€ | 26% | Appartement and others | 9% |
| Household yearly gross income, 50,000€–100,000€ | 47% | Constructed <1946-1974 | 36.5% |
| Households > 100,000€ | 14% | Constructed 1975-1991 | 36.5% |
| Do not want to share this information | 12% | Constructed 1992- 2005+ | 27% |
| | | < 50 €/month – 100 €/month | 50% |
| | | 100 €/month – > 150 €/month | 40 % |
| | | Don't know this information | 10 % |

**Table 31 Descriptive Statistics of sample**

#### 5.3.3.1 Psychosocial health and comfort variables

Homeowners were asked to scale the level of inconveniences of health and comfort related attributes. A Likert scale reveals that homeowners (N=478) show an average concern of noise disturbance of 2.53 and draft in the attic of 1.91. Less concern are damp sport and dry air, see **Table 32**.

| **On a scale from 1 (never), 3 (medium) to 5 (often), how often do you suffer from:** | **Average 1.95** |
|---|---|
| noise disturbance from the outside? | 2.53 |
| draft (for example in the attic). | 1.91 |
| damp spots / mold in bathroom, toilet or / and kitchen. | 1.54 |
| Dry air (dry throat or nose). | 1.81 |

**Table 32 Psychosocial variables**

#### 5.3.3.1 Attitude towards sustainability

The awareness over environmental concerns were asked with two questions, see **Table 33**. The participants (N=478) rated themselves high in their daily life actions to prevent waste and plastic consumption. Also, high average yields when asking if climate change is more important than economic concerns.

| On a scale from 1 (not at all), 3 (I don't know) to 5 (totally agree), do you agree with the following statement? | | Average 4.05 |
|---|---|---|
| | I act environmentally conscious, for example by separating waste and using less plastic. | 4.20 |
| | I think mitigating global warming is more important than improving the economy. | 3.88 |

**Table 33 Environmental awareness**

## 5.4 Result

### 5.4.1 Estimation result for general model

The estimated results yield the coefficients for each attribute variable, L1 (L0 is taken as a reference), see **Table 34**. The first two columns show the attributes and the level definitions. The coefficients *($\beta$)* represent the utility weights of the attributes. The $\beta$´s of the multinomial logit model were obtained with R Studio. The standard errors allow to calculate the statistical significance of the outcome, where * is a 10% significance and *** is a 1% significance. All attributes are highly statistically significant.

McFadden's rho square ($\rho^2$) is used to describe the model's goodness of fit. The log-likelihood of the estimated model ($LL_\beta$) reveals -2274.5, and the log-likelihood of the Null model ($LL_0$), the ln (0.33) multiplied by the number of choice situations, yields -2649.70. The adjusted Rho² results with 0.142, that shows a very low predictability of the model.

The reference package ($X_j$=*0*) is the combination of levels L0 of all the coefficients. The constant indicates the preference of homeowners whether to refurbish or not to refurbish. The coefficient equals -0.500 and is statistically significant. The negative sign shows that the option not to refurbish has overall a negative effect and people tend to prefer refurbishing their homers. Further, the reference package (L0) is defined by:

L0 for installation of insulation via cavity injection.
L0 for investment costing with a one-time payment of 2500€.
L0 for energy reduction potential of 300 €/yr.
L0 for $CO_2$ footprint reduction by 400 $kgCO_2$/yr.
L0 for noise reduction by 25%.
L0 for no comfort improvement.

A positive coefficient by level L1 of an attribute indicates that changing the level from L0 to L1 increases utility. Meaning that the participants find L1 more appealing than L0. While a negative effect shows less utility, meaning more importance towards the reference model (L0).

This behaviour can be clearly seen in the results, see **Table 34**. Taking the attribute installation method as an example. The utility of choosing inside insulation compare towards the cavity injection yields relatively low preference, shown with a negative effect of -1.143. In fact, this measure shows the most negative effect, that concludes that inside layer, and consequentially the construction work and decrease of living space is highly unattractive for homeowners.

The cost attribute represents the one-time payment for the installation. Due to a relatively low difference of only 1000€ towards the base model, the cost coefficients yield a low negative effect of -0.230. This shows that homeowners have only little tendency to invest in lower monetary value. The next attribute, the energy reduction value, clearly shows that homeowners tend to reduce energy in higher amounts. An annual energy reduction of 500€/yr is highly preferred by a positive coefficient of 0.53 (50% more than L0).

The $CO_2$ footprint reduction shows a significant coefficient with a positive effect of 0.321. This implies that overall homeowners do value carbon reduction when refurbishing their homes. A higher reduction of 800kg$CO_2$/yr is preferred by 30% than 400kg$CO_2$/yr. However, it shows a lower coefficient than the energy reduction coefficients. It can be argued that people value 400kg$CO_2$ reduction less than 200€/yr energy reduction.

Finally, the health and comfort attributes, namely noise reduction and comfort improvement are analysed. The positive coefficient of a noise reduction by 50% is significant and indicates that homeowners value noise reduction measures relative to no improvement. Similarly, the coefficient of comfort improvement for L1 yields a positive effect and shows significantly that homeowners prefer to improve comfort additionally to the energy reduction.

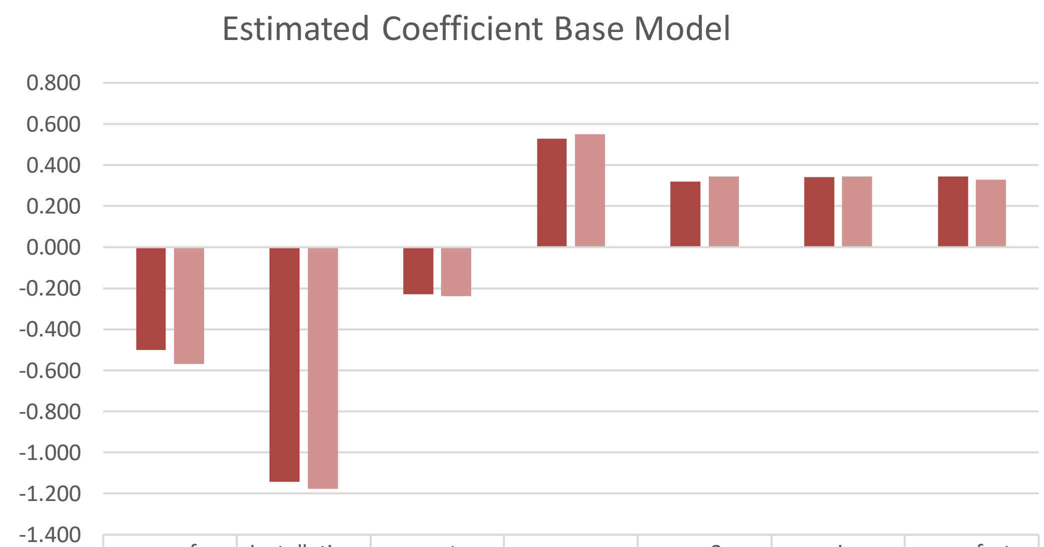
| **Attributes** | **Levels** | | **Coef. (β)** | **Std. Error** | **z-value** |
|---|---|---|---|---|---|
| No refurbishment | No refurbishment | | -0.500 | 0.086*** | -5.8168 |
| Installation method | L0 Injection | | 0.00 | | |
| | L1 Inside | | -1.143 | 0.062*** | -18.5174 |
| Investment Cost | L0 2500 € | | 0.00 | | |
| | L1 3500 € | | -0.230 | 0.061*** | -3.7672 |
| Energy reduction | L0 300 €/yr | | 0.00 | | |
| | L1 500 €/yr | | 0.530 | 0.063*** | 8.4457 |
| $CO_2$ reduction | L0 400 kg$CO_2$/yr | | 0.00 | | |
| | L1 800 kg$CO_2$/yr | | 0.321 | 0.064*** | 5.0081 |
| Noise reduction | L0 25% | | 0.00 | | |
| | L1 50% | | 0.341 | 0.066*** | 5.1621 |
| Comfort improvement | L0 No | | 0.00 | | |
| | L1 Yes | | 0.345 | 0.063*** | 5.4609 |
| Signif. codes: | 0 '***' | 0.001 '**' | 0.01 '*' | 0.05 '.' | 0.1 ' ' 1 |
| #respondents | 478 | | | | |
| #choice situation | 7170:3 = 2390 | | | | |
| $LL_\beta$ | -2274.5 | | | | |
| $LL_0$ | -2649,7 | | | | |
| $\rho^2$ | 0.141 | | | | |

**Table 34 Estimated Results General Model**

The estimated results, when comparing L1 to L0, can be concluded following the earlier assessed socio-demographics. Homeowners have on average higher annual income than for instance social housing tenants. The low negative coefficient of higher investment cost shows that people are willing to invest. Furthermore, homeowners show high education levels as well as good environmental awareness towards global warming issues. This actual behaviour is reflected in the preference of choice to reduce carbon emission and improve comfort-related attributes. The psychosocial health analysis shows that noise-related concerns are dominant and thus influence the homeowner's decision to choose a measure to reduce noise when refurbishing their home.

### 5.4.2 Cross effect for energy collectives

Multiple energy collectives contributed to this experiment. The cross-effect analysis for the estimated results per collective group was run via the multinomial logit model. Dominating groups are, 040energie, best Duurzaam and individuals (that contain AlexEnergie). The estimated coefficients of the multinomial logit are shown for the general model and per energy collective, where 040energie is identified as the reference model and the effects for Best Duurzaam and individuals are estimated in deviations, see **Appendix F.** In there, the number of participants is shown in the bottom line. Most participants are from 040Energie and yield as only group significant coefficients for all attributes. Best Duurzaam and individual participants don't show statistically significant difference from 040energie. People from different collectives seem to have comparable preferences. **Figure 38** shows the statistically significant coefficients for the base model and the energy collective 040Energie. It can be concluded that the coefficients for 040Energie perform similar to the base model. Therefore, differences in the groups will not be considered and further analysis will be conducted solely for the base model.




| | no ref. | installation | cost | energy | co2 | noise | comfort |
|---|---|---|---|---|---|---|---|
| Model (N=478) | -0.500 | -1.143 | -0.230 | 0.530 | 0.321 | 0.341 | 0.345 |
| 040energy | -0.568 | -1.178 | -0.237 | 0.552 | 0.345 | 0.345 | 0.329 |

**Figure 38 Estimated Coefficients General model and 040energie**

### 5.4.3 Willingness to pay

The willingness to pay (WTP) introduces the monetary value of an attribute. The level coefficients are determined and will be put independently in ratio to the cost coefficient and multiplied with the range of investment cost. **Formula 21** describes the WTP for any attribute *(Ossokina et al., 2019).*

$$WTP_j = \frac{\beta jn}{\beta c} * 1{,}000\ € \quad (21)$$

Where:
$\beta jn$ = coefficient of any chosen attribute, L1.
$\beta c$ = coefficient of cost attribute L1.
1,000€ = cost range of L0 (2,500€) to L1 (3,500€)

In **Formula 21**, the coefficients of the general model are used. It determines the willingness to pay for changing an attribute from Level 0 to Level 1. The resulting negative WTP can be directly inverted, see **Figure 39**. The WTP for homeowners for no refurbishment and an installation for an inside wall and roof shows a negative value. The option not to refurbish shows a WTP of -2,173€ and for inside insulation -4,980€.

Homeowners are willing to invest 2,300€ for energy refurbishment when the annual energy reduction is 200€ per year. The experiment assumed a time span of 12 years for the refurbishment investment, which creates a long horizon. Accepting an energy reduction of 200€ per year for an investment of 2,300€ seems therefore to be a fairly rational decision. The WTP to reduce the carbon footprint remains relatively low, compared to the energy investment. For 400kg $CO_2$ reduction per year homeowners are willing to invest up to 1,400€. The savings of 400kg$CO_2$/yr equals 20 trees to be planted. Therefore, homeowners are willing to pay 70€ to plant one tree. This seems to be a high investment considering market prices of trees in the garden centre. One could buy up to three trees for 70€[69]. Moreover, the homeowners WTP for a noise reduction and for an improvement of the indoor environment yields 1,500€. This high willingness to invest seems logical, since homeowners show relatively high concerns about nuisance and draft, considering the socio-demographics of the experiments´ participants (**Section 5.3.3 Analysis of sample**). Attention must be given to the model assumption of linear behaviour. A doubling of the WTP in ratio towards the doubling effect of the level cannot be assumed. Noise reduction must be treated carefully, due to the logarithmic curve behaviour of decibel (dB).

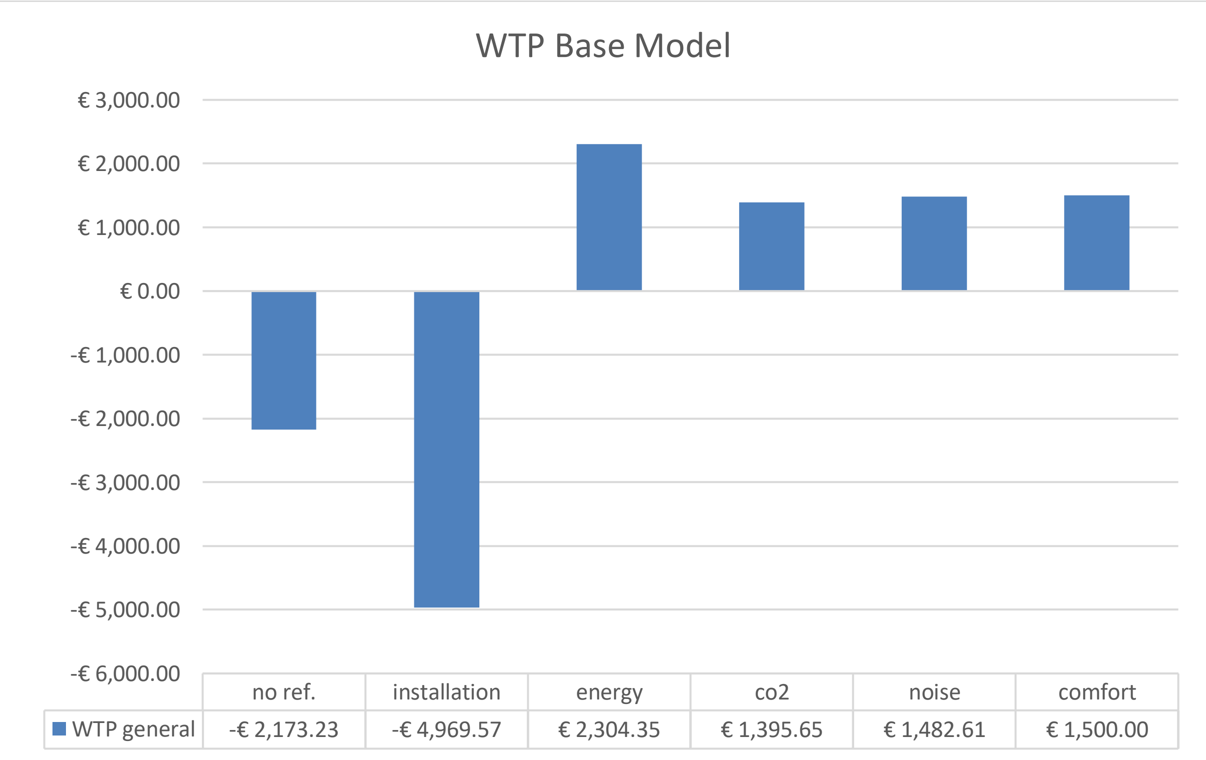



**Figure 39 WTP for difference of L0 to L1**

## 5.5 Sensitivity analysis

The sensitivity analysis studies the sensitivity of the estimated results of the general model, as explained in **Section 5.4.1 Estimation result for general model**. Heterogeneity of the participants that evaluate the attributes can be distinguished by socio-demographics, health concerns and energy

[69] https://www.baumschule-newgarden.de/laub-und-nadelgehoelze/nadelgehoelze/fichte-picea/?p=1

consumption. This has the potential to cluster target groups in order to create more adaptable refurbishment packages. The following studies heterogeneity of the participating homeowners (N=478) in terms of gender, age, noise disturbance and gas consumption. A cross effect analysis determines whether differences in socio-demographic groups influence the propensity of any given attribute. For instance, whether men or women preserve the attribute of investment cost differently, or if homeowners with different levels of noise complaints behave differently towards noise reduction measures. If the analysis yields a statistically significance, then the analysed group shows different preferences. Find all tables in **Appendix F.**

### 5.5.1 Gender

In this research primarily men participated. The cross effect shows that women and men perform the same throughout the attributes, except of the option not to refurbish and the investment cost. Results show that men tend to refurbish their homes slightly more than women do (about 28%). Also, gender difference matters in regard to accepting higher investment costs. It seems that women tend to invest much lower than men do. Men show a higher tendency to invest than women do (about double as much). Find the tables in **Appendix F.**

### 5.5.2 Age

Age groups were distinguished between two groups, younger and older than 50 years. The experiment sample shows that especially people around 50 years participated. The cross effect shows that there is a significant difference in choosing no refurbishment, energy reduction and $CO_2$ reduction. Homeowners older than 50 people seem to have a higher tendency to financially invest more in higher energy reduction measures than younger people have. On the contrary, homeowners younger than 50 years seem to have higher interests to reduce $CO_2$ footprints. Thus, it can be concluded that age matters in the decision to refurbish and in the level of ambition they have to reduce energy and $CO_2$ reduction. The reason could be that younger people might live in buildings with higher energy efficiency and also have a higher environmental awareness towards carbon reduction, see **Table 35.**

| **Attributes** | **Older (> 50years)** | | | |
|---|---|---|---|---|
| | Coef. (β) | | Std. Error | |
| No refurbishment | -0.419 | | 0.096*** | |
| + younger (<50yrs) | | -0.475 | | 0.223* |
| Installation technique | -1.137 | | 0.069*** | |
| + younger (<50yrs) | | -0.053 | | 0.152 |
| Investment Cost | -0.197 | | 0.068** | |
| + younger (<50yrs) | | -0.130 | | 0.150 |
| Energy reduction | 0.459 | | 0.070*** | |
| + younger (<50yrs) | | 0.330 | | 0.155* |
| $CO_2$ reduction | 0.244 | | 0.072*** | |
| + younger (<50yrs) | | 0.356 | | 0.159* |
| Noise reduction | 0.378 | | 0.074*** | |
| + younger (<50yrs) | | -0.114 | | 0.163 |
| Comfort improvement | 0.307 | | 0.070*** | |
| + younger (<50yrs) | | 0.180 | | 0.159 |
| #respondents | 375 | | | |
| | | 103 | | |

**Table 35 Coefficients per age group**

### 5.5.3 Income level

The income level was defined in gross household income of smaller and bigger than 50,000€ annually. The significant difference is shown in the interest of refurbishing, in the installation technique, in $CO_2$ reduction measure, in noise reduction and comfort improvement. Low income households, have a higher tendency not to refurbish, meaning households with higher income tend much higher to refurbish. The households with less income seem to have less problem with an inside insulation than higher income groups. Moreover, higher income yields more likelihood to invest into $CO_2$ reduction, then lower income. For noise reduction and comfort improvement, differences are visible in high income and people who do not want to share their income, see **Table 36**.

| **Attributes** | **High income (>50,000€/yr)** | | | |
|---|---|---|---|---|
| | Coef. (β) | | Std. Error | |
| No refurbishment | -0.645 | | 0.113*** | |
| Low income (<50,000€/yr) | | 0.338 | | 0.198. |
| Income n.a. | | 0.479 | | 0.269. |
| Installation technique | -1.353 | | 0.081*** | |
| Low income (<50,000€/yr) | | 0.531 | | 0.141*** |
| Income n.a. | | 0.360 | | 0.200 |
| Investment Cost | -0.193 | | 0.079* | |
| Low income (<50,000€/yr) | | -0.074 | | 0.139 |
| Income n.a. | | -0.066 | | 0.198 |
| Energy reduction | 0.593 | | 0.081*** | |
| Low income (<50,000€/yr) | | -0.097 | | 0.144 |
| Income n.a. | | -0.226 | | 0.203 |
| $CO_2$ reduction | 0.398 | | 0.083*** | |
| Low income (<50,000€/yr) | | -0.282 | | 0.146. |
| Income n.a. | | 0.174 | | 0.211 |
| Noise reduction | 0.418 | | 0.086*** | |
| Low income (<50,000€/yr) | | -0.049 | | 0.152 |
| Income n.a. | | -0.429 | | 0.209* |
| Comfort improvement | 0.465 | | 0.083*** | |
| Low income (<50,000€/yr) | | -0.225 | | 0.145 |
| Income n.a. | | -0.348 | | 0.204. |
| #respondents | 295 | | | |
| | | 127 | | |
| | | 56 | | |

**Table 36 Coefficients per income level**

### 5.5.4 Noise disturbance

In the psychosocial health and comfort analysis in **Section 5.3.3 Analysis of sample**, the participant ranked the noise disturbance in their current living situation. Where 1 = never, 3 = sometimes and 5 = very often. An average value of 2.53 was achieved and is therefore further investigated. The model was run for respondents who rate 1-2 as low noise disturbance and 3-5 with higher disturbance levels. The cross effect yields significant differences in the attribute investment cost and comfort improvement. A low level of noise complaint seems to have a positive effect to financially invest higher. This is unexpected, because it would be more logical if people with high disturbance would invest higher. Also, people with higher noise disturbance show a much higher significance in the comfort improvement. No significant difference in the noise attributes were found. Find the tables in the **Appendix F.**

### 5.5.5 Gas consumption

The gas consumption differs per household in levels reaching from <50€/month up to >150€/month. The following two groups are defined, households with lower gas consumption (<100€/month) and households with higher gas consumption (>100€/month). Results of the cross effect show that depending on the gas consumption the installation technique and noise reduction measure show significant differences. Gas consumption, in general, does not seem to have any effect on homeowner’s choice to invest into energy reduction and $CO_2$ reduction. Find the tables in the **Appendix F.**

The sensitivity analyse reveals insights in the likelihood of acceptance for attributes in refurbishment measures of different socio-demographic groups. Observation shows that primarily men with high income and high educational levels contributed to this experiment. It shows that this group has the highest likelihood of choosing refurbishment measures. The most important attributes are the installation method to be an injection of insulation materials and a high energy reduction potential. Older people tend to refurbish their homes more than younger people do. A possible explanation is that younger people already live in newer houses with a generally better energy performance. However, younger people tend to improve in higher environmental measures more likely. Moreover, higher income groups tend more to choose insulation packages than not to refurbish. Also, higher income classes mind an inside insulation layer much more than lower income group do. It could be argued that higher income classes can afford extra measures taken that avoid inside constructions, while lower income groups seek to refurbish either way. Noise level disturbance seems to have no significant influence on the noise reduction potential, which is unexpected. Also unexpected was that households with higher gas consumptions do not choose significantly more to reduce energy and $CO_2$, than households with lower gas consumptions. For future experiment it is recommended to provide information before the experiment is execute to alert households with high gas consumption about their carbon footprints and available carbon budget per household.

## 5.6 Result use case

The use case application towards the Terrace house (Rijwoning) is performed using five package definitions, see **Table 37**. The interval between the numeric level definition for investment cost and energy reduction is rather small. Therefore, a linear model is assumed, meaning a linear coefficient behaviour, using the slope as a constant. This assumption can only be used to support engineering design of one building. Upscaling the use case to a neighbourhood level requires further analysis.

| **Package Performance** | **Unit** | **P1** | | **P2** | | |
|---|---|---|---|---|---|---|
| | | M1 EPS | M2 Glass wool | M1 Glass wool | M2 Rock wool | M3 Wood Fibre |
| Investment cost (with subsidy) | € | 2700 | 2630 | 2900 | 3500 | 3730 |
| Gas savings | m$^3$/yr | 230 | 230 | 360 | 360 | 360 |
| Gas cost savings | €/yr | 200 | 200 | 300 | 300 | 300 |
| CO2 savings | kg$CO_2$/yr | 330 | 440 | 572 | 530 | 605 |
| Street noise reduction | % | 25% | 50% | 50% | 50% | 75% |
| Comfort improves | No/Yes | No | No | Yes | Yes | Yes |

**Table 37 Use Case application**

The performance values per package and the coefficients resulting from the multinomial logit are applied in the utility formula of **Section 5.1.2 Probability of choosing a package**. The sum of all utilities, that perform within the alternative, can be put in the exponent and results in the probability of an individual choosing this package. The experiment asked the participant to choose between three options, namely: No refurbishment, insulation package 1 and insulation package 2. The same logic is applied to analyse the probability of choosing one package over the other. The probability formula is applied to create pairwise comparisons for four scenarios: P1M1 EPS - P2M2 Glass wool; P1M1 EPS - P2M3 Wood Fibre; P1M2 Glass wool - P2M2 Rock wool; P1M2 Glass wool - P2M3 Wood Fibre, see **Figure 40**.

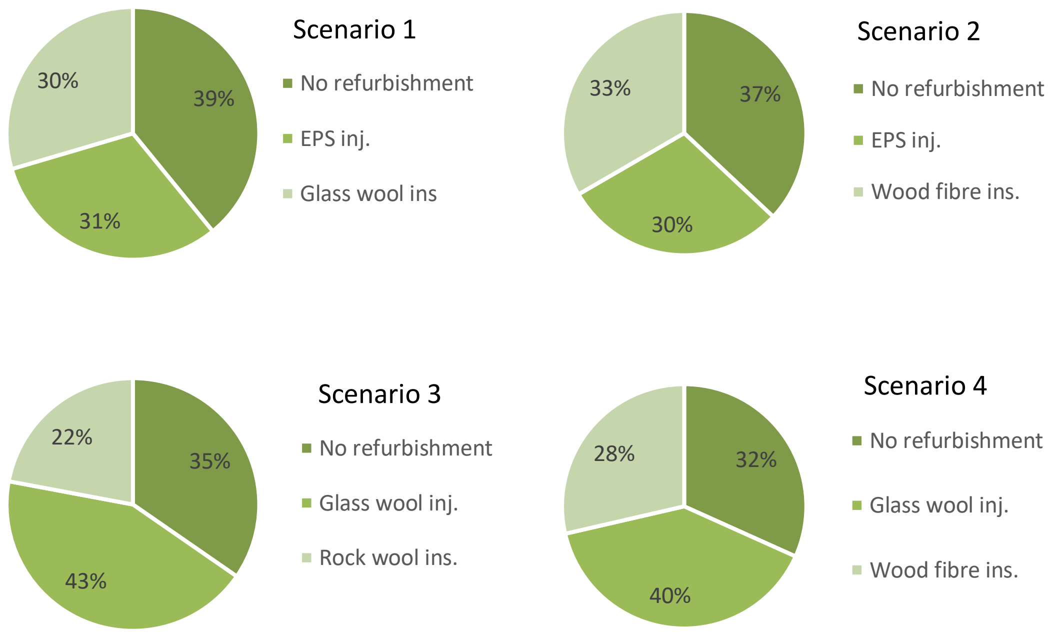



**Figure 40 Use Case Probably of accepting insulation packages**

Given the coefficients from the **Section 5.4.1 Estimation result for general model**, conclusion can be drawn about the likelihood of acceptance per package comparison. The first scenario compares the injectable EPS (P1M1) with the inside installed glass wool (P2M1). The EPS dominates by 1 percentage point. The second scenario presents the only comparison where P2 successed (P1M1 vs P2M3). The wood fibre is compared to injectable EPS. EPS shows a relatively low energy and $CO_2$ reduction. The wood fibre, however, higher energy and carbon reduction, plus noise cancellation and comfort improvement. In the third scenario the injectable glass wool (P1M2) clearly succeeds with 43% and presents the winner among all four scenarios. It shows low investment costs, good environmental footprint and street noise reduction. Thus, the glass wool performs the most attractive material throughout all solutions. In the scenario four, the glass wool (P1M2) and wood fibre (P2M3) were compared. Also, here the glass wool receives a higher acceptance than the wood fibre.

Results show that the option not to refurbish remains around 35% throughout all four package combinations. This seems logical, because not all participants are in the need to refurbish their homes with insulation measures. The package 2 has generally a lower acceptance rate, than package 1. This is because of a very negative coefficient for the inside insulation layer. On the contrary, package 2 considers higher energy and $CO_2$ reduction potentials. Also, higher comfort improvement and noise reduction coefficients are noticeable in the package 2, when applying all three materials.

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# CHAPTER 6

# Web-based assessment framework

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# 6 Web-based assessment framework

*This Chapter aims to combine the findings of Chapter 4 Evaluation System and the decision-making tool from Chapter 5 Preference Modelling. The proposed framework in Section 6.1 explains how the fundamental requirements of Chapter 3 Program of Requirements in accordance with the gained knowledge is designed. In Section 6.2 web development methods are used to elicit the user requirement. T9his contains an in-depth explanation of BIM exchange requirements and functional content requirements. In Section 6.3 the system requirements introduce the system architecture that satisfies all requirements. In Sections 6.4 and 6.5, the focus is on developing the design, by means of establishing all key components. This includes web page design, database and the data dictionary, as well as process maps. Finally, Section 6.6 and 6.7 is dedicated on the code implementation and evaluation of the web tool.*

## 6.1 Proposed Framework

The proposed framework **ROTUNDORO** allows engineers to evaluate and optimize refurbishment scenarios in a responsive web interface. The user-oriented tool focuses on the involvement of the construction engineers in the design process by letting her create refurbishment and materialisation scenarios. The proposed system aims to verify these scenarios according to the consumers´ choice of preference (potential market adoption), see **Figure 41**.

These assessments are done in the early design phase of collective refurbishments. The engineers are able to use the 3D BIM model (on the basis of IFC) and are able to perform the evaluation assessments with linked online hosted databases. It includes internally held calculations for operational performances and connection to other databases such as the Dutch national LCA database (NMD), Costing database (from manufacturers) and other material-related information (kennisbank.isso.nl[70]). The interactive and responsive tool allows to show comparisons between the packages in their performance criteria. At the final Section, the predicted probability of homeowners accepting the designed alternatives are presented.

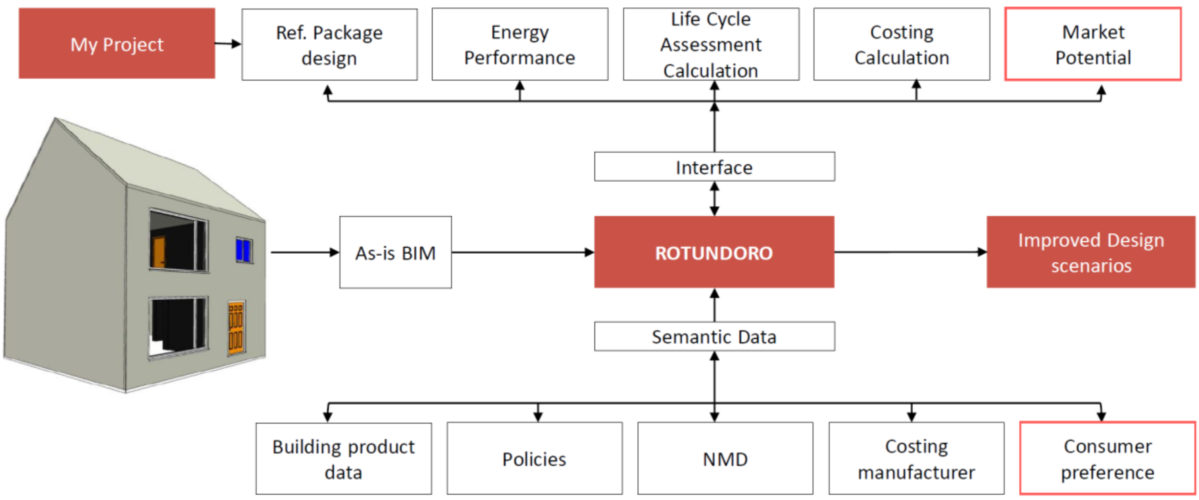



**Figure 41 ROTUNDORO Framework**

[70] https://kennisbank.isso.nl/publicatie/energievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen/2017/bijlage-3

The tool´s requirements are introduced in the **Chapter 3 Program of Requirements.** Engineering methods are used to translate these in a schematic development process, to clearly identify the deliverables of the web tool. The following two sections will focus on firstly, the user requirement elicitation, encompassing exchange, user and content requirements (**Section 6.2 User Requirement Elicitation**) and secondly the system requirements (**Section 6.3 System Requirements**).

## 6.2 User Requirement Elicitation

The requirement engineering (RE) approach is used to elicit the user requirements for the tool **ROTUNDORO**. It defines a process that enables web development and web application to be performed according to a user-centric approach. The motif is to satisfy involved stakeholder needs (goals), to define them into user requirements and to find a direct translation towards the system representation *(Escalona & Koch, 2004; Toma & Komazec, 2013).*

Firstly, the group and use case specifications are commonly performed at this point. The user of the developed web tool is the engineer and is hence the primary stakeholder and focus group to determine the user requirements. Furthermore, the engineer must comply in line with the clients´ (homeowners and energy collective) wishes and demands. Therefore, both stakeholders were considered in the requirement elicitation (as explained in Chapter 3). The use case definition helps to identify the overall context of the tool. That means, it shows the framework boundaries of the actual tool, as well as the pre-requisites before using the tool. The abilities and pre-sets of the ROTUNDORO tool are expressed in a) exchange requirements, b) functional user - and content requirements and c) system requirement.

*"A requirement is defined as a condition or capability that must be met or fulfilled by a system to satisfy a contract, standard, specification, or other formally imposed documents"*[71]

The exchange requirement is presented in the form of a data dictionary. It specifies the pre-requisites for the engineer to make use out of the developed tool. This includes the establishment of a 3D BIM model in line with data prerequisites as defined in the exchange requirements (**Section 6.2.1 Exchange Requirements**). The tool should be able to read the 3D model to perform refurbishment scenarios. Thereby the IFC schema with certain data structure is suggested to be used. Furthermore, the engineer is asked to utilize a web browser to access the tool and to sign-in or log-into the web tool.

The functional user and content requirements represent the heart of the tool performance. This encompasses multiple specifications, such as the functional and non-functional requirements as well as interface and navigational requirements *(Escalona & Koch, 2004)*. The functional requirements represent the system´s capabilities that must meet the user's objectives for instance, the system is required to read data, evaluate, and perform calculations. The non-functional requirements represent the system framework and its quality in terms of security and user friendliness *(Shukla, 2015)*. Furthermore, the site view specification and style guidelines specification are tangled in this step *(Toma & Komazec, 2013).* In the context of ROTUNDORO, the user's objective is the evaluation of refurbishment and material scenarios in respect of energy, LCA and costing performance within an interactive user experience.

[71] IEEE Standard 610.12-1990 as cited in Citied from Escalona & Koch, 2004, page 2.

Finally, the system requirements determine the successful implementing of the functional user requirements. Since the web tool indicates to be accessible from the web browser, the technology used to determine the system requirements underlies the theory of web-based assessment frameworks with the ambition to use federated databases on the web.

**Table 38** shows a step-by-step approach introducing the exchange requirements, the functional user, content requirement and the system requirements. The representation is listed in chronological order and indicates next to the functional description, two indices explaining the process of implementation. **C** stands for complexity of implementation, reaching from 1 to 5, where 1 = simple, 3 = medium, 5 = highly complex. **IP** stands for Implementing phase according to the level of implementation. *For the first cycle we identify five step approach, 1 = Initial Planning, 2 = Requirements, 3 = Analysis & Design, 4 = Data/Code implementation, 5 = Test and Evaluation.*

**Exchange requirements (Cycle 1)**

| | **The engineer has to ...** | **C** | **IP** |
|---|---|---|---|
| **3D digital BIM** | • Assess the building as-is performance. | 1 | 1-5 |
| | • Have knowledge regarding as-is energy performance (Gas heating, appliance electricity, DHOW gas/electricity). | 2 | 1-5 |
| | • Create a BIM model, including parametric enrichments to achieve LOD 300. | 1 | 1-5 |
| | • Comply with the exchange requirements (according to 6.2.1) | 2 | 1-5 |
| | • Have fundamental knowledge of client's objectives. | 3 | 1-5 |

**Functional User and Content requirements (Cycle 1)**

| | **The engineer wants to be able to...** | **C** | **IP** |
|---|---|---|---|
| **My Project** | • Create and store a new project, add specific building data (e.g.: using IFC). | 4 | 1-3 |
| | • Receive the primary energy consumption, the related operational carbon emission, and the energy label. | 3 | 3-4/5 |
| | • See resulting values in the form of table view and Pie Charts. | 3 | 3-4/5 |
| | • See the 3D BIM model as-is (Based Model). | 1 | 5 |
| **Refurbishment** | • Receive information about national policy and governmental subsidy regulation regarding energy and carbon refurbishment. | 1 | 1-5 |
| | • Perform refurbishment packages and compare results towards the base model in an interactive way (including operational energy, carbon and cost performance). | 4 | 1-4 |
| | • See the affected building elements in the 3D BIM model. | 5+ | 1-3 |
| **Material Application** | • Gain knowledge about material application methods. | 1 | 1-5 |
| | • Gain knowledge about installation possibilities and receive information about material characteristics, containing thermal knowledge, embodied energy and carbon, costing. | 3 | 1-5 |
| | • See the affected building elements in the 3D BIM model. | 5+ | 1-3 |
| **Life Cycle Assessment** | • Analyse embodied energy and carbon footprint per material package and in combination with operational energy and carbon performance. | 3 | 1-3 |
| | • Evaluate the LCA (embodied and operational performances) in the form of Pie Charts and on the 3D model. | 5 | 1-3 |

| | | | |
|---|---|---|---|
| **Costing** | • Analyse investment costing of material package and in relation to operational cost performances. | 3 | 1-3 |
| | • Evaluate the costing in the form of Pie Charts. | 5 | 1-3 |

| | | | |
|---|---|---|---|
| **Market Potential** | • Receive an overview of all performances established so far. | 2 | 1-5 |
| | • Find the trade off´s between sustainable key criteria based on insulation material. | 4 | 1-5 |
| | • Receive the market potential as the percentage probability of consumer preference. | 4 | 1-5 |

**System requirements (Cycle 1)**

| | **To comply with the functional user and content requirements, the system must ...** | C | IP |
|---|---|---|---|
| **Web tool** | • Be hosted on a server and accessible via the web browser. | 3 | 1-5 |
| | • Allow a semantic enrichment and connection between graphical and non-graphical building information. | 5 | 1-3 |
| | • Allow a connection/an input to external Databases. | 4 | 1-5 |
| | • Allow a BIM-based evaluation system by querying and validating the 3D model with the predefined data model. | 5 | 1-3 |
| **UI/UX** | • Allow active user interaction, rather than submission of forms. | 3 | 1-5 |
| | • Allow the user to interactively add and query project related information in a reactive web environment. | 1 | 1-5 |
| | • Allow adapting layouts to a variety of screen and window sizes within a responsive web environment. | 1 | 1-4 |
| | • Indicate results within the 3D model viewer, table view and in the form of a report. | 1 | 1-4 |

**Table 38 User and content requirements ROTUNDORO**

### 6.2.1 Exchange Requirements

The exchange requirements help the engineers with their creation of the BIM model. Prerequisites for the BIM model are intended to be kept simple and easy to apply for the engineer. Parametric enrichments are however mandatory to comply with the evaluation system from **Chapter 4 Evaluation System**. A common classification schema is mandatory to use in order to allow future semantic enrichments.

#### 6.2.1.1 BIM model

The assessment and documentation of the existing building is the starting point of the process. An as-is model in the form of a 3D building information model is performed. This is based on existing documentations that provide documentation of graphical and non-graphical definitions. Remember, that graphical information refers to the 3D geometries (objects) and non-graphical information describe the additional information (object attributes) that can be used with or without the geometry. The building(s) inventory itself can be done with technical drawings, laser scanning and point cloud modelling. Different from the as-built, the as-is model is a pure momentarily stocktaking and relies on historical knowledge about the building. So, maintenance work over the past years should be included too and added to the central geometry model (“the single source of truth”). An accurate documentation process to digitalize the existing building stock is an important prerequisite for refurbishment that is performed in the present but more importantly for future benchmarking purpose and buildings evolutionary traceability. For the sake of the latter argument, it is recommended to keep modelling within the archetype framework according RVO, construction time, style, building performance levels (see **Chapter 2 Literature Review**).

To document the as-is state a parametric 3D building information model is created. Software such as Autodesk Revit, Graphisoft Archicad, Allplan, or similar is recommended. Regardless which modelling software is chosen, the translation of the models native file format towards IFC is relevant. In order to accurately translate the model content to IFC two prerequisites are identified. The model must own graphical and non-graphical data. Firstly, graphical data includes an accurate handling of geometry of objects, and secondly non-graphical information is the enrichment of parametric information to the geometry. The latter needs to be added by the engineers manually. The level of detailing is bases on LOD 300. This emcopasses a modelling of each element and its separate layers. For instance, one wall building element has multiple material layers, such as brick wall – air surface – brick wall. The construction layer definition differs by building typology. Thus, modelling guidelines are crucial and formulate a fundamental step for any BIM model.

Find in **Chapter 4.1 Base model definition** the basic definition of the archetype used in this thesis. It is assumed in this study that any archetype has at least structural building elements, walls, roof, floors, as well as an insulation layer modelled on the outside, between or inside of the structural layer. Openings such as windows and doors.

To summarize, the following lists the necessary content related to building and material characteristics and parameters associated with the IFC definition, see **Table 39**. Find the shared parameter definition in **Appendix G.**

| | | |
|---|---|---|
| **Building shape, height, and true north orientation** | | |
| **Rooms and Spaces (refer to energy modelling)** | | |
| **Building elements (including Wall, Roof, Floors, Windows, Doors, Openings, Stairs, Fundament)** | | |
| Element ID (int) | IFCWALLTYPE | '0LY7ucsG17DeU2KDmTk$6v' = `852853` |
| Type Name (string) | IFCPROPERTYSINGLEVALUE | 'NLRS_41_AIR_80mm' |
| Element location | IFCDIRECTION,<br>IFCLOCALPLACEMENT | `0,0,-1`<br>'Location Line'<br>'Adjacent to' |
| **Building material layers per element: (Example #26177 (wall), #26698 (window))** | | |
| Material Name (string) | IFCMATERIAL | 'Analytical Surface - Air Surfaces' |
| Rc and U Value | IFCPROPERTYSINGLEVALUE | 'Thermal Resistance(R)',<br>$,IFCREAL(0.170212765957447),$ |
| Material Thickness (m) (double) | IFCPROPERTYSINGLEVALUE | 'Width',<br>$,IFCLENGTHMEASURE(80.),$ |
| Total Area ($m^2$) (double) | IFCPROPERTYSINGLEVALUE | 'Area',<br>$,IFCAREAMEASURE(65.1138185156662),$ |
| Glass Area ($m^2$) | IFCPROPERTYSINGLEVALUE | 'Glass Area',<br>$,IFCAREAMEASURE(4.13136),$ |
| Window Frame Area ($m^2$) | IFCPROPERTYSINGLEVALUE | 'Frame Area',<br>$,IFCAREAMEASURE(0.45904),$ |
| NL-SfB code | IFCPROPERTYSINGLEVALUE | 'NL-SfB',$,IFCTEXT('41'),$);<br>'NL-SfB',$,IFCTEXT('31'),$ |

**Table 39 Model View Definition, Base Model use Case – Rijwoning**

## Rc-Value, U-Value, Thickness, Area(s)

The refurbishment package definitions are primarily based on the thermal performances of building elements. Thus, the BIM as-is model must define the Rc-Values and U-values of the existing material layers. The engineer must enrich the materials with the lambda values ($\lambda$) that will in combination with the material thickness ($d$) retrieve the Rc-Value (keeping in mind that $Rc = \frac{d}{\lambda}$). Openings, such as windows and doors must be enriched with the as-is U-Values. Furthermore, the building elements and material areas are stored. Homogeneous building elements and materials include areas per default. For Windows on the contrary, it is crucial to apply parametric knowledge containing the Window Glass area and the Window Frame area (LCA performance requires a differentiation between frame and glass). This can be done via shared parameter and underlying calculations of the existing window area. 1/10 of the total window area was assumed to be framing and the remaining 9/10 was assumed to be the glass surface.

### NL-Sfb and NMD

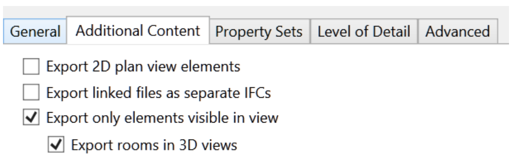
The NL-Sfb code needs to be applied to each element layer to allow linking the building elements with various material products, for example deriving from the NMD. A detailed analysis of both, the NL-SfB and the NMD data revealed several differences in element and product code. The most relevant building elements for refurbishment projects, in this thesis, are the insulation material layers. **Table 40** explains which building element and materials must be enriched with a particular NL-SfB code. A more elaborate table containing more elements can be found in the **Appendix G.**

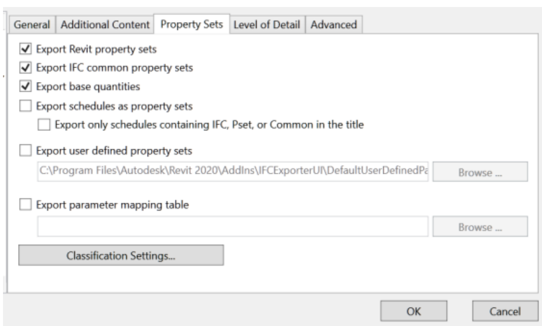
| | NL-SfB (element code) | NMD (product code) |
|---|---|---|
| Façade insulation (Buitenwandafwerkingen) | 41.0 | 41.02.038-41.02.046;<br>41.04.001-41.04.0046; |
| Roof insulation (Isolatielagen plat dak) | 47.0 | 47.07.002-47.07.024; |
| Roof insulation (Isolatielagen hellend dak) | 47.0 | 47.08.001-47.08.038 |
| Floor insulation (Vloerafwerkingen) | 43.0 | 43.03.001-43.03.024; |
| Exterior Wall windows (Buitenwandopeningen) | 31 | |
| Window frame (Buitenramen) | 31.1 | 31.02.001-31.02.020.<br>31.03.004-31.03.015; |
| Window Ramen (Buitenbeglazing) | 31.2 | 31.07.001-31.07.026 |
| Exterior Doors (Buitendeuren) | 31.3 | 31.04.002-31.04.010; |

**Table 40 BIM and NL-SfB Code**

### 6.2.1.2 BIM to IFC

In this thesis Autodesk Revit was used for the BIM model creation. Firstly, the IFC version “IFC 2x3 Coordination View 2.0” is used. Next, it is recommended to export only elements that are visible in a dedicated export view (3D View). Thirdly, a correct parameter export must be guaranteed. Within Revit there are three types of parameter creation. These are the system parameter, type and instance parameter (regardless of being project or shared parameters). In standard IFC export options, only system and type parameter are exported. However, since the engineer also might apply instance parameters in the form of shared parameters, such as the NL-SfB code per building element or instance, some additional export settings must be taken. These are “Export Revit property set”, “Export IFC common property sets” and “Export base quantities”, see **Figure 42.**



```
6173= IFCMATERIALLAYERSET((#26172),'Basic Wall:NLRS_41_AIR_80mm');
6176= IFCMATERIALLAYERSETUSAGE(#26173,.AXIS2.,.POSITIVE.,-40.);
6177= IFCWALLTYPE('0LY7ucsG17DeU2KDmTk$6v',#41,'Basic Wall:NLRS_41_AIR_80mm',$,$,
6178= IFCPROPERTYSINGLEVALUE('NL-SfB',$,IFCTEXT('41'),$);
```

**Figure 42 IFC export settings**

### 6.2.2 Functional user and content requirements (ROTUNDORO)

Once the building is documented in the form of a BIM model (as-is), the usage of the web tool ROTUNDORO starts. In this Section the focus is on the functional user and content requirements of the tool. The elicited requirements as listened in the **Table 38** are discussed and the User Experience (UX) proposal and tool design is introduced. This is done to evaluate input and outputs of the tool. Given the early application of the tool within the design phase, the usage of the tool must be easy to use with the maximum result.

#### 6.2.2.1 UML Use case

A UML use case diagram is created that helps to visually communicate between engineers and web developers. The elicited functional user and content requirements are put into the context of the web development. Unified Modelling Language (UML) use case diagrams are commonly used, as they present an abstract representation of scenarios that describe functional behaviour of systems *(Escalona & Koch, 2004)*. It will help to cluster involved actors and to identify the scope of activities performed within the use case system boundaries (ROTUNDORO) *(Aurum & Wohlin, n.d.)*.

As can be seen in **Figure 43** for the development of the web engineering process there are four major agents in the UML Use Case diagram. These are the engineers, using the web tool, the client (energy collectives and homeowners) collaborating with the engineers, the databases, allowing data aggregation between BIM (IFC data), NMD (LCA data) and manufacturers information (Costing) and most importantly the application programming interface (API) as being the intersection between user browser and the backend processing of data and algorithms. The user input of engineers and the development of the API and DB´s is represented by the student.

Each agent has active and passive tasks assigned (indicated with red and grey scaled arrows and boxes). While the engineers (and the energy collective) represent the forefront, shown as "Activity" to satisfy the functional user request, the API and the DB represent the background shown as "API In/Output" to guarantee that the system responds. Inside the system boundary (the grey dashed line around the tasks) four main sections are identified. These sections result from an in-depth analysis of user requirements of the engineer in comparison with the system's capabilities to support. They split the total tasks in four activity experiences. The user experience (UX) will be remembered when developing the user interface (UI).

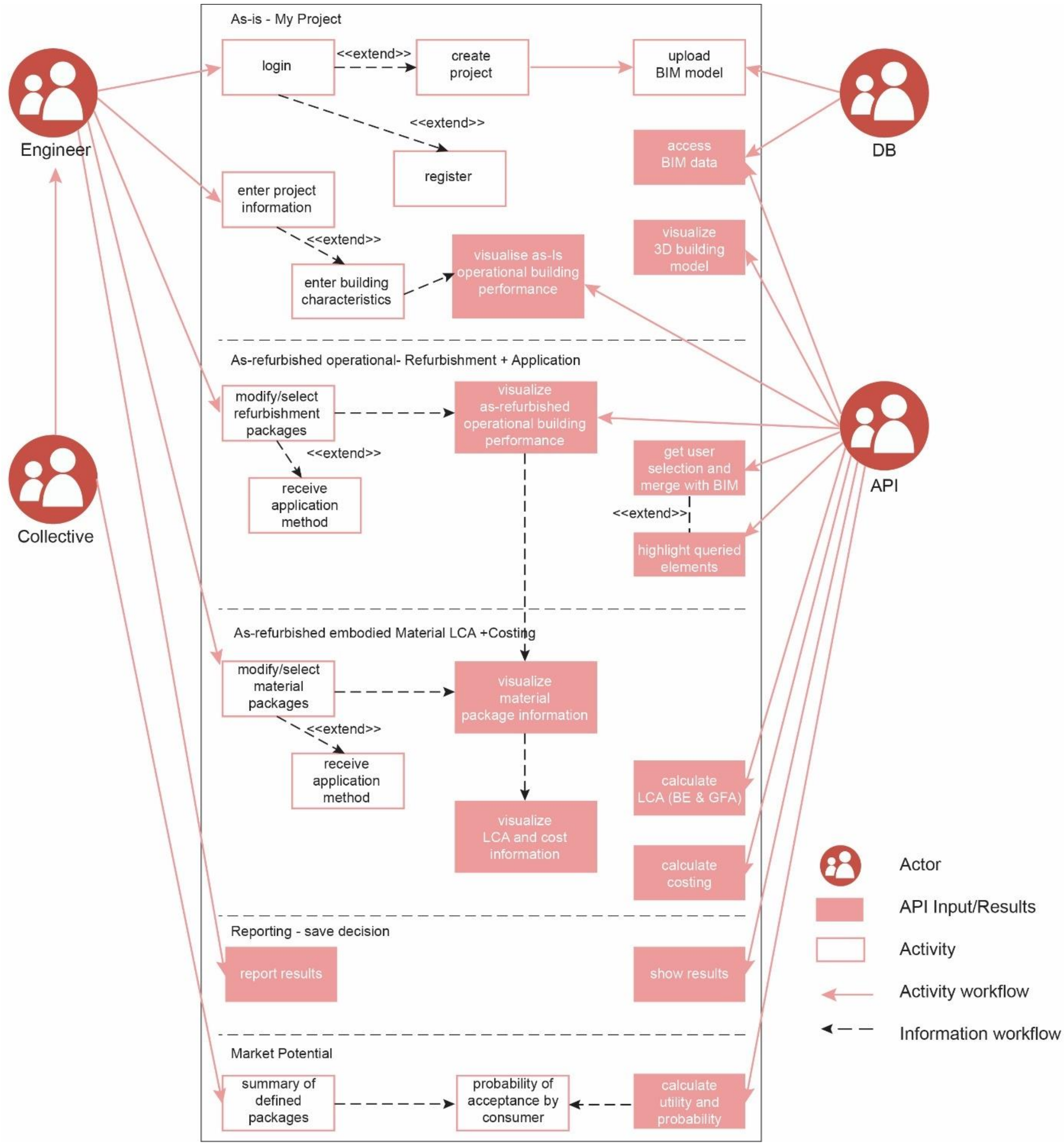



**Figure 43 UML Use Case**

**As-is:** To start with, in the **My Project** section the engineer aims to receive operational energy and carbon performances on the basis of the as-is BIM model (complying with the exchange requirements). The model-based evaluation system reads the BIM model and assigns the manually entered project information and building characteristics to the project. Performance calculations are included in the tool, such as the primary energy and operational carbon consumption. The integration of any model represents the most crucial step when striving towards a model-based evaluation system (no digital building model – no refurbishment evaluation). Since the BIM model is based on the RVO schemes, future developments of the tool could be to integrate pre-defined building models that are an integrated part of the web tool. Generic archetypes could be selected by the user and modified by geometry and dimensions inside the web tool. This is yet outside of the scope in this thesis.

**As-refurbished operational:** The **Refurbishment + Application** section allows the user to retrieve general knowledge about refurbishment applications possibilities, aligned to the newly created project. It focuses on a selective process of various refurbishment measures (e.g.: wall and roof insulation) that should lead to the creation of multiple packages. As a result the operational improvement performances yield energy, carbon and cost performance per building as-refurbished for packages (x..n). The packages are visualized in a numeric dashboard view and can be queried within the 3D model view. Building components can be selected and suggested measures can be applied to the model. This leads to a dynamic validation of packages while comparing them in the table form, as well as brings insight on the actual application of the measures on the 3D building components.

**As-refurbished embodied:** The **Material LCA + Costing** section focuses on materials and thus on dedicated building element layers. Contrary to the operational improvements from above, in this step the engineer wants to be able to create material scenarios and wants to validate them in their hidden emissions and costing attributes. Also here, a dynamic validation inside the 3D model as well as in the form of multiple material package creation yields a comparative analysis of the applied measures in numbers and 3D visualisation. Moreover, a combined presentation of operational and embodied investment (LCA and costing) must be allowed, for instance via pie charts.

The **Disseminating** of results enables the engineer to save and distribute her decision. Thereby the linked information from various databases towards building elements and materials are saved in the form of URL´s. The disseminating of the decision should be done via access and request controlling. For instance, the client can request from the engineer to receive a number of material performance proposal with the lowest embodied carbon and with the most governmental subsidy possibilities. The engineer can start evaluating the model and distribute dedicated URLs to the client for validation, which in return can be approved or disclaimed.

As a crucial part of the dissemination of performance results, the consumer preference research in the form of the **Market Potential** is addressed. The market potential encompasses knowledge of all performed assessments. This includes, operational energy reduction, installation and material application methods, LCA information, such as carbon, and finally costing assessments. The engineer wants to use this particular page as the communication towards the energy collective's decision-making process. Thereby the knowledge gains out of the stated choice experiment, from **Chapter 5 Preference Modelling**, is used and implemented. Both stakeholders want to find the performances as summary overview and want to make pairwise comparisons between two improvement packages juxtaposed towards the base model, in this case no refurbishment. The probability of acceptance by the target group, the homeowners, will be shown and consults in the decision which package to choose.

## 6.3 System Requirements

In the previous section a strong focus towards user centric requirements was given. To find answers in technical terms, the system requirements are elaborated in the following section. This encompasses the system architecture and the defined framework of the web-based tool. We introduce the reader to analysis and design implementation. This includes the definition of the technical requirements, the database models and the overall scripting framework of the application programming interface (API). Before defining the system architecture, the system requirements are discussed, from **Table 38**. The following points demonstrate what the web-based system must comply with in order to fulfil the user and content requirements (as explained earlier).

Firstly, as the name indicates the tool must be hosted on the web and be accessibly by any user when having access rights (via log in account). As explained in **Chapter 3.3 Proposed Decision Support Tool**, traditional web tool development is based on the synchronous communication. The in this thesis proposed framework will build upon the LBDServer and uses an asynchronous communication. Thereby a more efficient communication process (routing) between the backend (data processing) and the frontend (user request) is created, performing Hypertext Transfer Protocols (HTTP) simultaneously.[72] To provide users with dedicated access (request-responds), the web access control (WAC system)[73] is used that allows access by stakeholders for particular operations and reasons. For example, engineers have the full authority to perform, evaluate and disseminate data, while clients have solely view rights for quality controlling or result checking.

Secondly, to allow the user to make assessments with externally held databases in combination with the uploaded BIM model, the tool must be capable to connect graphical and non-graphical information. This means, the systems API must allow to read the BIM models geometry including its parametric information (from the exchange requirements) and must allow to read externally held database that can then be connected to the building geometry. Therefore, the system is required to be a BIM based evaluation system. It should have the ability to link information from any DB with the BIM model on the basis of a common classification schema, as in this case the IFC (relying on the NL-SfB code). LCA and costing data (and thus related assessments) can be performed independently from operational improvement calculations, as the integrated DB is linked and connected to the building elements. This approach guarantees the user to rather browse through the assessment (UX/UI) steps than following a step by step performance procedure.

Further, to receive the linked information between the building model and the DB's, the querying and rendering of information must happen interactively and reactively. It allows the user to see direct responses on the entered actions, without refreshing the web page. For instance, while creating refurbishment or material packages by clicking through the embedded material library the system yields the results from the embedded calculations and displays them on the dashboard[74].

To store these activities, the web tool must allow the user to save the selections temporarily on the local user account. Because of the targeted interactive nature of software on the web, the system architecture must allow a dynamic response to changing/improving requirements within the development phase. The responsive web design (RWD) allows to adopt the layouts to a variety of screens and windows sized within a responsive web environment. A percentage sizing of UI grid containers is thereby common procedure in web tool development. Finally, the visualisation of results should be in numeric values, pie charts and 3D model viewer, by highlighting the buildings elements.

The defined system requirements are translated into so called components that are brought into relations. The system architecture defines how the components are organised and assembled, how they communicate between them and outlines the system constraints, such as scalability and

[72] https://openliberty.io/docs/21.0.0.5/sync-async-rest-clients.html
[73] http://solid.github.io/web-access-control-spec/
[74] https://sosmediacorp.com/interactive-responsive-and-reactive-whats-the-difference/#:~:text=Responsive%3A%20adapting%20layouts%20to%20a,server%20without%20refreshing%20the%20website.

availability. Thereby, complex systems are presented more transparently and comprehensively to enable efficient and reusable working methods *(Kappel et al., 2013).*

### 6.3.1 System Architecture

The system architecture can be understood as the overall framework that allows the requirements to be implemented in one system. It structures the programming script including the code in the background of any software/web tool.

There are multiple system architectures that are based on Enterprise Applicating Architecture. Among others, the Service Oriented Architecture (SOA), the Plug-in architecture and the Event Driven Architecture (EDA) are commonly used for web developments. SOA is based on a rearrangement of independent components to offer new services. For instance, it is possible to create a geographical map highlighting all retailers in a city to ease shopping, by combining Google Maps, and PayPal method[75]. Google Maps and PayPal hereby serve as services used by the main application. The Plug-in architecture on the contrary has a core system in which multiple modules, plug-ins, can be complemented to add functionalities. For example, WordPress represent a web tool that allows users to make use of the core system, the creation of a web page. It also allows to extend functionalities, such as graphics, contact forms and log-in registers, by activating plug ins. Finally, in an event-based architecture all components communicate exclusively via events. Each component is responsible to match user oriented data input with databases running in the background. It exists of three roles, the event emitter, the event broker and the event subscriber. The component thinking allows reusability of the components in various constellations within the current application and in future context. The benefit of EDA over the SOA is the real time reaction of events rather than services provided in a chronological order. Thus, for this thesis, the event based architecture is chosen *(Bukhsh et al., 2015; Clark & Barn, 2011; Clark & Barn, 2012).*

#### 6.3.1.1 Model View Controller

Within the software modelling paradigms (SOA, EDA, Plugin), multiple methods exist to organise and develop code. The Model View Controller (MVC) approach is thereby commonly used for online applications and web development. It is used to develop graphical user interfaces (GUI) in combination with data storage and computational components, and it is based on three components: the model, the viewer and the controller (including routing). **Figure 44** illustrates the relations between the three components and their place in front and back-end. The model represents a domain-specific class definition that acts as own entity regardless of the assigned views. External and internal dataset connections are done within the model. The controller is responsible to react on actions made in the view (from the user) by representing the model or encapsulated information. The viewer, on the contrary, holds responsibility to represent the model's content in dedicated UI locations *(Veit & Herrmann, 2003).* While, model, DB, controller and router are part of the back-end development (invisible for end users), the user browser interaction towards the viewer, the GUI, can be seen as the front end (visible for end user).

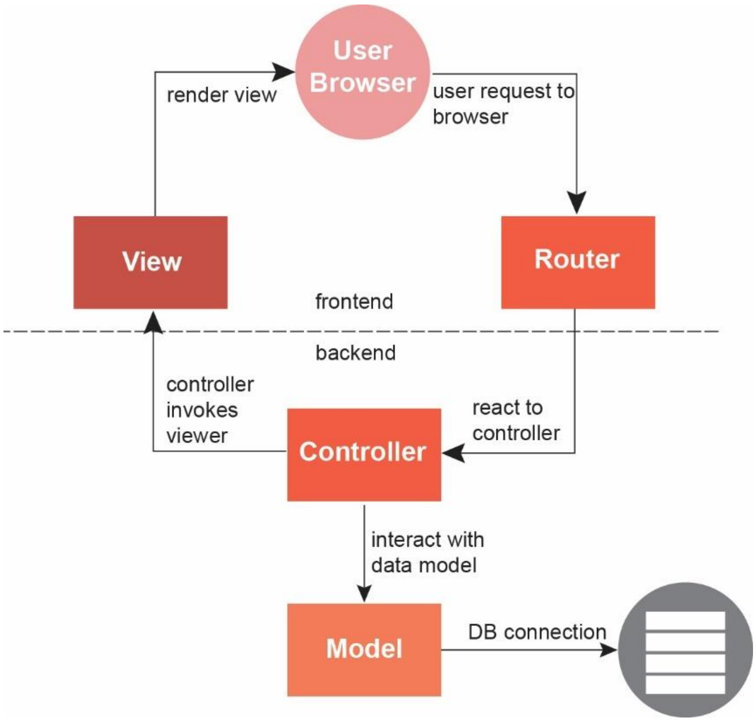



**Figure 44 MVC**[76]

### 6.3.1.2 Application Programming Interface

An Application Programming Interface (API) enables the communication between two software systems. Essentially, the API provides an interface, allowing to interact, access and exchange data and functionalities. Among other types of API (e.g. API of stand-alone tools like Revit or EnergyPlus), the web API is addressed in this research to satisfy the system requirements. The API represents the bridge between the user browser and the demanded information container (from the DB). The MVC, as explained above, is encompassed within the APIs framework and manages the user request with the database and calculation performances.

The functional user and system requirements can be demonstrated within the web tool´s system architecture, see **Figure 45**. Firstly, the web browser represents the engineer's functional user requirements. Deriving from the UML use case analysis, five UI site views covering the project creation, refurbishment consultancy and scenario definition until the LCA and cost assessments. Mediated by the project creation, all performance tasks are to perform independently from each other. Secondly, the API encompasses the MVC as explained above. Next to model´s component and database input definitions the controller is routing and navigating the user through the five UI site views (from the web browser) in five possible view components, such as dashboard view, performance view, pie chart, 3D viewer and reporting. It can be understood as a nested branch system. Each of the five web browser pages has five view components embedded. For instance, in the web browser "Life Cycle Assessment" performance task enables a "Dashboard" view to enrich the user with knowledge about LCA, and a "Performance" view allows the user to actually calculate LCA and a "3D view", that enables the user to visualize the performances on the building model elements and perform object-oriented modifications. The model of the API connects with external and internal databases. Internal DBs are

[76] Figure 19 aligned to https://www.bogotobogo.com/RubyOnRails/RubyOnRails_Model_View_Controller_MVC.php

Graph DB and Mongo DB, externally held DB´s are developed on MySQL and hold information regarding material, LCA and cost data. Note, the dashed line boxes indicate the additional implementation focus (frontend) of this thesis on top of the existing LBDServer.

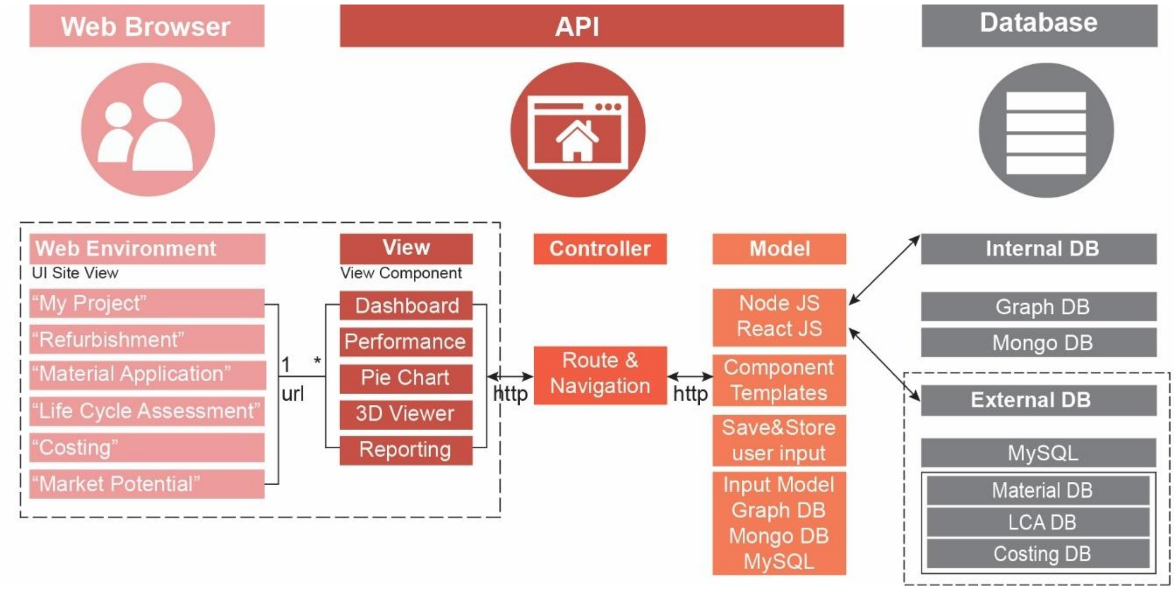



**Figure 45 System Architecture**

*The following will explain the system design in more detail (API´s MVC and DB) and puts all elements in an activity process. Eventually this will lead to the web browser UI proposal.*

## 6.4 System Design

For this thesis, web-based frameworks were analysed and studied. Generally, software development focuses on front and back end developments. As explained above in the MVC, the back-end containing the API´s model and DB connection and bridges via navigation and routing to the front-end viewer and user browser. Because a generic differentiation between the front-end and back-end depends per software framework, the following will discuss each component and will eventually set them in relation via a BPMN activity diagram.

### 6.4.1 System API

#### Model

The back-end and the front-end of the API is developed using NodeJS in combination with ReactJS, respectively. It is a common combination to develop platforms that can be hosted and run as a web-based server. Both environments are based on JavaScript (and TypeScript) and are using open-source JS libraries. The Linked Building Data Server (LBDServer), developed by Andrew Malcolm and Jeroen Werbrouck from Ghent University, is built upon this logic and uses NodeJS as application framework (back-end) and ReactJS as UI constructor (front-end). The model is developed in visual studio code.

NodeJS is a runtime environment that manages data communications on the server, while ReactJS responds on these communications and is used to render the output in the user interfaces. Note the difference of React to ReactJS. React offers the framework for building applications, where ReactJS is the JS library which allows to create UI layers in combination with CSS. To do so, HTML web pages are routing through React and compile to JavaScript code. This makes React respond to a front-end framework that can communicate directly with the back-end framework. Other possible fusions to back-end frameworks are Mongo DB, Express, NodeJS (JS runtime), PHP or Python Django.

*Note: To understand better back-end framework development, the student analysed and established a Python Django back-end framework at first. Out of economic reasons, the LBD Server was continuously used as it represents a greater opportunity to be developed in the future. The LBD Server back-end NodeJS was installed and extended with strong focus on front-end development in ReactJS.*

### View

A crucial part of front-end development is the viewer, being responsible to represent the API functionality at the forefront. It includes the components that are visible and usable to the end user, for instance table views, drop down selection and 3D model viewer. As explained earlier, ROTUNDORO provides the user with five UI site views on the web browser. Each site view encompasses five view component. This nested logic yields out of the ReactJS component thinking. Every component is coded once in ReactJS and brought into a new context for each UI site view. These components are accessed via URL´s that are requested from the user and sent to the viewer. The viewer forwards them to the controller and router, which query the selection from the model and the integrated databases. The resulting query will be posted back to the viewer and will be visible on the user browser. In technical terms, the user requests information from the UI (ReactJS), the browser will respond to this server request and will send the data via a HTTP response from the back-end (NodeJS). Since the back-end provides the full set of data communication, the routing (in the form of the Controller) is crucial for the ReactJS response to know which components to render from the back-end, see **Figure 45**.[77]

### Controller & Router

The controller is responsible for routing and navigating the requests and responses between the data model (back-end) and the user view (front-end). Thereby, the router analyses the request and decides which controller will handle the request. The controller accepts the requests and handles it. So, the routing is a substantial part of the controller. Web-based platforms are based on creating HTTP services. Thereby HTTP describes how content transfers between user browser and webservers. Protocols enable standard Create, Read, Update and Delete (CRUD) operations and are therefore critical in web development. The relevant CRUD operations in HTTP are GET, POST, PUT, DELETE, in which the first two are the most commonly used ones. Furthermore, to protect the data and content that is sent to a web browser, the HTTPS (security) was developed. It encrypts the data that is being retrieved by HTTP. HTTPS uses Secure Sockets layer (SSL), and enables all communication to be encrypted. This HTTPS method is now standard and needs to be used by default.

A UML sequence diagram is created to illustrate how the component thinking in relation to the user request works, see **Figure 46**. The example shows the UI site view "Life Cycle Assessment" and the view component 3D viewer. Also, the user´s request for possible material solutions via GET and POST is illustrated.

[77] https://www.simform.com/use-nodejs-with-react/#:~:text=Both%20Nodejs%20and%20React%20are,server%2Dside%20rendering%20comparatively%20easy.

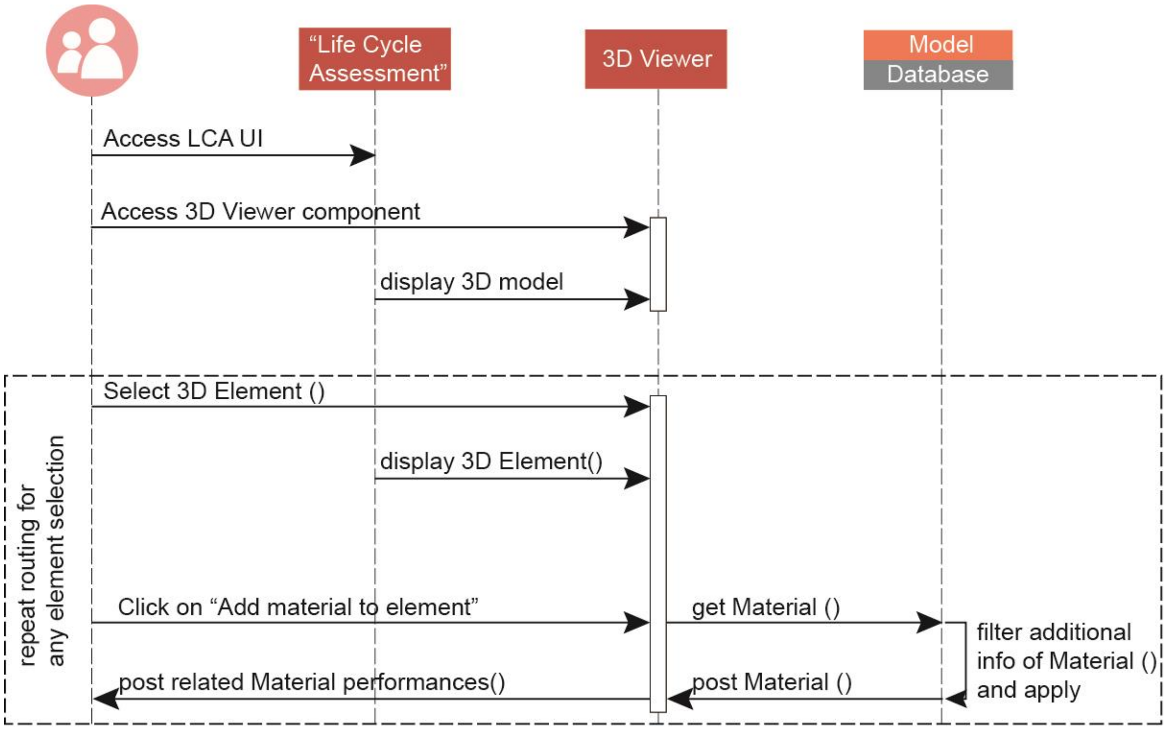



**Figure 46 UML Sequence Diagram**

### 6.4.2 Database

The model builds upon the input from the database and performs the data operations regardless of the user and controller requests. The key objective in the data management is based upon the discussion of data exchanging and disseminating, from the literature. Current practices lack on enabling seamless connectivity of BIM models and externally held data while relying on one single source of truth. In order to fulfil this system requirement, that allows a semantic connection, this thesis proposes to build upon the LBD Server by enriching the internal DB´s with knowledge from externally connected DB´s, see **Figure 47.**

The existing internal DB, such as the Mongo DB is used as NoSQL database and handles non-graphical data like the local user data in the form of documents. These documents are further complemented with graph knowledge deriving from the digital building model (in the form of IFC using RDF Graphs). The extension and selling point of this thesis is the connection to relational externally located databases such as Material DB, LCA Data (from the NMD), and Cost Data (from manufacturer).

Ideally speaking, such external databases like material data and LCA data will in the future be made publicly available by the manufacturer and government agency. Retaining the classification codes, e.g., on a national level the NL-SfB scheme, enables non-graphical data to be fetched within APIs, such as the web tool ROTUNDORO. End users and web developers that focus on the AEC industry should be enabled to use these datasets free of charge and embed them inside their web based workflows (web tools). As for the current state of development in this thesis, these DB´s are documented using Microsoft Excel and passed on into the relational database MySQL. The following will discuss the used and established databases in this thesis.

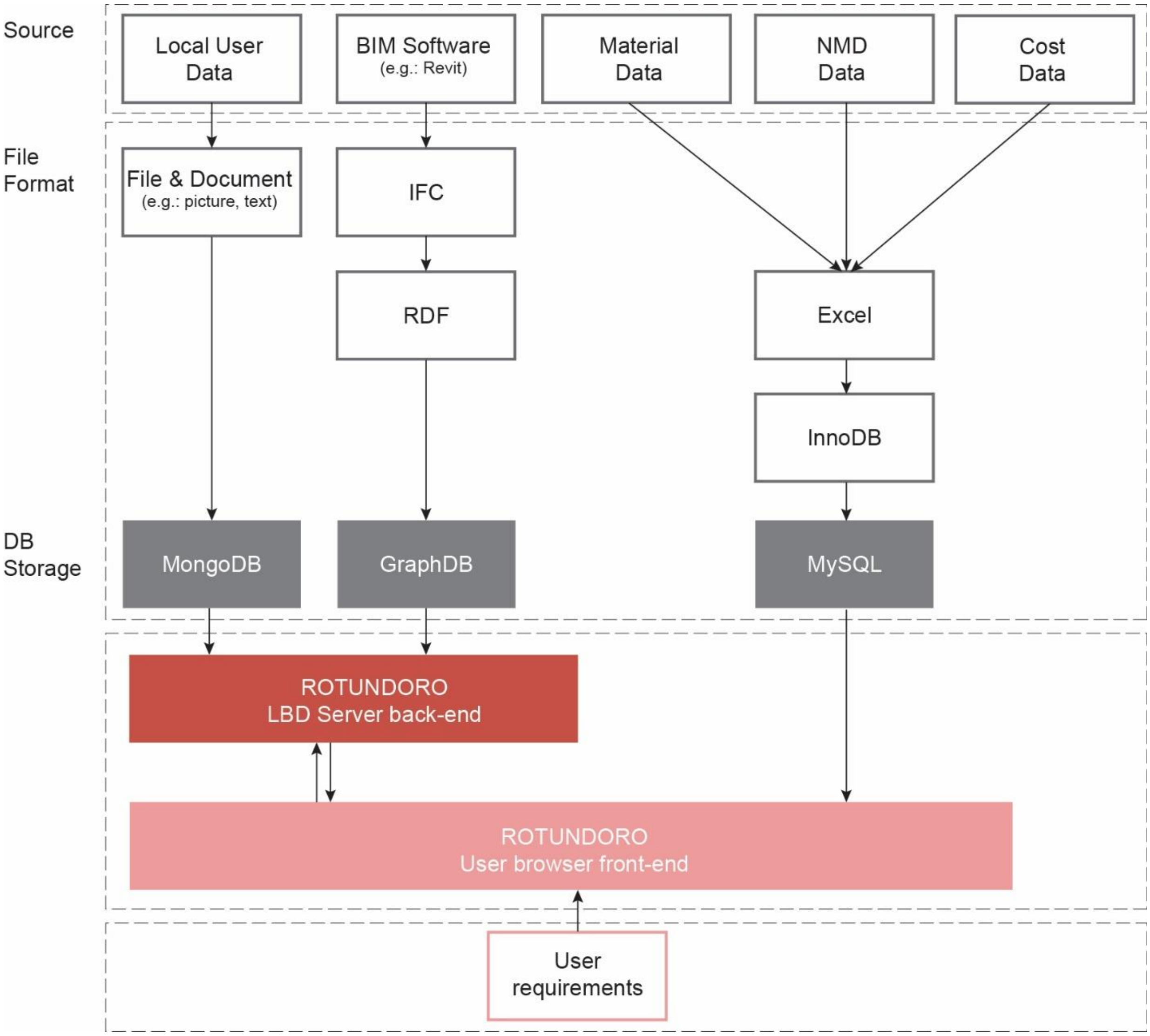



**Figure 47 Database management**

## Mongo DB

Mongo DB is a NoSQL Database, which means that storage is not focused on links but rather on documents. It represents a collection of documents where every document holds a key value/attribute. Contrary to relational table based records, mongo DB holds documents as standalone entities, which allows them to share similar key values, for instance user ID. This means that documents don't follow schemas in which they must relate to each other but can allow dynamic changes. It allows to easily make changes without losing performance[78].

In this thesis, Mongo DB is responsible for all non-graphical related information, such as text, pictures and file data. Further, it manages the local user data (key values) as it keeps track of log ins and stores them in the form of meta data. File, project and user data can be seen in **Figure 48**.

[78] https://www.credera.com/insights/mongodb-explained-5-minutes-less/

```
_id: ObjectId("6006b4e231e66e3534a55c81")                                        ObjectId
ma… : Binary('ew0KICAgICJhc3NldCI6IHsNCiAgICAgICAgImdlbmVyYXRvciI6ICJDT0xMQURBMkdMVEYiLA0KICAgICAgICAi   Binary
project : "https://lbdserver.org/lbd/e8baf101-9169-422a-9286-295f9e1dbfec "     String
url : "https://lbdserver.org/lbd/e8baf101-9169-422a-9286-295f9e1dbfec/files/6006b4e231e66e3534a55c81   String
createdAt : 2021-01-19T10:30:58.332+00:00                                        Date
updatedAt : 2021-01-19T10:30:58.332+00:00                                        Date
__v : 0                                                                          Int32

_id: "e8baf101-9169-422a-9286-295f9e1dbfec"                                      String
url : "https://lbdserver.org/lbd/e8baf101-9169-422a-9286-295f9e1dbfec "         String
__v : 0                                                                          Int32

_id: ObjectId("5ff5a3d4410bb14ffc171b68")                                        ObjectId
guest : false                                                                    Boolean
username : "Julia "                                                              String
password : "$2a$08$4hvmQs5Hd1liZ4jJR7lcGezQ/FuGufxqBqNTTTcig1LHg81jbF2t6 "       String
email : "j.k.kaltenegger@student.tue.nl "                                        String
url : "https://lbdserver.org/Julia "                                             String
> tokens : Array                                                                 Array
> projects : Array                                                               Array
__v : 10                                                                         Int32
```


**Figure 48 Mongo DB User key values**

## Graph DB

The Graph DB is used to host the RDF graphs. RDF offers to connect multiple data concepts with each other based on a triple store repository (subject-predicate-object)[79]. It sets subjects into certain relations to objects via a predicate. Thus, data can be stored in the form of a network while enriching itself via new relations between objects. The unique identification and connection of objects can be achieved using Uniform Resource Identifiers (URIs) *(Berners-Lee et al., 2018; Malcolm et al., 2020).* So, ideally speaking, externally kept data is going to be connected via URIs towards the building models RDF graph *(Werbrouck et al., 2019).*

To better understand the term graph, **Figure 49** demonstrates a graph model in the example of a wall element within the context of a building. In this graph model, data can be organized as nodes, relationships, and properties. Nodes are in this context entities that are starting points for n number of properties (= relationships). Nodes can be tagged with labels, representing different roles in the domain. Relationships represent the connections between any two nodes. A relation consists of a direction, a type, a start, and end node. Even though the direction is unidirectional, relationships can be navigated in either direction. A node can share any number of type of relationships without sacrificing performance. As already mentioned before, the idea to use RDF graphs is to enrich data points with semantic knowledge. For instance, as shown in **Figure 49**, the wall_27 could be additionally linked with LCA data using URIs. To do so, a major focus was spent to create databases using MySQL.

[79] https://en.wikipedia.org/wiki/Triplestore

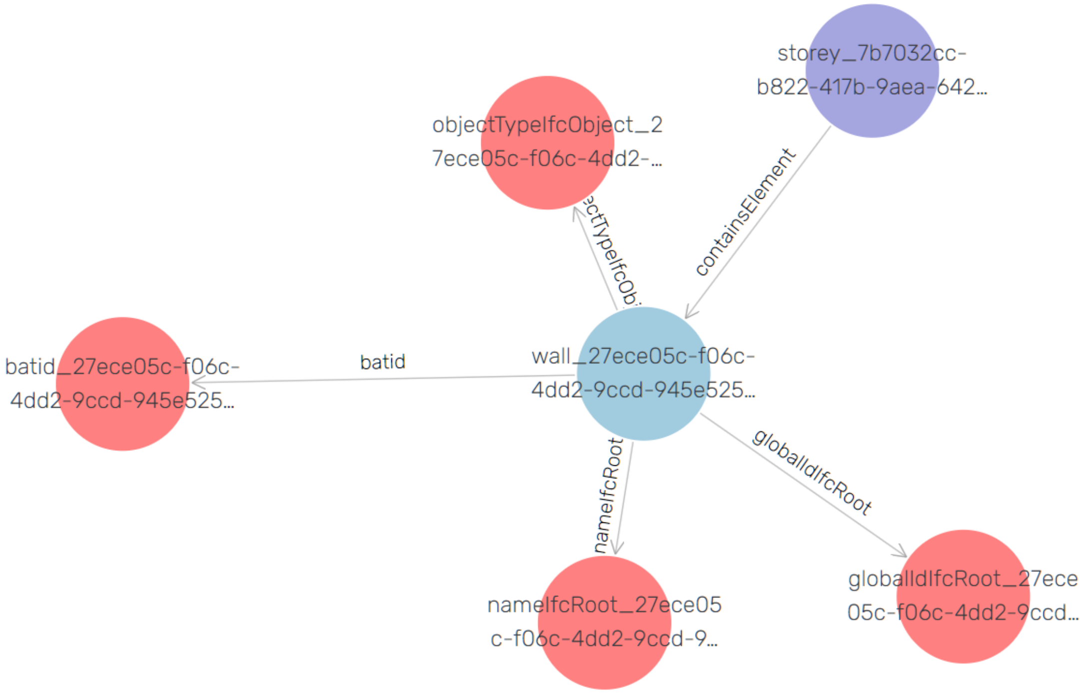



**Figure 49 RDF in Graph DB**

The IFC geometry and the embedded IFC data are addressed in two separate conversion processes. Firstly, the translation of the IFC geometry (graphical) is discussed. The LBD Server provides an internal conversion process that allows the user to upload an IFC model which is then translated to the Graphics Language Transmission Format (glTF) (*Malcolm et al., 2020).* The IFC is converted to COLLADA using ifcConvert[80]. COLLADA[81] is a 3D asset exchange schema that is based on XML. It is an intermediate step that allows handling 3D geometry through multiple applications (*KhronosGroup 2012*[82]*)*. Next, the COLLADA file is further converted to the glTF that saves the geometry. Thereby the JavaScript Object Notation (JSON) schema is applied to structure the geometry as mesh-objects *(Malcolm et al., 2020), see* **Figure 50** (left). The IFC backend converter can be installed and downloaded from the LBD Server GitHub repository[83]. When converting the IFC to mesh-objects the glTF holds the globally unique identifier (GUID) for each geometry. The GUID is further used to connect the geometry to the actual IFC information.

To make the IFC information (non-graphical data) accessible to the LBD Server the IFC is converted to a turtle file (TTL) and must be uploaded separately. The TTL holds other building element information, such as the global ID and component parameters. Semantic information is stored there, such as material data, see **Figure 50** (right). It can be linked to geometry via the GUID. A possible converter is IFCtoRDF[84] *(Pauwels, 2021; Bonduel et al., 2018).* In this thesis, the 3D model viewer inside the LBD Server is used to visualise the glTF. The TTL file could be successfully established and is aimed to be used in future research together with SQL DB´s, see the following section.

[80] http://ifcopenshell.org/ifcconvert
[81] https://www.khronos.org/collada/
[82] https://www.khronos.org/gltf/
[83] https://github.com/LBDserver/converter_backend
[84] https://github.com/pipauwel/IFCtoRDF

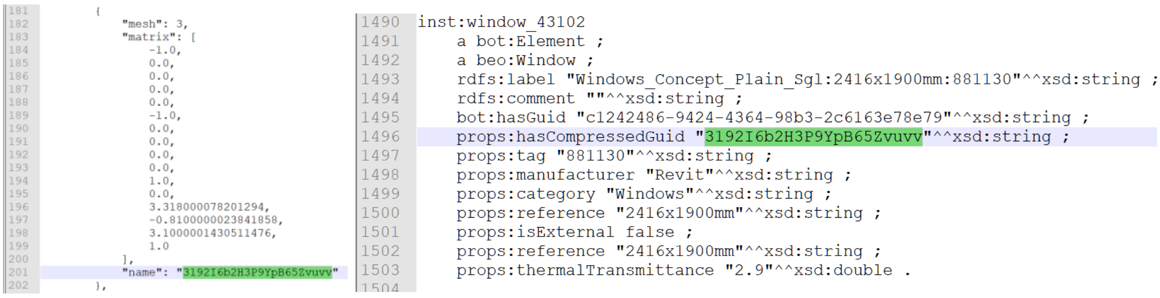



**Figure 50 IFC geometry shown as glTF (left), IFC information shown as TTL (right)**

## MySQL

MySQL Workbench is based on SQL and is a relational database. It is commonly used for multiple data sources containing related information *(Veen, 2014).* Compared to Graph DB, MySQL is relatively static and less focused on a world-wide expanding network of linked data. An Entity Relationship Diagram (ERD) helps to illustrate the structural relationships of data. ERD´s are standard practice in SQL database design and will also be used for this thesis. An ERD represents the relationships of system entities stored in the databases. Entities count as a classification that create sets of objects and attributes *(Thayer & Thayer, n.d.).* The data values in a row form a record in a table and each column represents a field that carries specific information about every record. In preparation, an ERD is set up that clarifies and predefines the database structure.

**Figure 51** shows the MySQL user interface to demonstrate records kept within data tables. The ability to create and import data tables allows to make relations between the data records. Data entry must comply with specifications that allow an easy maintenance. Datatypes, reaching from numeric to alphanumeric and other definitions such as the primary keys and not null, are required to be used wisely of course.

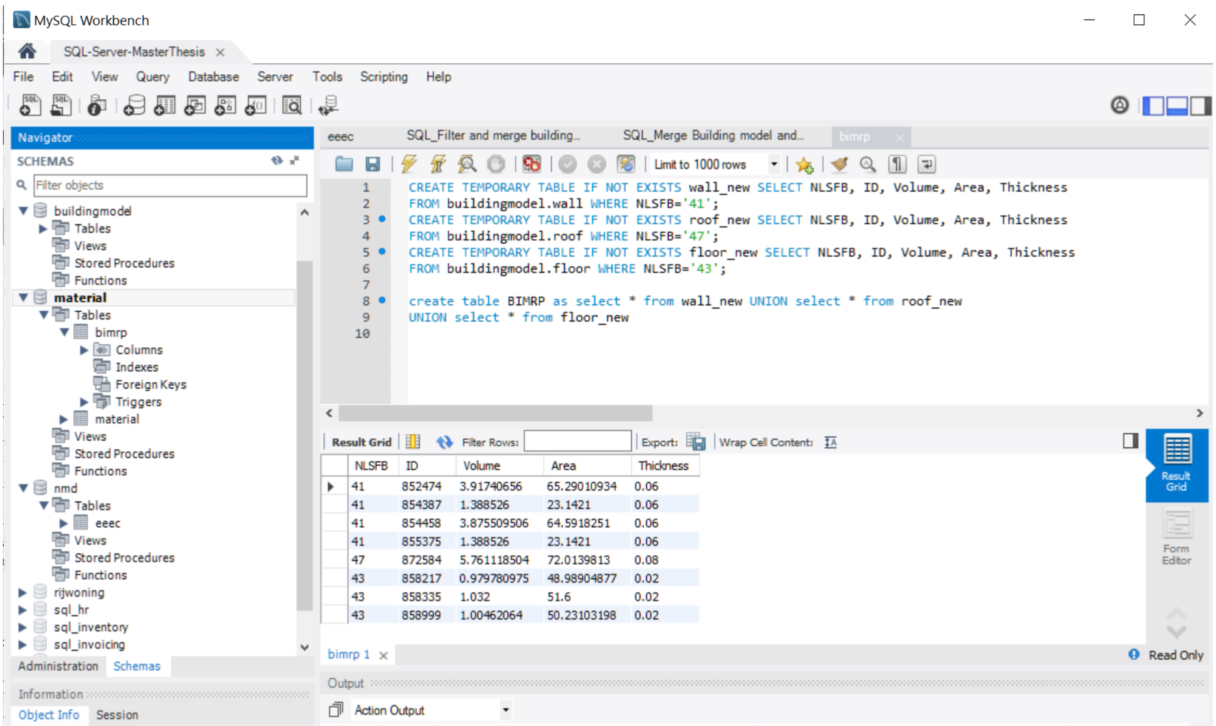



**Figure 51 MySQL Workbench**

In this thesis MySQL will be used to store the material-related information. This includes material database, the LCA database derived from NMD (version 2.3)[85] as well as the gathered cost values from manufacturers.

In fact, since the previous Section showed that the material-related attributes and performances depend on the thermal resistance (Rc) and the material thickness (d), a data structure has to be established that allows automatic querying of material information regarding user selected refurbishment measures (Rc-Value of materials). To create logic and structure the databases, two main operations are applied. Firstly, Boolean operations allow to combine datasets under certain logics, such as union, intersect or difference. Using AND, OR, NOT or AND NOT excludes datasets based on keywords that eventually result in the efficient merging of datasets. Secondly, the filtered data sets are combined with each other with many to many (n:m) relations. This is utilized to structure one ERD for the purpose of fulfilling the user requirements. For instance, n building elements have m number of possible material applications, so we use n:m.

So far, we studied the systems design. This include the web tools API and MVC, the DB´s that are included in the LBD Server as well as newly added material related DB´s. Moreover, the site view definitions of the web pages are introduced to fulfil the functional user and content requirements. Next, a BPMN Activity Process Diagram will introduce how these components interact with each other.

[85] https://www.milieudatabase.nl/viewNMD/

### 6.4.3 BPMN Activity Process Diagram

As the name already indicates, the BPMN Activity process diagram showcases the process of using the web tool in the form of an activity diagram. The process map indicates four swim lanes representing the stakeholder, see **Figure 52**. These are the engineers as the user, the UI representing the five UI Site Views for the web browser (“My Project”, “Refurbishment”, “Material Application”, “Life Cycle Assessment”, “Costing” and “Market Potential”) and the related View components (“Dashboard”, “Performance”, “Pie Chart”, “3D view” and “Reporting”). The API includes the MVC, showing primarily the computing performances of the data model and finally the DB´s that are connected to the data model and called by user request. Essentially two different process workflows are identified (Start 1-End 1 and Start 2-End 2).

(Start 1) Firstly, the project is created in the web tool, including the user log-in, uploading, and storing of the BIM model, entering as-is building performance and receiving first calculations by the tool. This first activity is mandatory for any further performance assessments, since it encompasses the basic knowledge - the 3D building model (End-1). (Start 2) In the second section the user can browse to either one of the remaining UI Site Views. Whether the engineer wants to perform refurbishment assessment or apply various materials and perform LCA analyses, the tool allows a parallel entering of each of these processes (see parallel decision gateway). For every follow up task, the tool´s API routes to the dedicated DB and data model. The follow up performances of the previously selected assessment remain similar between each other. Default value assumption and performance results are presented to the user. She needs to decide whether to keep the generic definition or to amend according to client’s requirements. User input is primarily limited by letting her select via drop down functionality through embedded databases. The API reads the user selections and performs the calculations, specifically for each assessment method (for instance refurbishment packages or LCA performance). The calculation output is rendered at the UI and the engineer eventually verifies and validates the results. It is crucial to understand that this process is supposed to be applicable to either the performance view (table views) or the 3D view (building element level). The following section is going to elaborate on possible UI scenarios that encompass all of this.

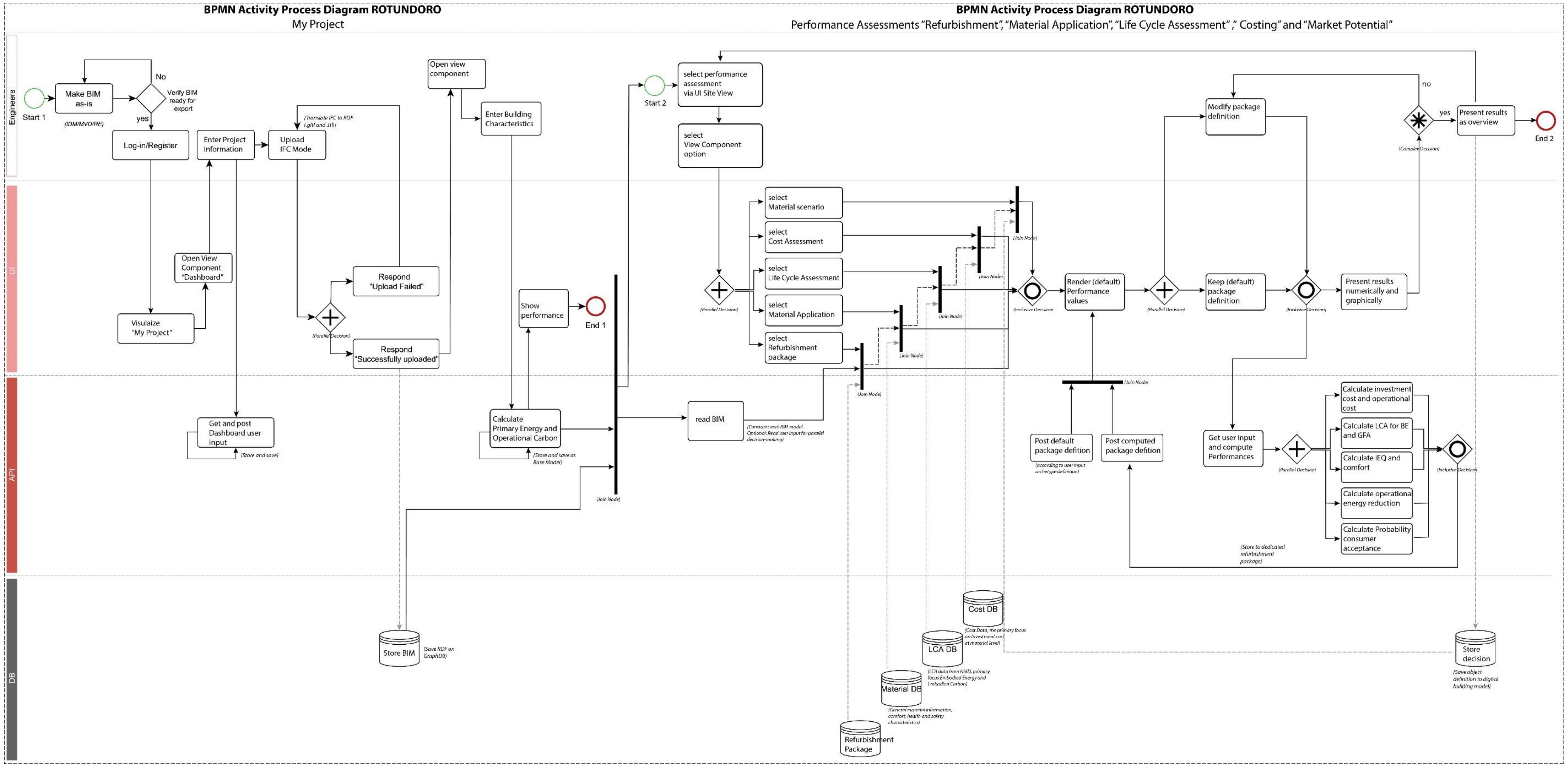



**Figure 52 BPMN Activity Process Diagram**

### 6.4.4 Web Browser

The system requirements highlight the nature of interactively querying project-related information within a responsive web environment while browsing through multiple dashboards. The following UI design describes the six UI site views and elaborates the task according to the view components. To guide the reader through the UI design, the functional user requirements are highlighted in bold. Find the legend of user interface components in **Appendix G.**

#### My Project

➔ **The engineer wants to be able to create and store a new project, add IFC model, and adding project and building-related information.**

The engineer enters the web tool, by creating a new project, under the UI site view **"My Projects"**, see **Figure 53**. Part one of this section will ask to enter project information, such as project name, client name and building typology. Entering the project information, a new project will appear in the table view of the "Dashboard". With the button "new Model", the engineer is asked to upload the IFC model.

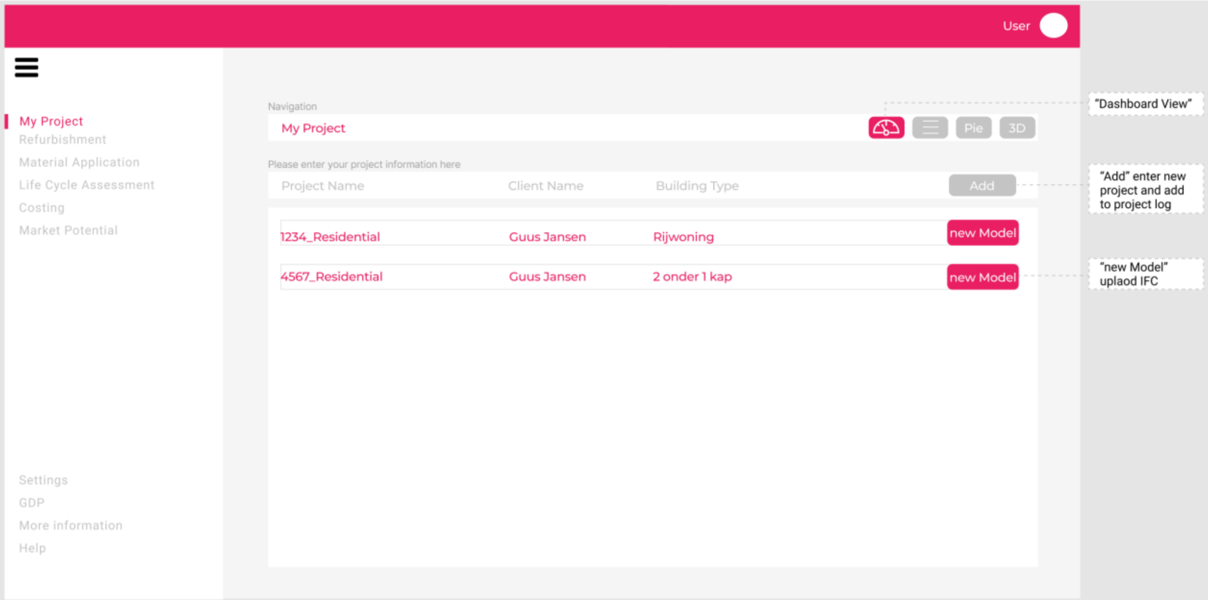



**Figure 53 UI My Projects Dashboard**

Once the model has been successfully uploaded; the user should have the ability to further edit this newly applied project and should be able to see the uploaded 3D model. The view component "Performance" and "3D view" can be activated by the user, see **Figure 54**. The 3D visualisation allows all other project stakeholders to observe visually the building as-is and provides room for discussion between engineers and clients about affected building elements. While assessing the building visually, the building characteristics are to be entered. In addition to the project information, the construction years and the expected lifespan of the refurbished building will be entered.

➔ **The engineer wants the tool to analyse the primary energy consumption, the related operational carbon emission, and the energy label.**

➔ **The engineer wants to see the 3D model as-is (Based Model)**

The operational energy and carbon performance of the existing building (as-is) are partly entered and partly computed by the tool. The energy demand (space heating, electricity and water consumption) and the related costs are derived from the building owners itself and is based on their annually and monthly energy and electricity bill. The tool should have the ability to compute the primary energy and operational carbon performance out of this entered energy demand information. The calculation formulae from **Chapter 4 Evaluation System** are used. See **Figure 54** indicating the user input and calculation performance as computed.

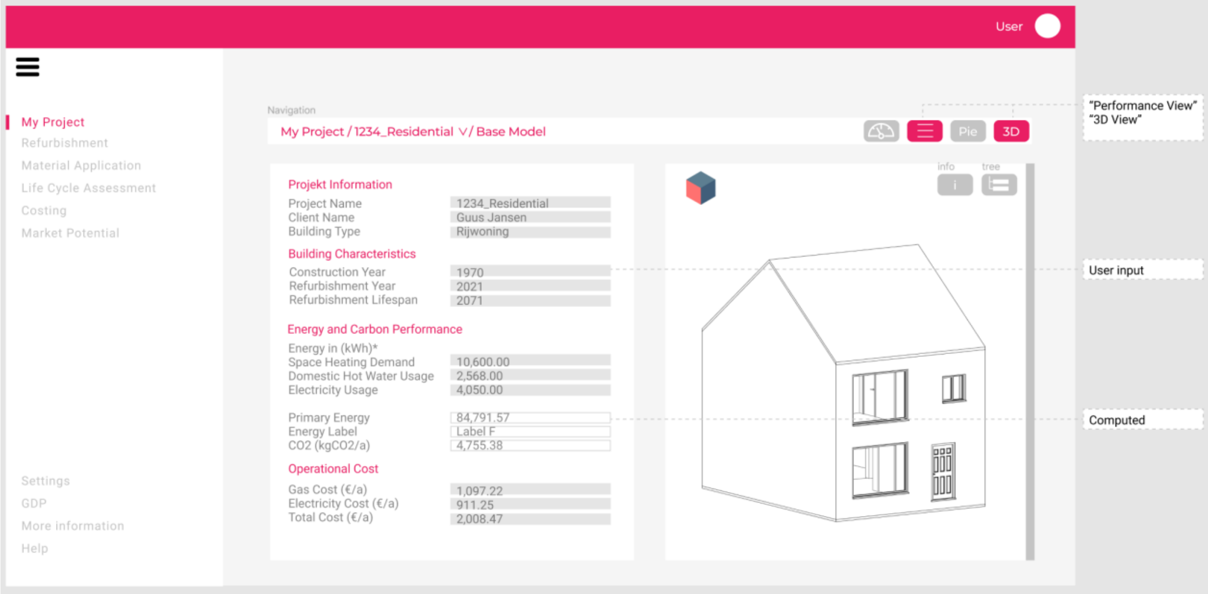



**Figure 54 UI My Projects Performance and 3D Viewer**

➔ **The engineer wants to be able to see resulting values in the form of Pie Charts.**

Additionally, the tool should have the ability to illustrate the entered energy, carbon and cost values in the form of pie charts. The charts should give the engineers and the clients a percentual overview of the used resources. This step is out of scope for now.

The above-explained steps are needed to perform any of the following steps. The engineer wants to build upon the 3D Model (IFC) the refurbishment packages XOR perform material application XOR LCA performances of materials XOR Cost analysis of investment cost.

## Refurbishment

➔ **The engineer wants to receive information about national policy and governmental subsidy regulation regarding energy and caron refurbishment.**

The next section will focus on the refurbishment performance for the new project, by navigating in the hamburger menu to the **"Refurbishment"** page. Firstly, to prepare the project team for choosing adequate refurbishment measures, the tool should be able to provide generic information about national climate targets and improvement possibilities. It is crucial at this early project stage to manage the expectations of all involved stakeholders. Therefore, the project team is provided with national standard definitions of energy and carbon reduction measures as well as subsidy regulations that support energy refurbishment projects in the Netherlands. This encompasses information according to the RVO building improvement strategies and subsidy concepts *(according to the Dutch Ministry of Economic Affairs and Climate, 2019; and the Agentschap b NL, 2011).* This step helps to tackle project participants' interest in attractive and feasible refurbishment measures. Eventually, after this step, the engineer can account for client interests that stay in line with national policies.

➔ **The engineer wants to be able to perform refurbishment packages and wants to compare results towards the base model in an interactive way (including energy, carbon and cost performance).**

Next, the engineer will enter the "Performance" page that introduces the user to the refurbishment evaluation page. Here, the user will find the ability to compute refurbishment packages, in line with the information gained from the previous step. The UI is divided into two parts. Firstly, the engineer will be presented with pre-defined packages that include one or multiple measures. This is changeable by the user via the drop-down functionality. Secondly, the user will find the computed results regarding operational energy, carbon and cost reduction.

To elaborate on the top section, the engineer should have the ability to find the packages represented in the form of a table view. In there, she should be able to add columns to create refurbishment package(s) and add rows to select predefined measures in a drop-down selection. Ideally speaking, editing the table is done via right-click add/remove column/row right/left. Measures to select are insulation for walls, roof, window, door, foundation, and floor. In the future also heating system improvements such as heat pumps (air and water-based) and solar panels are to be included. Relevant for the engineer is to see the related thermal improvements of the chosen measures. This means the Rc-Value, U-Value as well as COP value of heating systems. The results in the lower section are representation in a correlated table view. The Base model definition, as defined by the engineer in the very first step ("My Project"), is shown too. This will help to directly compare the newly created refurbishment packages in their performance criteria. The tool must react in an interactive and reactive way towards the measures taken by the engineer. This means that it is required to compute energy, carbon and cost calculations in the background and represent them on the UI.

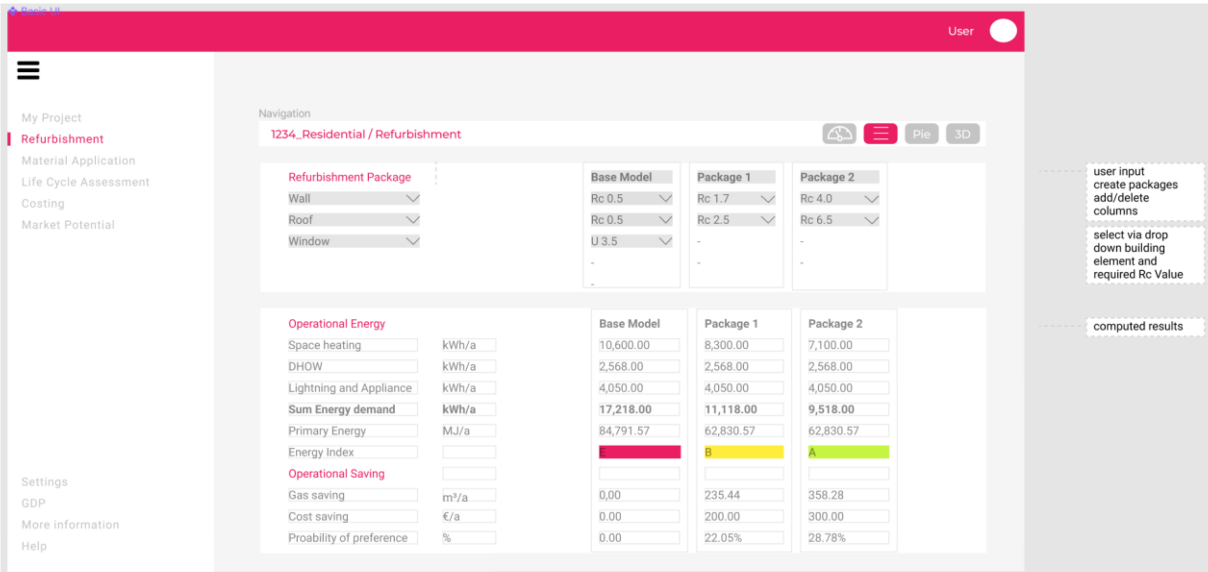



**Figure 55 UI Refurbishment Performance**

➔ **The user wants to see the affected building elements in the BIM model.**

The above-explained performance of refurbishment packages allows the user to directly compare results within the table views. However, as the nature of the engineering approach seeks to perform building model-based evaluation scenarios, the user wants to be able to apply refurbishment measures within the BIM model, on a building element level. **Figure 56** shows the UI site view of the 3D view. The evaluation process, based on building elements' thermal properties (Rc and U-Value), remains the same. But elements can be selected individually, and new performance values can be applied using the information window (on the right side of the model). Total building performance results are to be extract from the previous view component (the "Performance view").

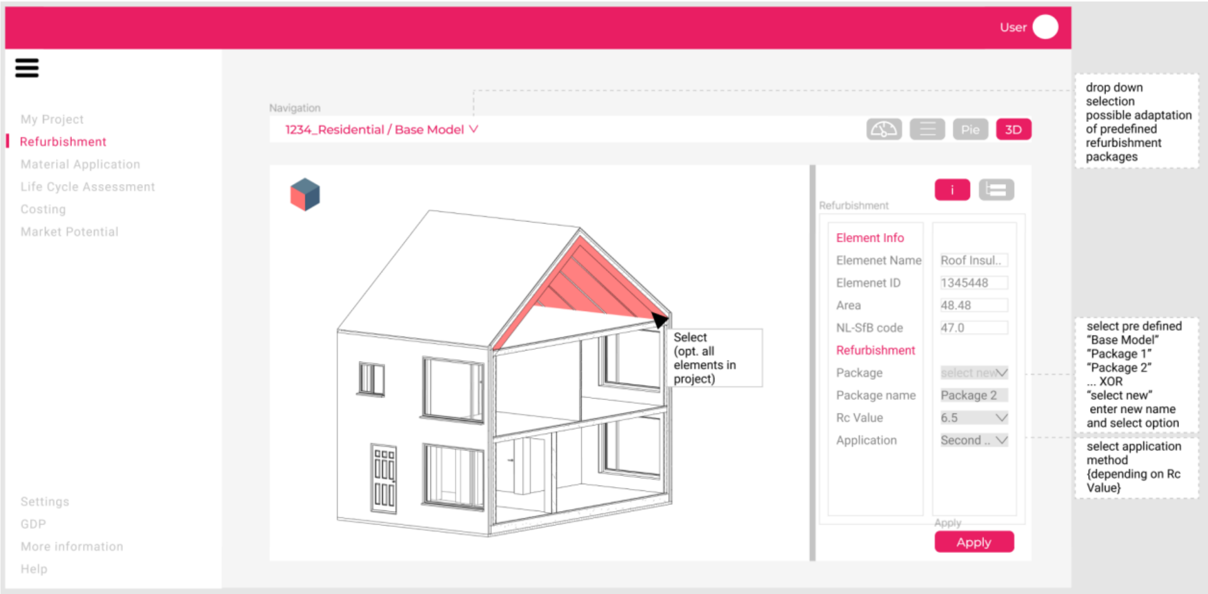



**Figure 56 UI Refurbishment 3D viewer**

## Material Application

The material application is an essential definition that influences further performance assessments for LCA and cost evaluation. The engineer is asked to define which materials are applied (regardless of having applied refurbishment packages or using the as-is BIM model). Thus, the site views "Material Application", "Life Cycle Assessment" and "Costing" are intertwined by the user input, but different by the computed output.

➔ **The engineer wants to gain knowledge about application methods.**

In this section, the user wants to enrich the base model and/or the earlier performed refurbishment packages with possible application methods and materials. The page **"Material Application"** is called by the engineer. In the dashboard view, the user should be enabled to receive information regarding application possibilities and material-related characteristics.

Further, in the performance view, the user will enter either one of the previously defined refurbishment packages, via the navigation bar, for instance, "Refurbishment Package 2", see **Figure 57**. According to the selected package, the measures, and their improvement values (Rc, U and COP values) appear. Next to each measure, the application method can be selected via the drop-down menu. Possible selection for insulation measures is either "Cavity Injection", "Second Wall inside" and "Second Façade" on the outside of the external wall. For windows, it should list whether to replace "Frame and Glass" or only the "Glass". For PV Panels, the true north orientation on the roof should be listed and for the heat pumps the size and room name where the equipment should be placed. While the engineer can choose the preferred application method the system should examine the feasibility in the next step.

➔ **User wants to be able to analyse which materials are possible and receive information about material characteristics, containing thermal knowledge, embodied energy and carbon, costing.**

While the application method is chosen, the tool should analyse which materials can be used. In essence, the BIM model is analysed in the background and the thickness of the insulation material layer is queried, identified via the NL-SfB. Further, the Rc-Value of the chosen refurbishment measure, will call the embedded material database and juxtapose the thickness of insulation material as-is to as-refurbished. If the engineer chooses any particular Rc-Value where the required material thickness is bigger than the available thickness in the existing 3D BIM model, then this material is not applicable, and vice versa. For instance, if the measure Wall Rc 4.0 is chosen and the user wants to apply this inside the cavity wall, cavity injection, then the tool returns the information "Sorry, no material can be injected when Rc-Value is 4.0". Instead, the user chooses a roof measure with an Rc of 6.5 selected as second layer inside, then the correlated material database will be called in the lower section of the UI and will reveal a filtered material list of possible insulation materials, that is applicable for roof insulation when Rc is 6.5. Sharing information regarding application method as well as possible material selections is crucial to inform engineers about holistic possibilities per package. A relevant content requirement represents the knowledge sharing of material DB per Rc-Value. The tool will return the material database including possible thickness, lambda values, fire resistance values and other material-related criteria.

As an additional note, in this step, it is crucial to inform the user of the tool about the consequences when selecting second layers in and outside. The additional sub constructions material is integrated as default definition (see **Chapter 4 Evaluation System** for detailed information regarding Refurbishment Package calculation). It must be noted that in the future development of this tool the user should also be able to define the sub-construction materials and dimensions, which is however out of scope for this thesis.

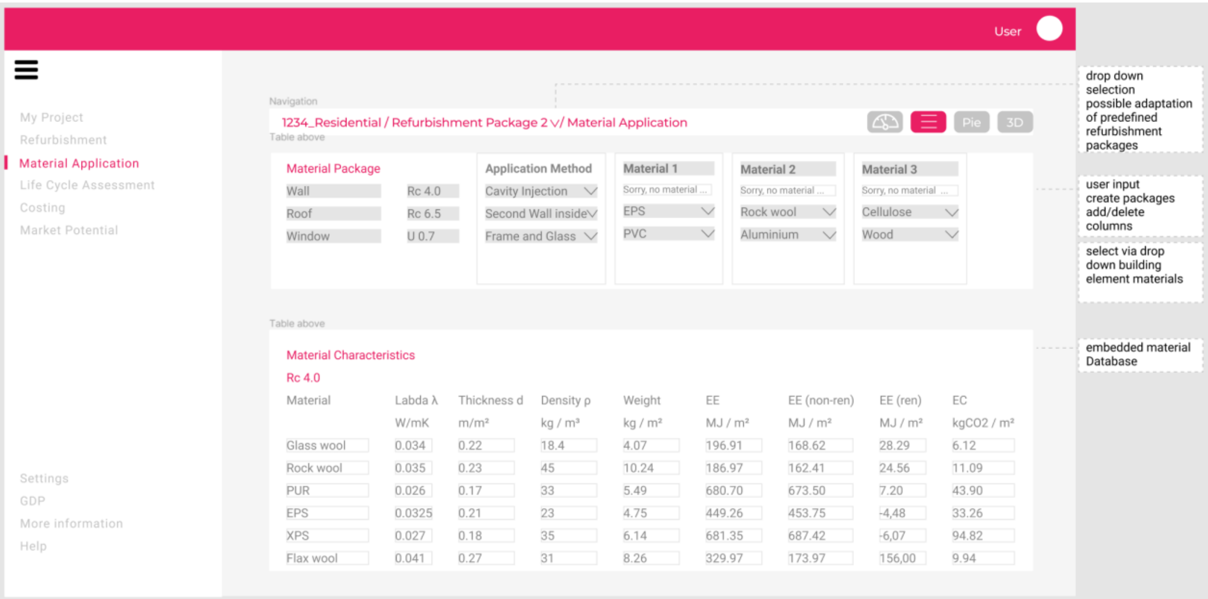



**Figure 57 UI Material Application Performance**

➔ **User wants to see the affected building elements in the 3D BIM model as selected in the application method.**

For each possible measure, the 3D Model viewer should be able to highlight the affected elements in red. If the "Cavity injection" is selected, the model will show the as-is and existing material layer with the NL-SfB code.

For future developments of web-based and model-based building performance assessments, another application method such as “Second Wall inside” and “Second Façade” could be included. The Model viewer could have the ability to add geometry. As from the previous step, the BIM model identifies the existing available insulation thickness and juxtaposes it to the required thickness selected from the material selection. For instance, the Roof with an Rc-Value of 6.5 should be applied as a second layer inside with material Rock wool. The material thickness 0.23 will be called. The task of the model viewer lies in the indication of the application method via modelling a new layer. For instance, the 3D model should access the element of interest (e.g.: exterior wall), should understand the outside borders and should model a new layer in the requested thickness (inside or outside). This is out of scope for current developments and can be thought of in the future.

The engineer should be able to do this procedure for each previously created refurbishment package. Thereby he/she is asked to find possible material scenarios while being introduced to the reasons of possible and not possible measures. The tool applies the material selection per refurbishment measure and package and will remember these as a suggestion for further LCA and costing calculations.

### Life Cycle Assessment

- ➔ **The engineer wants to analyse LCA impact categories (embodied energy and carbon footprint) per building element and per material package and in combination with operational energy and carbon performance.**

In this step the LCA assessments of the created material scenarios (and optional to any dedicated refurbishment packages) are performed, on the **“Life Cycle Assessment”** page. Similar to the refurbishment assessment, also here the user should have two options. Firstly, with the help of table view to allow direct comparison of scenarios, and secondly a direct interaction with the 3D model´s building elements.

Let´s assume the user has created refurbishment packages, and we use Package 2 as an example. In the LCA performance view, see **Figure 58**, the user will find either the formulized material selection from the previous step or an empty dropdown table view where she can add material scenarios. In the lower part of the UI, the computed LCA performance is shown in a correlated table view. As can be seen there, the Embodied Energy (EE) and the Embodied Carbon (EC) illustrate the impact per building material (BE) and total gross-floor impact of the building (GFA). *Keep in mind that in this thesis the sub-construction of additional wall and roof construction is included per default*.

The actual LCA performance in this step helps engineers to make sensitivity analyses between various pre-filtered possible materials applied on their use cases quantity. By using drop-down menus, the user can browse through the embedded and linked material DB for this particular measure. By selecting different materials, the calculated LCA performance should amend accordingly. This is done by accessing the LCA DB and calling the related EE and EC factor per Rc-Value and per m² of the selected material. This factor will be multiplied with the area of the wall and roof of the improved application.

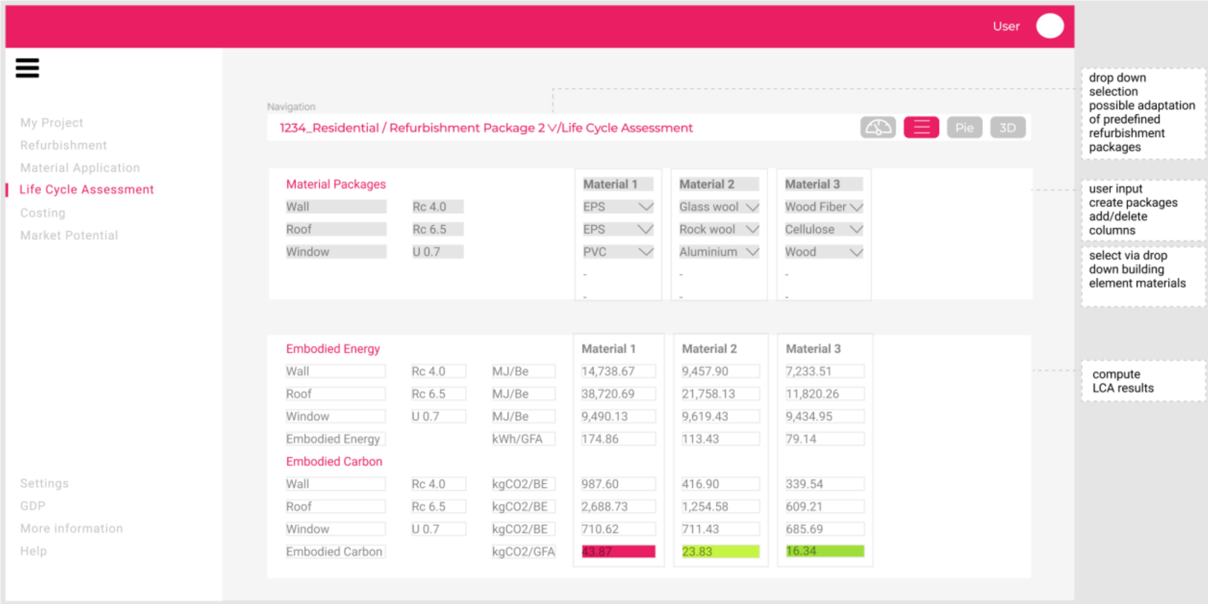



**Figure 58 UI Life Cycle Assessment Performance**

➔ **The engineer wants to evaluate the LCA (embodied and operational performances) in the form of the 3D model and Pie Charts.**

While the engineer can create tables and dedicated material scenarios for refurbishment packages, the application of the embedded material list is also possible using the 3D model viewer, see **Figure 59**. To do so, the user can navigate to the base model or access any earlier created refurbishment package, using the navigation bar. The user can then select the building elements and can derive the related information in the window on the right-hand side. In this window material packages can be selected, either by applying already created packages or creating new ones. Furthermore, for this package, the user can apply materials on building elements, via the same drop-down menu logic as in the previous step. Crucial to understand is that a simultaneous synchronisation between the performance table view and the 3D view building element definition must be guaranteed by the tool as the material definition should be kept updated throughout the entire building project.

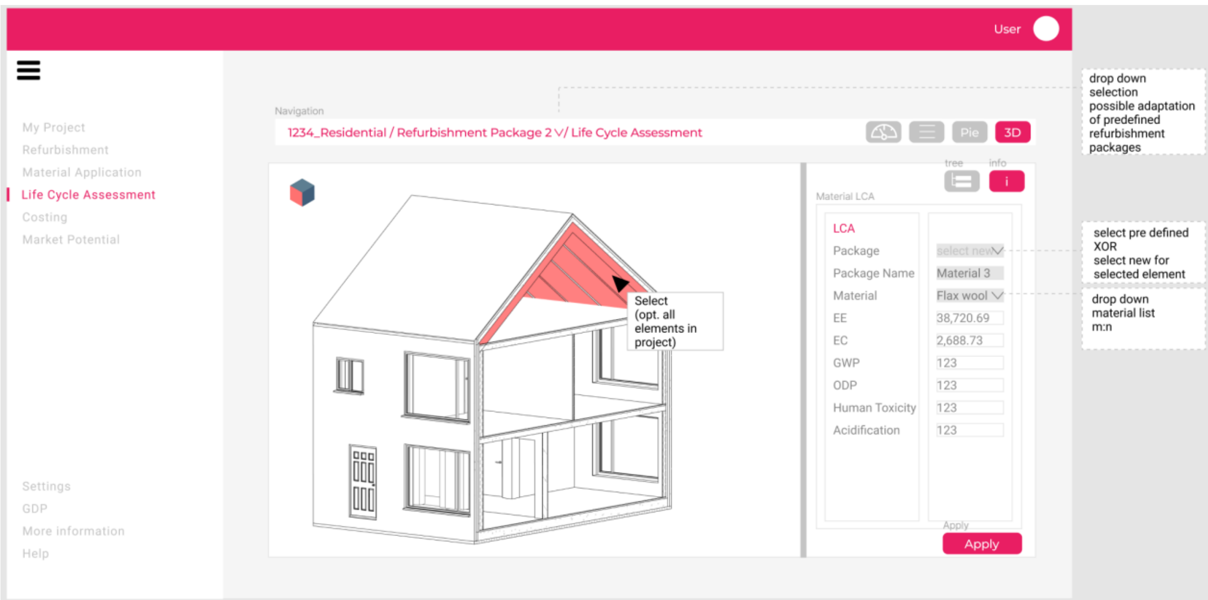



**Figure 59 UI Life Cycle Assessment 3D Viewer**

Additionally, to show the results in the form of Pie charts, the system should be able to save the created Material Packages following the earlier defined refurbishment package. This asks for a locally stored database that combines operational energy and carbon values with embodied energy and carbon (out of scope for now).

### Market Potential

➔ **Receive an overview of all performances established so far.**

The market potential page represents the bridge between the engineering design workflow and the collective decision-making process, see **Figure 60**. It allows all project stakeholders to come together and evaluate in one overview the package definition in all its performance criteria. The previously performed refurbishment packages, the material scenarios as well as the operational savings are parsed.

➔ **Find the trade off´s between sustainable key criteria based on refurbishment package and per defined material selection.**

The trade off´s are presented in the key criteria, used in the consumer preference model. These are the installation method, the investment cost, the gas-saving potential, the carbon reduction, the noise reduction and the comfort improvement. The tool is supposed to showcase these criteria depending on the material selection.

➔ **Receive the market potential as the percentage probability of consumer preference.**

The probability of consumer acceptance is presented in the bottom line of the trade-off table. It gives insight in the likelihood of potential market adoption according to the utility calculation of **Chapter 5 Preference Modelling.**

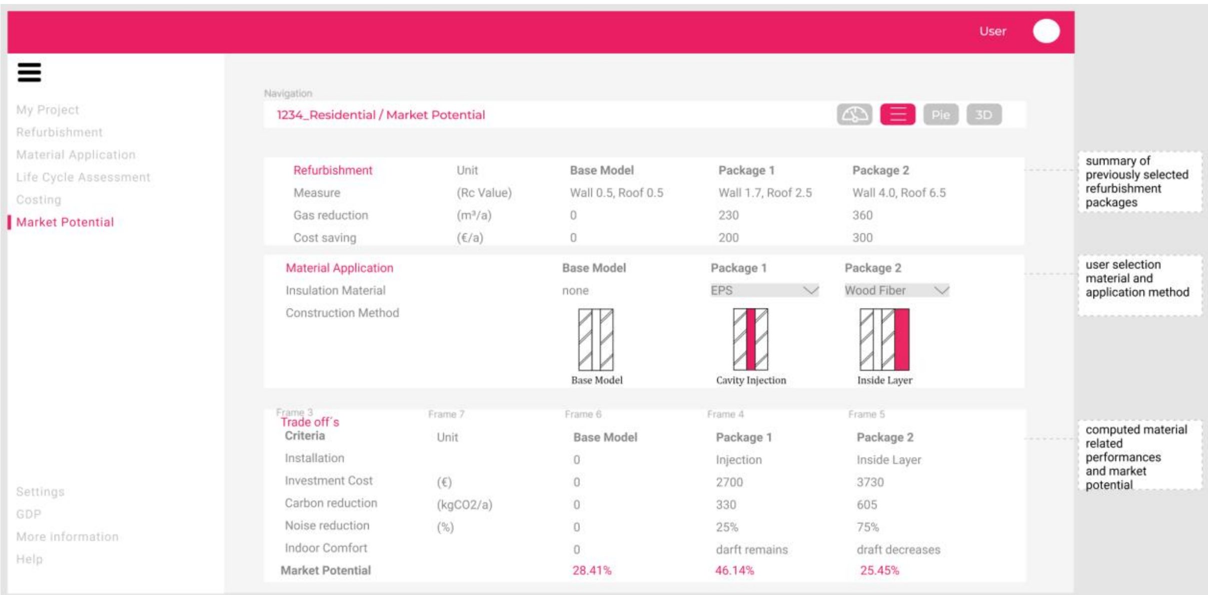



**Figure 60 Market Potential Performance**

## 6.5 Data Dictionary (data requirements)

In this section the data dictionary is introduced that will explain the relations between the externally held databases. The tool ROTUNDORO aims to enrich the BIM practice with databases from MySQL, as elaborated in **Section 6.4.2 Database**. It should link building data (in the form of RDF) with externally held databases. This means, that IFC models in the form of TTL should be enriched. Therefore, multiple data table are discussed in this section to satisfy the user and functional requirements. It includes data to create refurbishment packages, material scenario, LCA and cost assessments. These databases are aimed to be created as MySQL database. A systematic approach to design and build databases are introduced by using Entity Relationship Diagram (ERD). The UML Class Diagram is used to structure the information model between the building element classifications and the external database.

### 6.5.1 Entity Relationship Diagram

The Entity Relationship Diagram (ERD) helps to understand the relation between SQL Databases. The ERD is drawn to conceptually visualise the database design and will help to build the physical databases in a later stage. MySQL workbench 8.0 CE is used to design the databases and to create relational logic (=ERD). Each entity created provides arguments about the database content (at the object and attribute level), its cardinality (relationship), and its connective efficiency. **Figure 61** explains the logic based on an example. The entity "material_db" holds records of NL-SfB, material name and related Rc-Values while the entity "eeec_db" keeps information about NL-SfB and LCA information (embodied energy and carbon) per Rc-Value. To allow a correct relationship between these entities, diverse relationship cardinalates are available. Commonly used cardinalities are one-to-one, many-to-one and many-to-many. To identify the most efficient way of linking the entities with each other, key values are assigned. Primary keys (PK) are used to uniquely identify entities in the DB.[86] The primary key is also used to query the cardinalities. In the example, a many-to-many relationship, "material_db_has_eeec_db", allows many materials to have many LCA performance values, while being connected via the PK, the NL-SfB.

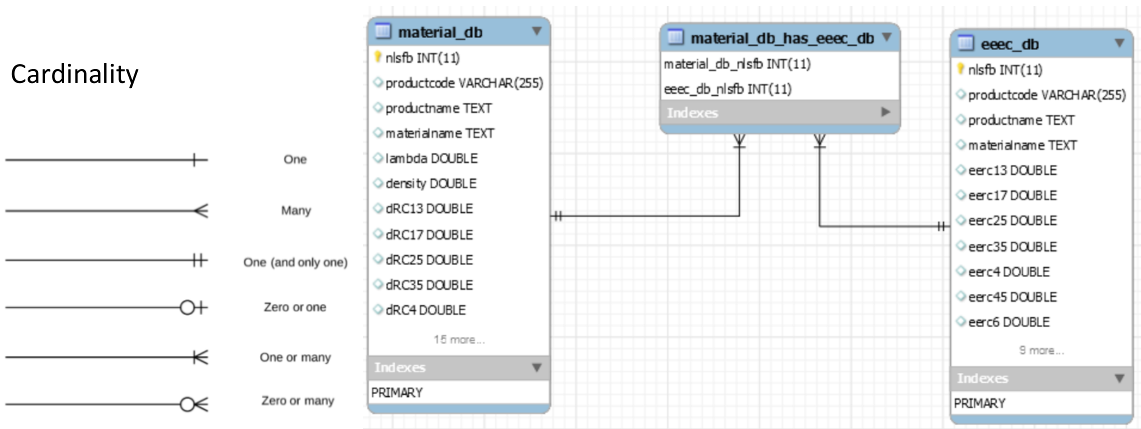



**Figure 61 ERD Example**

### 6.5.2 BIM glTF and TTL

The BIM model in the form of an IFC represents a prerequisite to access components and attributes (e.g.: wall and roof; ID and quantities) via the dashboard view. Although the actual web tool will use converted IFCs in the form of glTF and TTL files the information content remains the same, thus should not be lost in the exchange. The LBDServer allows to access the components via SPARQL queries. It

[86] https://www.lucidchart.com/pages/ER-diagram-symbols-and-meaning

calls user queries (via GET and POST) and accesses thereby the backend graphDB and MongoDB. The TTL file retrieves the building component GUID and can thereby accesse related information. Building components´ basic exchange requirements can be queried, such as the NL-SfB parameter, area and other quantitative parameters. It is aimed to reuse the same logic to allow user queries of digital building components and connect to externally help SQL database, as explained in the following.

### 6.5.3 ERD Schema

The ERD introduces the database structure, the primary key and the relation of the entity schemas. Because the user of the tool retrieves data from different information sources, the logic of the ERD is divided in four major schemas. We define the refurbishment package, the material selection, the LCA and the cost data and the relationships between those, see **Figure 62**.

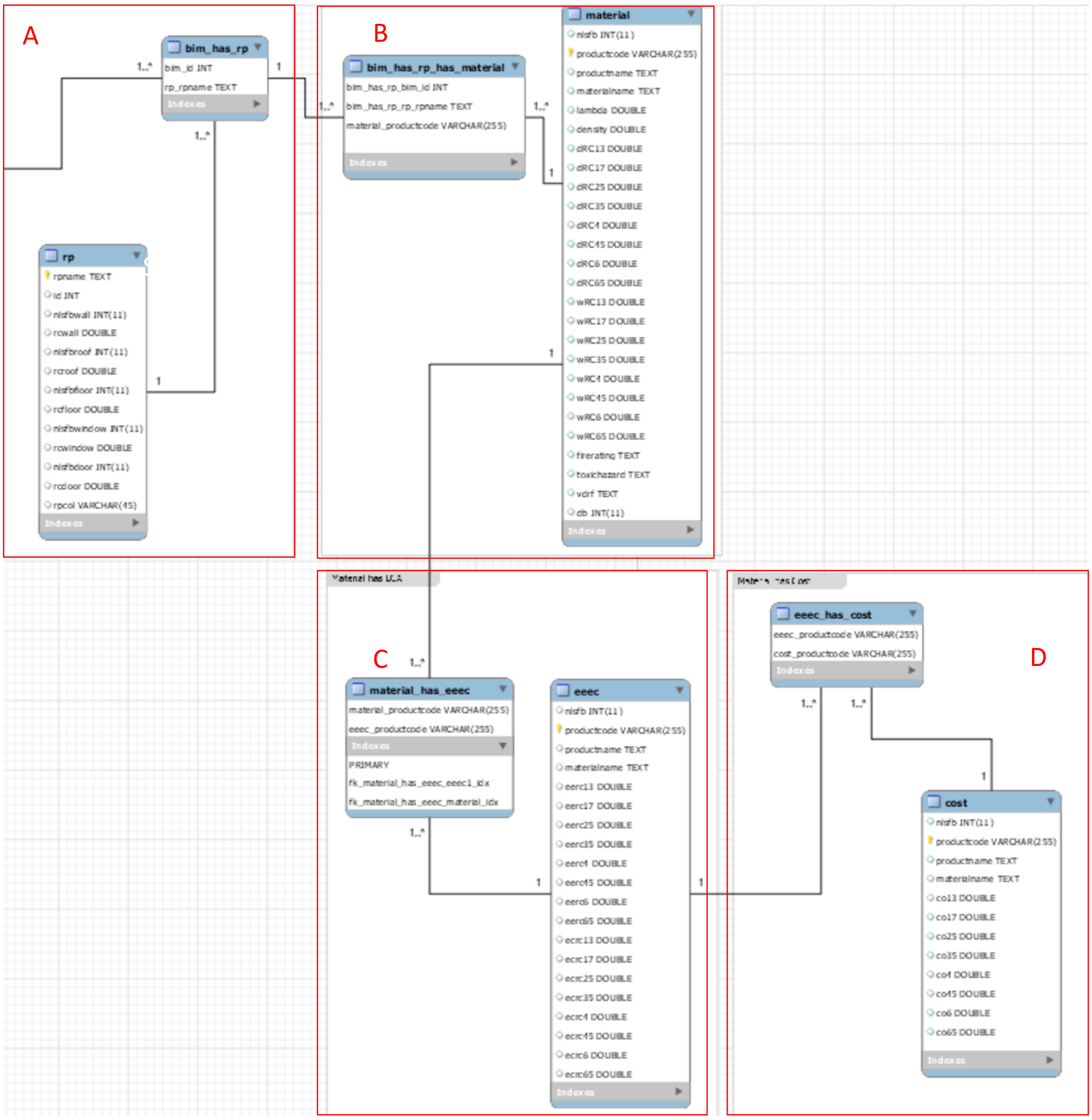



**Figure 62 MySQL Entity Relationship Diagram**

A) It is assumed to use the uploaded BIM model (IFC file structure) as the base model. The entity refurbishment package (RP) is defined with two packages per default. It includes wall and roof insulation improvements. The user is asked to choose possible improvements (Rc-Values) from the drop-down menu at the dashboard. Once selected, the DB (BIM_has_rp) matches the building elements from the BIM model with the user selection. For instance, the user wants to apply the new measure to the wall insulation. The tool accesses the Graph DB tripled store file and queries all wall components with the NL-SfB 41 (=wall insulation). Object properties to be read are described in the UML Class Diagram in **Section 6.5.5 UML Class diagram.**

B) The material entity has a many-to-many relation towards the filtered BIM elements that are affected by the insulation measure. The dashboard allows the user to select a material name that is filtered according to the previously selected NL-SfB code. For instance, if the Rc is 1.7, the material DB shows all possible material names with Rc 1.7. Depending on the user selection of the name (for instance Glass wool) all material parameters are called in the background, such as thickness and weight.

C) In the third section, the LCA data is gathered from the NMD database with a focus on embodied energy (EE) and embodied carbon (EC). Note, this can be extended with the remaining impact categories in the future. The material selection, from above, encompasses the material´s attribute NL-SfB code and name (41 - Glass wool). In the literature study, it is shown that the NMD and the official NL-SfB vary in terms of detail. While the official NL-SfB classifies the exterior wall insulation with NL-SfB 41.02, the NMD data extents this number with two more integers. See NMD and NL-SfB code matching in **Section 6.2.1 Exchange Requirements**. Thus, the LCA DB must allow a one-to-many relation. Only then all possible glass wool products can be filtered and shown to the clients. Depending on the user selection of the glass wool product, the embodied impact values are retrieved and performed in the LCA calculation.

D) Cost data are derived from manufactures (primary Netherlands) and are listed inside MySQL according to the Rc-Value, NL-SfB and material name. Thus, we can find multiple Rc-Values and monetary values stored in one material record. It remains challenging at this point to guarantee a match between the NMD product towards the cost data.

### 6.5.4 ERD Data Tables

The previously defined ERD diagram schema is the basis for creating the database structure. Every data table should have a primary key to identify each record uniquely. The primary keys per table are used to define the relations to each other. In this step, the database is filled with actual data values. MySQL allows querying (with SQL) the relations as a proof of concept. It helps to verify that the primary key definitions and data queries are correct.

**A) Refurbishment packages**

➔ **rp**

As the first step, the user creates refurbishment packages. A new database is established and stored. For instance, the user selects two packages where each package has the ability to include multiple elements, such as wall, roof, window and doors. For each of the chosen building elements a Rc-Value or U-Value can be selected, which will be saved to the refurbishment package. The primary key in this is the package name or id.

| rpname | id | nlsfbwall | rcwall | nlsfbroof | rcroof | nlsfbfloor | rcfloor | nlsfbwindow | rcwindow | nlsfbdoor | rcdoor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| package1 | 1 | 41 | 1.7 | 47 | 2.5 | 43 | 0 | 31 | 0.8 | 31 | 0.8 |
| package2 | 2 | 41 | 4 | 47 | 6.5 | 43 | 0 | 31 | 1.25 | 31 | 1.25 |
| package3 | 3 | 41 | 4 | 47 | 6.5 | 43 | 0 | 31 | 1.25 | 31 | 1.25 |

**Figure 63 DB Refurbishment packages**

➔ **bim_has_rp**

While the refurbishment packages are defined, the building model (BIM) will be filtered according to the user selection. The drop down selection allows the user to select from various building elements. For instance, when wall, roof and floor is selected by the user, the DB will access the elements NL-SfB code. In this case it would be 41, 47 and 43 respectively, and lists the elements with their ID and quantity information.

```
CREATE TABLE IF NOT EXISTS wall_new SELECT NLSFB, ID, Volume, Area, Thickness FROM
buildingmodel.wall WHERE NLSFB='41';
CREATE TABLE IF NOT EXISTS roof_new SELECT NLSFB, ID, Volume, Area, Thickness FROM
buildingmodel.roof WHERE NLSFB='47';
CREATE TABLE IF NOT EXISTS floor_new SELECT NLSFB, ID, Volume, Area, Thickness FROM
buildingmodel.floor WHERE NLSFB='43';
create table BIMRP as select * from wall_new UNION select * from roof_new UNION select * from
floor_new
```

The building elements identified in the refurbishment packages are Wall NL-SfB 41, Roof NL-SfB 47, Floor NL-SfB 43.

| NLSFB | ID | Volume | Area | Thickness |
|---|---|---|---|---|
| 41 | 852474 | 3.91740656 | 65.29010934 | 0.06 |
| 41 | 854387 | 1.388526 | 23.1421 | 0.06 |
| 41 | 854458 | 3.875509506 | 64.5918251 | 0.06 |
| 41 | 855375 | 1.388526 | 23.1421 | 0.06 |
| 47 | 872584 | 5.761118504 | 72.0139813 | 0.08 |
| 43 | 858217 | 0.979780975 | 48.98904877 | 0.02 |
| 43 | 858335 | 1.032 | 51.6 | 0.02 |
| 43 | 858999 | 1.00462064 | 50.23103198 | 0.02 |

**Figure 64 DB Select BIM components**

For instance, four walls apply to three different packages scenarios that result in 12 records. The same logic counts for the remaining building elements.

```
SELECT bimrp.NLSFB, bimrp.ID, bimrp.Area, bimrp.Thickness, bimrp.Volume, refpackage.nlsfbwall,
refpackage.rcwall, refpackage.nlsfbroof, refpackage.rcroof, refpackage.nlsfbfloor, refpackage.rcfloor
FROM bimrp
LEFT JOIN refpackage ON bimrp.NLSFB = refpackage.nlsfbwall OR bimrp.NLSFB = refpackage.nlsfbroof
OR bimrp.NLSFB = refpackage.nlsfbfloor
ORDER BY bimrp.NLSFB;
```

Result Grid | Filter Rows: | Export: | Wrap Cell Content:

| NLSFB | ID | Area | Thickness | Volume | nlsfbwall | rcwall | nlsfbroof | rcroof | nlsfbfloor | rcfloor |
|---|---|---|---|---|---|---|---|---|---|---|
| 41 | 854458 | 64.5918251 | 0.06 | 3.875509506 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 854387 | 23.1421 | 0.06 | 1.388526 | 41 | 1.7 | 47 | 2.5 | 43 | 0 |
| 41 | 854458 | 64.5918251 | 0.06 | 3.875509506 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 852474 | 65.29010934 | 0.06 | 3.91740656 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 855375 | 23.1421 | 0.06 | 1.388526 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 854458 | 64.5918251 | 0.06 | 3.875509506 | 41 | 1.7 | 47 | 2.5 | 43 | 0 |
| 41 | 852474 | 65.29010934 | 0.06 | 3.91740656 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 855375 | 23.1421 | 0.06 | 1.388526 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 854387 | 23.1421 | 0.06 | 1.388526 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 41 | 852474 | 65.29010934 | 0.06 | 3.91740656 | 41 | 1.7 | 47 | 2.5 | 43 | 0 |
| 41 | 855375 | 23.1421 | 0.06 | 1.388526 | 41 | 1.7 | 47 | 2.5 | 43 | 0 |
| 43 | 858999 | 50.23103198 | 0.02 | 1.00462064 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 43 | 858217 | 48.98904877 | 0.02 | 0.979780975 | 41 | 4 | 47 | 6.5 | 43 | 0 |
| 43 | 858999 | 50.23103198 | 0.02 | 1.00462064 | 41 | 1.7 | 47 | 2.5 | 43 | 0 |
| 43 | 858217 | 48.98904877 | 0.02 | 0.979780975 | 41 | 4 | 47 | 6.5 | 43 | 0 |

**Figure 65 Apply refurbishment package to BIM**

### B, C, D) Material/Embodied Impact/Costing

The next step will be used to access possible materials for each building element according to the selected Rc-Value. So, for instance, Wall (ID_854458) with an area of 64,59m², and RC-Value 4 XOR 4 XOR 1.7, the material database should list all possible materials per name. Of course, the double value (of Rc-Value of 4) could be simplified. To filter all possible materials for dedicated NL-SfB code and related Rc-Values, we must ask for a many-to-many relationship between the DB **BIM has RP** and **material/eeec/cost.** The primary key for material, eeec and cots is material code. So, multiple Rc-Values can have multiple materials, eeec and cost data.

The data tables for materials, embodied impacts and costing are structured the same way. They list the materials regarding NL-SfB, product code and name. Every record of a material contains information for every possible Rc-Value. Knowing the NL-SfB = 41 and the user´s queried RC-Value, the material, additional information can be queried with the product code starting with 41.

| nlsfb | productcode | productname | materialname | lambda | density | dRC13 | dRC17 | dRC25 | dRC35 | dRC4 | dR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 47 | 47.07.004 | EPS | EPS | 0.0325 | 22.5 | 4 | 6 | 8 | 11 | 13 | 15 |
| 47 | 47.07.007 | XPS | XPS | 0.027 | 35 | 4 | 5 | 7 | 9 | 11 | 12 |
| 47 | 47.08.001 | Glaswol MWA 2012; platen; | Glass wool | 0.034 | 18.4 | 4 | 6 | 9 | 12 | 14 | 15 |
| 47 | 47.08.002 | Steenwol MWA 2012; platen; | Rock wool | 0.035 | 45 | 5 | 6 | 9 | 12 | 14 | 16 |
| 47 | 47.08.009 | Vlaswol | Flax wool | 0.041 | 31 | 5 | 7 | 10 | 14 | 16 | 18 |
| 47 | 47.07.024 | Houtvezel flexibele isolatie (55 kg/m3) | Wood Fiber | 0.038 | 45 | 5 | 6 | 10 | 13 | 15 | 17 |
| 47 | 47.08.008 | Cellulose | Cellulose | 0.04 | 70 | 5 | 7 | 10 | 14 | 16 | 18 |
| 41 | 41.04.008 | EPS | EPS | 0.0325 | 22.5 | 4 | 6 | 8 | 11 | 13 | 15 |
| 41 | 41.04.006 | XPS | XPS | 0.027 | 35 | 4 | 5 | 7 | 9 | 11 | 12 |
| 41 | 41.04.001 | Glaswol MWA 2012; platen; | Glass wool | 0.034 | 18.4 | 4 | 6 | 9 | 12 | 14 | 15 |
| 41 | 41.04.002 | Steenwol MWA 2012; platen; | Rock wool | 0.035 | 45 | 5 | 6 | 9 | 12 | 14 | 16 |
| 41 | 41.04.009 | Vlaswol | Flax wool | 0.041 | 31 | 5 | 7 | 10 | 14 | 16 | 18 |
| 41 | 41.04.040 | Houtvezel flexibele isolatie (55 kg/m3) | Wood Fiber | 0.038 | 45 | 5 | 6 | 10 | 13 | 15 | 17 |
| 41 | 41.04.039 | Celluloseplaten, incl dampremmende ... | Cellulose | 0.04 | 70 | 5 | 7 | 10 | 14 | 16 | 18 |
| 43 | 43.03.002 | Glaswol MWA 2012; platen; | Glass wool | 0.034 | 18.4 | 4 | 6 | 9 | 12 | 14 | 15 |
| 43 | 43.03.003 | Steenwol MWA 2012; platen; | Rock wool | 0.035 | 45 | 5 | 6 | 9 | 12 | 14 | 16 |
| 43 | 43.03.004 | XPS | XPS | 0.027 | 35 | 4 | 5 | 7 | 9 | 11 | 12 |
| 43 | 43.03.005 | PUR (lucht) | PUR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 66 Apply material properties to Refurbishment package**

| | nlsfb | productcode | productname | materialname | eerc13 | eerc17 | eerc25 | eerc35 | eerc4 | eerc45 | eerc6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ▶ | 47 | 47.07.004 | EPS | EPS | 88.7 | 117.5 | 170.3 | 239.9 | 273.4 | 309.4 | 410.2 |
| | 47 | 47.07.007 | XPS | XPS | 0 | 178.2 | 258.2 | 0 | 414.5 | 0 | 0 |
| | 47 | 47.08.001 | Glaswol MWA 2012; platen; | Glass wool | 0 | 51.5 | 74.6 | 0 | 119.8 | 0 | 0 |
| | 47 | 47.08.002 | Steenwol MWA 2012; platen; | Rock wool | 0 | 48.9 | 70.8 | 0 | 113.7 | 0 | 0 |
| | 47 | 47.08.009 | Vlaswol | Flax wool | 0 | 86.3 | 125 | 0 | 200.7 | 0 | 0 |
| | 47 | 47.07.024 | Houtvezel flexibele isolatie (55 kg/m3) | Wood Fiber | 17.7 | 23.5 | 34.2 | 48.2 | 55.1 | 62.1 | 82.4 |
| | 47 | 47.08.008 | Cellulose | Cellulose | 0 | 8.8 | 12.7 | 0 | 20.4 | 0 | 0 |
| | 41 | 41.04.008 | EPS | EPS | 88.7 | 117.5 | 170.3 | 239.9 | 273.4 | 309.4 | 410.2 |
| | 41 | 41.04.006 | XPS | XPS | 0 | 178.2 | 258.2 | 0 | 414.5 | 0 | 0 |
| | 41 | 41.04.001 | Glaswol MWA 2012; platen; | Glass wool | 0 | 51.5 | 74.6 | 0 | 119.8 | 0 | 0 |
| | 41 | 41.04.002 | Steenwol MWA 2012; platen; | Rock wool | 0 | 48.9 | 70.8 | 0 | 113.7 | 0 | 0 |
| | 41 | 41.04.009 | Vlaswol | Flax wool | 0 | 86.3 | 125 | 0 | 200.7 | 0 | 0 |
| | 41 | 41.04.040 | Houtvezel flexibele isolatie (55 kg/m3) | Wood Fiber | 17.7 | 23.5 | 34.2 | 48.2 | 55.1 | 62.1 | 82.4 |
| | 41 | 41.04.039 | Celluloseplaten, incl dampremmende ... | Cellulose | 0 | 84.1 | 117.3 | 0 | 178.3 | 0 | 0 |
| | 43 | 43.03.002 | Glaswol MWA 2012; platen; | Glass wool | 0 | 51.5 | 74.6 | 0 | 119.8 | 0 | 0 |
| | 43 | 43.03.003 | Steenwol MWA 2012; platen; | Rock wool | 0 | 48.9 | 70.8 | 0 | 113.7 | 0 | 0 |
| | 43 | 43.03.004 | XPS | XPS | 0 | 178.2 | 258.2 | 0 | 414.5 | 0 | 0 |
| | 43 | 43.03.005 | PUR (lucht) | PUR | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 43 | 43.03.007 | EPS | EPS | 88.7 | 117.5 | 170.3 | 239.9 | 273.4 | 309.4 | 410.2 |
| | 43 | 43.03.008 | Fenolschuim platen | Fenolschuim ... | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 43 | 43.03.011 | Cellulair glas | Cellulair | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 43 | 43.03.012 | Cellulose | Cellulose | 0 | 8.8 | 12.7 | 0 | 20.4 | 0 | 0 |
| | 43 | 43.03.013 | Vlasplaten | Flax wool | 0 | 86.3 | 125 | 0 | 200.7 | 0 | 0 |
| | 43 | 43.03.024 | Schapenwol | Sheep wool | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 67 Apply embodied impact to material selection**

### 6.5.5 UML Class diagram

UML class diagrams are used to build data-oriented meta-models which then typically result in object-oriented code (e.g., Python code, C# code, Java code). Although this UML class diagram looks similar to the ERD, they are different in the sense that the latter is mostly used for SQL databases. So, in this step, an UML class diagram will be created that forms the backbone of the JavaScript calculation. It thus relates to the BIM data as well as the MySQL data, yet it is a stand-alone UML class diagram that is crucial for the code development. The structure of the information model is thereby of interest, rather than their specific object state/state of information. It allows the modelling of static system structures of data that are related by properties and attributes *(Aurum & Wohlin, n.d).* **Figure 68** illustrates the concept of the class diagram. A class is defined as the classification of multiple objects that share the same properties, attributes and operations. Classes have associations with each other that explain a bidirectional relation between classes. Other relations are available as well (subsumption, one-directional relation, etc.). An operation can request a service of an object of a class in order to change behaviour of the system, for instance returning attributes.

The UML class diagram is meant to structure the BIM model components. The task of the tool will be to access building elements by the NL-SfB code and sets other databases into relation. Furthermore, the tool will have to perform calculations (mainly multiplications) with the building element quantities and the assigned value of SQL database. Thus, some other parameters are necessary to know. The UML class diagram, **Listing 1** allows to schematically illustrate the logic.

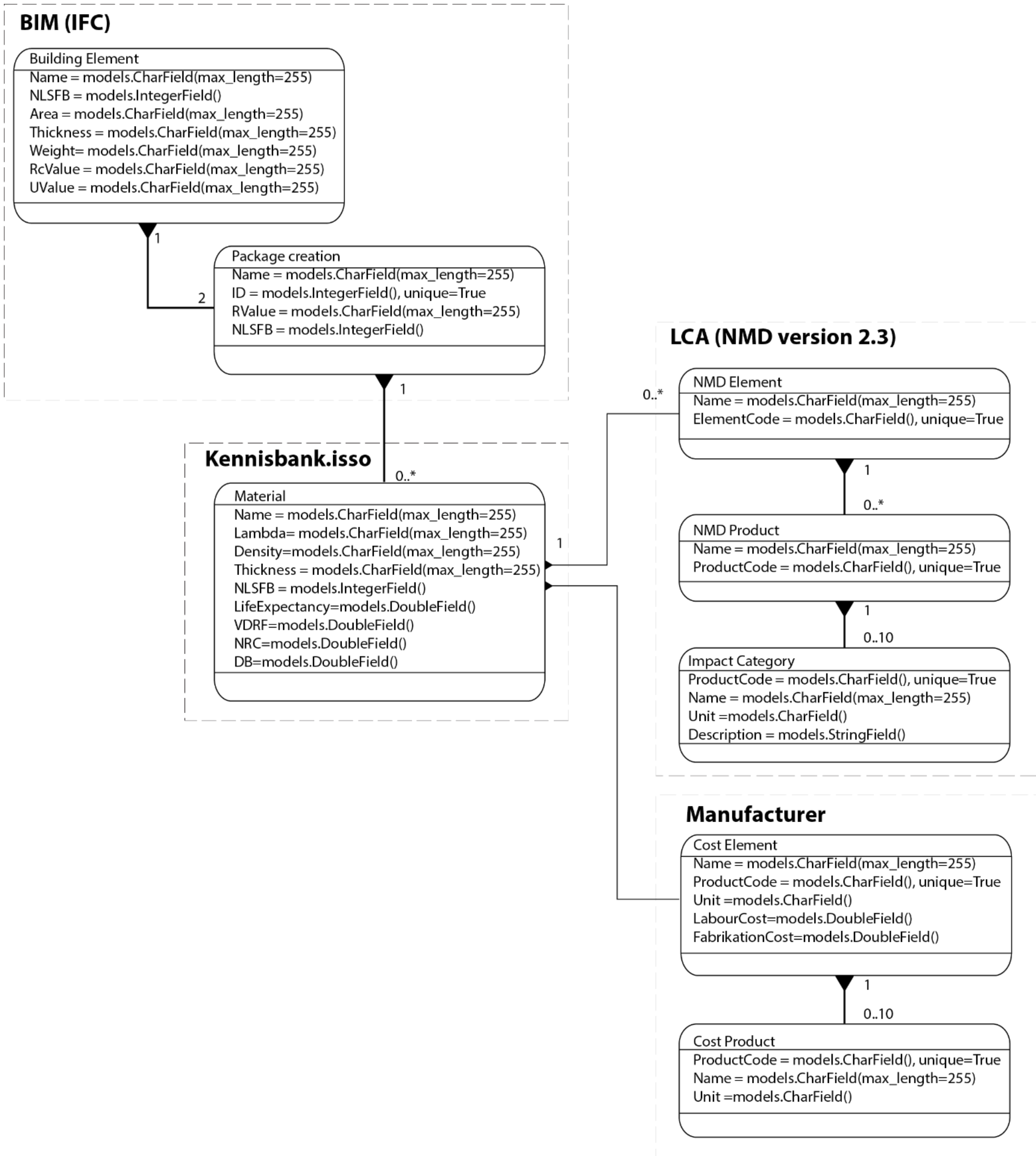



**Figure 68 UML Class Diagram**

```
class Wall(models.Model):
    Name = models.CharField(max_length=255)
    NLSFB = models.IntegerField()
    Area = models.CharField(max_length=255)
    Thickness = models.CharField(max_length=255)
    Weight = models.CharField(max_length=255)
    RValue = models.CharField(max_length=255)
    UValue = models.IntegerField()
```

**Listing 1 UML Class Diagram for BIM model components**

## 6.6 Code implementation

In the final section of the tool development, the code implementation is discussed. The System Architecture in **Figure 69** indicates the implementation steps, reaching from MVC, DB and web browser. The installation of the existing LBDServer (front- and backend) as well as basic understanding for ReactJS development will be discussed (Section 6.6.1). Next, the Controller will explain the navigation for the newly created frontend web pages (Section 6.6.2). The view components introduce the frontend layout and reusable component functionalities (6.6.3). Next, the connection towards the externally held database MySQL is created (Section 6.6.4). Finally, the web environment will introduce three out of six UI Site Views (My Project, Refurbishment and Market Potential) (Section 6.6.5). The full code implementation can be found in the **Appendix G.** A video of the established solution, the tool ROTUNDORO, can be found on YouTube.

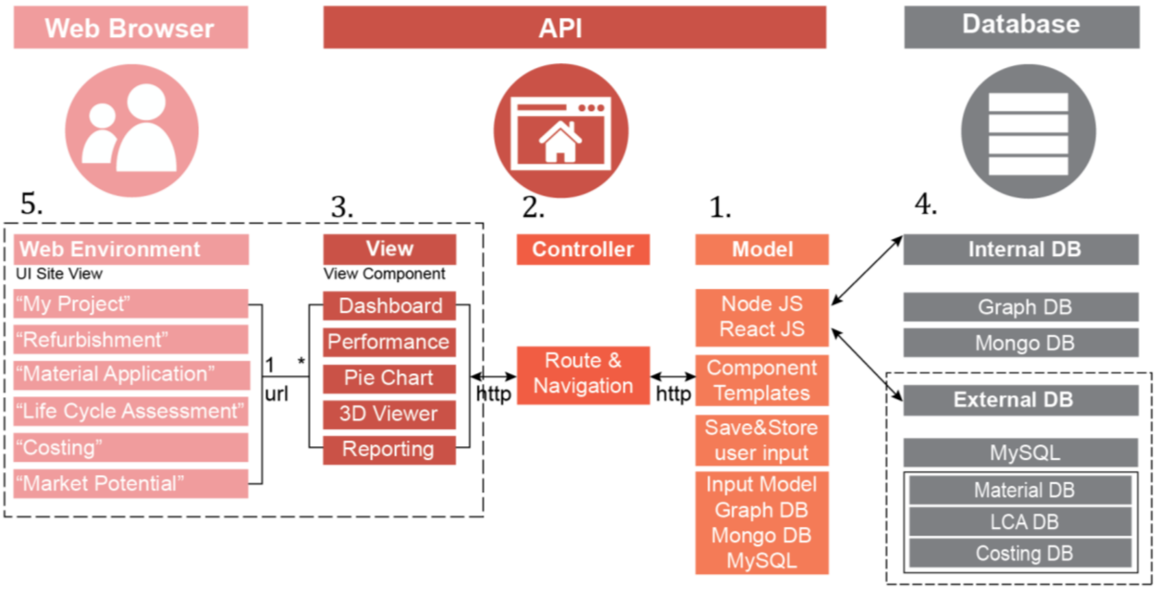



**Figure 69 System Architecture implementation steps**

### 6.6.1 Installation & Development instructions

The requirements, as explained in the Sections **6.3 System Requirements** and **6.4 System Design**, show that the LBD Server is built upon NodeJS (backend) and ReactJS[87] (frontend). ReactJS uses components that can be retrieved from the material-ui[88]. It is commonly applied as it provides a clear guideline to create components, structure and navigate between them. Further, Graph DB and Mongo DB are required to be installed. Visual Studio Code[89] is used as the coding environment. Necessary steps to successfully install the LBD Server can be found on the GitHub[90] repository. This thesis used the LBDServer version from January 2021. Download and instal Mongo DB[91], Graph DB[92] and NodeJS[93].

[87] https://reactjs.org/tutorial/tutorial.html#what-is-react
[88] https://material-ui.com/getting-started/usage/
[89] https://code.visualstudio.com/
[90] https://github.com/LBDserver
[91] https://www.mongodb.com/
[92] https://graphdb.ontotext.com/
[93] https://nodejs.org/en/

1. Download the "backend_prototype-main", "front-react-main" and "backend-converter" and store in a repository on the local drive.
2. Connect to Mongo DB, Graph DB and activate NodeJS.
3. Open Visual Studio Code and use terminal to navigate to the local drive repository to open backend and frontend code (optional: use command prompt).
4. Execute the backend code with "npm install" and "npm run dev".
5. Execute the frontend code with "npm install" and "npm start".
6. Install material-ui and run "npm install @material-ui/core" and "npm install @material-ui/icons" to eventually import icons from the @material-ui/icon
7. Imports libraries per default, see **Listing 2**.

```
import React, {useState, useContext, useRef, useEffect} from "react";
import {
  Grid,
  Button,
  Typography,
  TextField,
  Paper,
  Box
} from "@material-ui/core";
import useStyles from "@styles";
import AppContext from '@context';
import { Link, Redirect } from 'react-router-dom';
```

**Listing 2 React library import**

## Components and Props

ReactJS provide tool developers with great reusability and flexibility of code. The function component is commonly used in web development. It can be seen as a function that use properties (props) as arbitrary input value to return elements that are rendered on the UI, see **Listing 3**. The function component Welcome calls the property props.name. It is a conventional way of scripting in JavaScript, however, it is limited in its reusability. Different from conventional function-based component thinking, ReactJS also builds upon class components. Class components define a class that extends to the React.Component. The class component can extend the component thinking as it includes multiple functions that executes parts of the component, see **Listing 4**. Keeping one root class component gives variety to reuse it in any context. Once a component is created it can be passed on and embedded into other components using a syntax. The lifecycle method of React is used to define functionalities of the components.

```
function Welcome(props) {
  return <h1>Hello, {props.name}</h1>;
}
```

**Listing 3 Function component**

```
class Welcome extends React.Component {
  render() {
    return <h1>Hello, {this.props.name}</h1>;
  }}
```

**Listing 4 Function vs. Class component[94]**

[94] https://reactjs.org/docs/components-and-props.html

## React Lifecycle method

The lifecycle method in React defines a series of events for class component. It encompasses the creation, the execution and the final state of any component. It includes three stages, namely mounting, updating and unmounting, see **Figure 70**. For instance the render() method is a function that returns and displays the component on the UI. Once the render function is executed, the componentDidMount method is called to set up the component contents for the first time. The componentDidUpdate is called when the state of the component changed. The state can be changed by updating the component via the properties or the setState hook. Finally, the componentDidUnmount is called to dissolve the component. When setting up a code in Visual Studio, these methods have to be used separately from each other. The logic is to create a structure of a loop, that allows to run and execute each component after each other. Nested functions can become messy and should be avoided, see **Listing 5** for an example. The class component Clock is created and updates the state using this.state, then the mount and unmount function is called and finally, the render function.

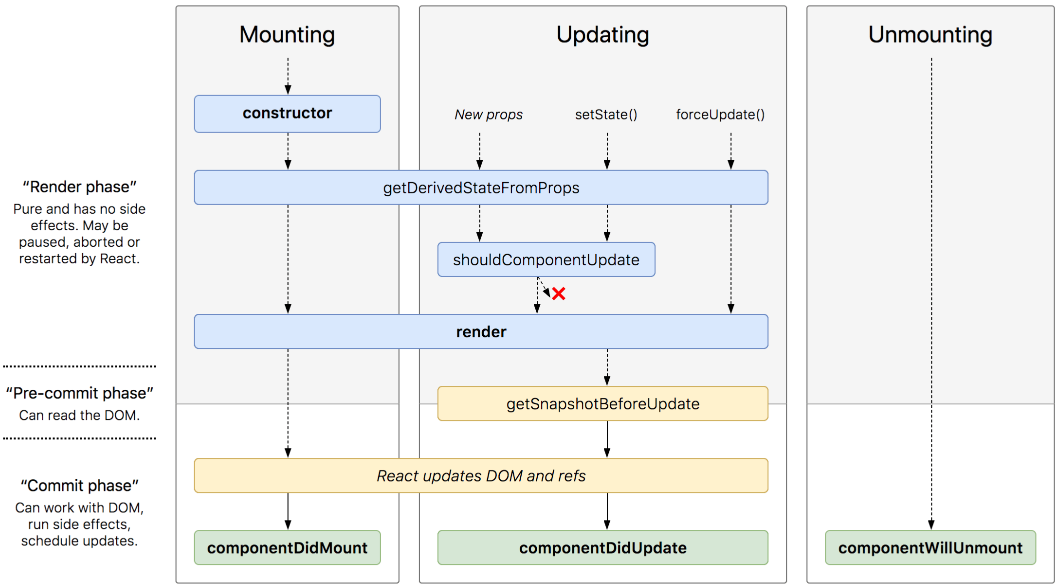



**Figure 70 React Life Cycle method**[95]

```
Class Clock extends React.Component {
  constructor(props) {
    super(props);
    this.state = {date: new Date()};
  }
  componentDidMount() {  }
  componentWillUnmount() {  }
  render() {
    return (
      <div>
        <h2>It is {this.state.date.toLocaleTimeString()}.</h2>
      </div>
    ); }}
```

**Listing 5 React Life Cycle method example**[96]

[95] https://programmingwithmosh.com/javascript/react-lifecycle-methods/
[96] https://reactjs.org/docs/state-and-lifecycle.html

### React Hooks

The update of the state can either be done using the properties via this.state or using React Hooks[97]. With hook functions, also called events, it is possible to hook into the state of a lifecycle stage of a component. Commonly used React hooks are useState and useEffect that set the state and handle changes. Hooks can only be used in function components, and not in class components, and must be listed and ordered in the same exact way at every page and component, on the top, see **Listing 6**.

```
import React, { useState, useContext, useEffect } from 'react';
```

**Listing 6 React Hooks**

The event is responsible to query the components´ as-is state and to change the state according to a function that the component underlies. This allows an automatic state update of data changed from user on the UI *(Pieruccetti, 2020; Clark & Barn 2012).* For instance, the function useState[] is applied to add new elements, a component state can be defined via defining a constant (const) initial variable. Thereby an object or class component is constructed in the form of an array. The myProjects represents every single project in the array, the setmyProjects allows to update and add new objects in the list.

```
const [myProjects, setmyProjects] = useState([])
```

**Listing 7 useState, set my Project**

The useEffect hook is the equivalent to the lifecycle method (mounting and updating). When using a useEffect function, React is called to run changes and to update them accordingly. The useEffect is called inside the component, in order to allow full access to the properties. Also, the state update is always run after the render, by default.[98]

## 6.6.2 Routing backend to frontend

The representation of the tools functionalities on the frontend is navigated via routing. The systems architecture shows that five web pages (UI Site Views) are designed encompassing a nested sub structure for five View components. For each of the page's a dedicated .js page needs to be created in the frontend code. In this thesis the focus is on the main pages, including dashboard and performance view, see **Figure 71**. In each page, the dedicated component is created and returned. This componetn will be then linked to a URL in the routing.

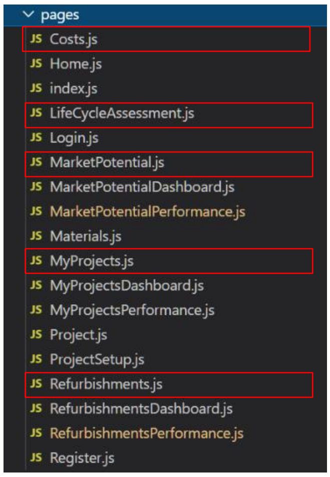



**Figure 71 Web pages**

### Routing

While the user requests information via the web browser, for instance via activating buttons, HTTP requests are sent towards the API, the controller routes. Routes match the request with the right paths. Routes can be accessible for both authenticated and unauthenticated users. AuthRoute is only accessible for authenticated users and NonAuthRoute is only accessible for unauthenticated users. For

97 https://reactjs.org/docs/hooks-intro.html
98 https://reactjs.org/docs/hooks-overview.html

the five main web pages, from **Figure 71**, a dedicated path is created, see **Listing 8**. The subpages Dashboard and Performance, are used within a navigation bar component, as explained in **Section 6.6.3.**

```
 <Switch>
<Route exact path="/" component={Home} />
<Route exact path="/project" component={Project} />
<AuthRoute exact path="/projectsetup" component={ProjectSetup} />
<NonAuthRoute exact path="/register" component={Register} />
<NonAuthRoute exact path="/login" component={Login} />
<AuthRoute exact path="/myprojects" component={MyProjects} />
<AuthRoute exact path="/refurbishments" component={Refurbishments} />
<AuthRoute exact path="/materials" component={Materials} />
<AuthRoute exact path="/lifecycleassessment" component={LifeCycleAssessment}/>
<AuthRoute exact path="/costs" component={Costs} />
</Switch>
```

**Listing 8 Routing**

### 6.6.3 View Components

The view components are used to deconstruct the web page design into subparts, as visualised in **Figure 69** (3). Each component can be brought into context when using a basic Layout Grid for the web page design. The Grids are used throughout all pages and are filled with multiple functional components. **Appendix G.4** shows the basic Grid layout for the UI.

Components developed in this thesis are shown in **Figure 72**. The component menu is used to navigate through the main web pages on the UI (My Project, Refurbishment, Material Application, Life Cycle Assessment, Costing and Market Potential). The navigation bar (Navbar) component is used to navigate through the nested UI components (Dashboard and Performance). More components are identified, such as tables to store newly created projects and the drop down selection buttons. Also, the 3D geometry viewer from the LBDviewer is reused. The components are built in such a way to make them reusable in any context.

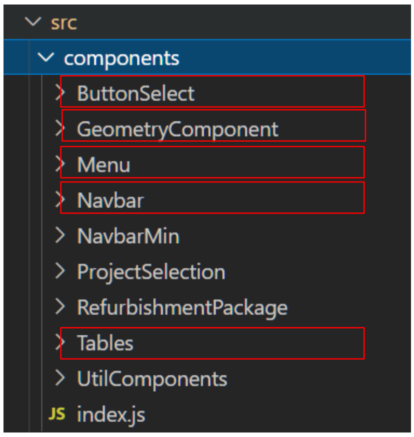



**Figure 72 View components**

#### Hamburger Menu

The hamburger menu is defined as a drawer on the left hand side of the UI. A drawer is used that allows a responsive adaptation of the screen and menu bar. A setState function is used to allow navigating through the routing, the return function is used to describe the layout of the menu drawer. Buttons are executed with a link component that navigates to the dedicated route page. A little hover highlight is used for indication purposes, see code in **Appendix G, Listing 15.**

#### NavbarMin

The navigation bar miniature allows the user to browse through the UI View Components, “Dashboard”, “Performance”, “3D Viewer” and “Pie Chart”” see **Figure 73**. In the dashboard view the user is enabled to receive general information about each performance step. The performance sections introduce the user with calculation methods applied to assess the building (from refurbishment energy package, to LCA and costing). The 3D viewer and Pie chart are meant to illustrate results after having performed the calculation performance. The latter two are out of scope for implementation and will be left out in further discussions.

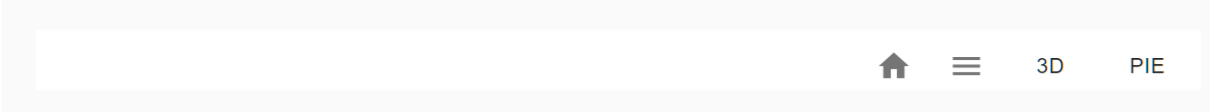



**Figure 73 Navigation Bar (UI)**

The navbar is executed as a nested component structure. This means that the mother component NavbarMin.js creates a constant holding a property with an variable {link}, which further is referenced with a list of links [0..3], see **Listing 9**. The child components, such as NavbarMinMP.js and NavbarMinRef.js imports the host component and defines with a constant the list of links [0..3] as navigation links to each dedicated sub URL, see **Listing 10**.

For instance:

[0] http://localhost:3000/refurbishments/dashboard
[1] http://localhost:3000/refurbishments/performance
[2] http://localhost:3000/refurbishments/3D
[3] http://localhost:3000/refurbishments/PIE

```
import React, { useContext, useState } from "react";
import { NavLink, Link } from "react-router-dom";
import "../../App.css";

import {
    Button,
    IconButton,
} from "@material-ui/core";
import MenuIcon from "@material-ui/icons/Menu";
import HomeIcon from "@material-ui/icons/Home";

const NavbarMin = ({links}) => {

    return (
    <div className="NavbarMin">
        <div className="leftSide"></div>
        <div className="rightSide">
            <IconButton component={Link} to={links[0]}>
                <HomeIcon />
            </IconButton>
            <IconButton component={Link} to={links[1]}>
                <MenuIcon />
            </IconButton>
            <Button disabled={true} href={links[2]}>3D</Button>
            <Button disabled={true} href={links[3]}>Pie</Button>
        </div>

    </div>
    );
};
export default NavbarMin;
```

**Listing 9 NavbarMin.js mother component**

```
const NavbarMinMP = () => {
    const [navigationlink, setnavigationlink] =useState(["/myprojects/dashboard", "/myprojects/performa
nce", "/myprojects/3D", "/myprojects/PIE"])

    return (
        <NavbarMin links={navigationlink}/>
    );
};

export default NavbarMinMP;
```

**Listing 10 NavbarMinMP.js child component**

### Component MPTable

The component MPTable stands for My Project Table and is used in the first web page “My Project”. On this page, the user needs to interact with the table and fill in the project definitions, such as project name, client name and building typology, see **Section 6.4.4 Web Browser**. The table contains table cells in which the user is asked to enter the information. A function calls the variables of the filled in variables and passes them on into the list, that will appear on the UI. Find the code in **Appendix G, Listing 16.**

### Controlled Open Select

The ControlledOpenSelect is created from the material.ui and is used as dropdown button for individual purposes. Firstly, the constant useStyle is defined to design the drop down menu, which then will be filled with possible selection options depending on the web page, see **Listing 11**.

```
const useStyles = makeStyles((theme) => ({
  button: {
    display: 'block',
    marginTop: theme.spacing(2),
  },
  formControl: {
    margin: theme.spacing(1),
    minWidth: 100,
  },
}));
```

**Listing 11 Drop Down Design**

Next, the function ControlledOpenSelect is defined which uses the class option and selectvaluechange as input. The handle change is meant to read and log the user selection. The class option represents the possible options of the drop down list. The render of the class is defined in the MenuItem, which includes the attributes option.ID, option.Name and option.Value. This class can later be filled with objects depending on the requirements per web page, see **Listing 12**.

```
export default function ControlledOpenSelect({options, selectvaluechange}) {
  const classes = useStyles();
  const [open, setOpen] = React.useState(false);
  const handleChange = (event) => {
    selectvaluechange (event.target.value)
    console.log(event.target.value)
  };
  const handleClose = () => {
    setOpen(false);
  };
  const handleOpen = () => {
    setOpen(true);
  };

  return (
    <FormGroup row>
      <FormControl className={classes.formControl}>
        <InputLabel id="demo-controlled-open-select-label">Select</InputLabel>
        <Select
          labelId="demo-controlled-open-select-label"
          id="demo-controlled-open-select"
          onChange={handleChange}
          class="dropdowntext">
          <MenuItem value={0}>
            <em>None</em>
          </MenuItem>
            {
              options.map(option => {
                return (<MenuItem key={option.id} value={option.value}>{option.name}</MenuItem>)
              })
            }
        </Select>
      </FormControl>
```

```
    </FormGroup>
  );
}
```

**Listing 12 Drop Down Component**

### 6.6.4 External Database

The system architecture shows the connection to an external DB, in this thesis MySQL, see **Figure 69** (4). The connection to the MySQL DB and tables can be seen in the **Listing 13**. The host, user, password and database name are needed as well as an explicit definition of the table(s). The below shows the connection of the NMD database. As explained in the **Section 6.5.1 Entity Relationship Diagram** multiple tables are created that need to be accessed here.

```
//Connect to MySQL
const mysql = require('mysql');

// nmd
// First you need to create a connection to the database
// Be sure to replace 'user' and 'password' with the correct values
const con = mysql.createConnection({
  host: '127.0.0.1',
  user: 'root',
  password: 'sd876341/&%dsla6SFo776o/(&doz',
  database: 'nmd'
});

con.connect((err) => {
  if(err){
    console.log('Error connecting to Db');
    return;
  }
  console.log('Connection established');
});

//Query eeec table from MySQL
con.query('SELECT * FROM eeec', (err,rows) => {
  if(err) throw err;

  console.log('Data received from Db:');
  console.log(rows);
});

con.end((err) => {
  // The connection is terminated gracefully
  // Ensures all remaining queries are executed
  // Then sends a quit packet to the MySQL server.
});
```

**Listing 13 MySQL connection**

A direct connection from the MySQL local host DB to the React front-end is sufficient for user queries (CRUD performed with https). It is recommended to store the selection of the user on a middleware in the form of a web hosted DB. The MySQL data requires an intermediate connection to Node.js, to the backend. This step avoids a direct overwriting of the user queries towards the MySQL DB.

### 6.6.5 Web Environment

The web environment presents the five web pages, UI Site Views, see **Figure 69** (5). The web page My Project, Refurbishment, and Market Potential are developed and introduced according to the functional requirements.

#### 6.6.5.1 My Projects /

In the My Projects section the user wants to:

- ➔ To create and store a new project, add IFC model, and add project and building related information. **-> /Dashboard**
- ➔ To receive the primary energy consumption, the related operational carbon emission, and the energy label. **-> /Performance**
- ➔ To be able to see resulting values in the form of table view and Pie Charts.
- ➔ To see the 3D BIM model as-is (Based Model)

#### / Dashboard

In the My Project Dashboard view, the user is allowed to create new projects, while entering basic information about the uploaded digital building model. Project and client name as well as building typology can be entered and will be used as the primary project to store any further created activities. The components NavbarMinMP and MPTable are imported and used. An elaborate description of the code implementation can be found in **Appendix G5, Listing 17** to **Listing 19.** As the follow up steps, the second view of the My Projects page is executed. The performance calculation for the as-is building.

#### / Performance

On the performance page, the as-is building performance can be entered by the user. The components NavbarMinMP and MPTable are imported to navigate to the /Performance page. The project information that was entered in /Dashboard is visualised and more detailed information about the building and household characteristics are to be entered by the user. The project definition is saved as a global parameter, const newProject, and stores the object as a JSON string on local storage, see **Listing 14**. The construction period and expected lifetime, the energy and electricity consumptions of the as-is building have to be entered for the analysed building use case.

```
const newProject = {
   projectName : typedInProjectName,
   clientName : typedInClientName,
   buildingType : typedInBuildingType,
   spaceHeating : 0,
   DHOW : 0,
   Electricity : 0,
   PrimaryEnergy : 0,
   EnergyLabel : 0,
   CO2op : 0,
   constructionYear: 0,
   refurbishmentYear: 0,
   refurbishmentLife: 0,
 }
```

**Listing 14 Const newProject**

While entering the space heating in gas, the gas for DHW and the electricity consumption, the operational Primary Energy, the resulting Energy Label and operational CO2 consumption is rendered interactively and shown on the UI. Three functions are defined that read the user input and simultaneously render the results of the calculations. Each calculation is coded separately. The calculation formulae for Primary Energy, Energy Label and operational CO2 are derived from **Chapter**

**4.4.2 Operational Energy and Carbon.** An elaborate description of the code implementation can be found in **Appendix G5, Listing 20** to **Listing 25**.

#### 6.6.5.2 Refurbishment

In the Refurbishment section the user wants to:

- ➔ To receive information about national policy and governmental subsidy regulation regarding energy and carbon refurbishment. -> **/ Dashboard**
- ➔ To perform refurbishment packages and compare results towards the base model in an interactive way (including operational energy, carbon and cost performance). -> **/ Performance**
- ➔ To see the affected building elements in the 3D BIM model.

#### / Performance

In the refurbishment performance assessment, the user can create refurbishment packages for the uploaded digital building model. The components NavbarMinRP, ButtonSelect and ControlledOpenSelect are imported, to allow navigation and dropdown selection. Two packages can be created that are applied as a nested sub-project to the main project. Thermal improvements of the building components can be selected. For this use case, the wall and roof insulation are proposed, and Rc-Values are predefined, according to the definition of **Chapter 4.1.2 Refurbishment Package definition**. As a result, the operational heat load demand will be computed in the background calculation. The calculation to retrieve primary energy, energy label and $CO_2$ operational, is computed in the same way as in the MyProjects/Performance section. The operational saving potential for gas and cost is introduced as a result. The algorithm is based on the calculations of **Chapter 4.4.2 Operational Energy and Carbon.**

To access the heat load demand per refurbishment packages, we rely on the MySQL DB knowledge. Although, it should be mentioned that it would be ideal if the tool could analyse energy reductions based on any uploaded building model. Therefore, energy simulation could be included. Clustering of building typologies and improvement concepts plays thereby a crucial role in future developments of the tool. In this implementation stage, the data has been hardcoded as part of the proof of concept. An elaborate description of the code implementation can be found in **Appendix G5, Listing 26** to **Listing 30.**

#### 6.6.5.3 Market Potential

In the Market Potential page, the user wants to:

- ➔ Receive an overview of all performances established so far.
- ➔ Find the trade off´s between sustainable key criteria based on refurbishment package and per defined material selection.
- ➔ Receive the market potential as the percentage probability of consumer preference.

#### / Performance

On the Market Potential page, the user wants to see an overview of all performance results so far and wants to be able to apply material scenarios per refurbishment package. The currently executed project (MyProject) is called, and additional material-related scenarios are added to the refurbishment packages. The material definition for EPS, Glass Wool, Rock Wool and Wood Fibre is the same as used for the consumer preference model, see **Chapter 5.2.1 Refurbishment Packages**. This page is meant to retrieve the performance from all pages before. For this stage of the implementation, the data has been hardcoded. Moreover, an interactive visualisation of the material performances is required. A function is coded that reacts when the user selects material in the drop-down menu. Depending on the material selection, the material performance results will change, and so does the probability of acceptance. For the latter, the utility coefficients per attribute from **Chapter 5.4 Result**, are coded as a constant. Finally, the probability calculation is executed and adopted depending on the material selection **5.6 Result use case**. An elaborate description of the code implementation can be found in **Appendix G5, Listing 31** to **Listing 40.**

## 6.7 Requirement evaluation

The requirement evaluation uses the requirement elicitation of the **Chapter 6.2 User Requirement Elicitation**. The in total 31 requirements are directly defined as the tasks of development, see **Table 41**.

To remind the reader about the indication on the right two columns. **C** stands for complexity of implementation, reaching from 1 to 5, where 1 = simple, 3 = medium, 5 = highly complex. **IP** stands for Implementing phase according to the level of implementation. For the first cycle we identify five step approach, 1 = Initial Planning, 2 = Requirements, 3 = Analysis & Design, 4 = Data/Code implementation, 5 = Test and Evaluation. The fields are coloured to verify the stage of implementation. Green = completed; red = future development priority 1; yellow = future development priority 2.

**Exchange requirements (Cycle 1)**

| | **The engineer has to ...** | **C** | **IP** |
|---|---|---|---|
| **3D digital BIM** | • Assess the building as-is performance. | 1 | 1-5 |
| | • Have knowledge regarding as-is energy performance (Gas heating, appliance electricity, DHOW gas/electricity). | 2 | 1-5 |
| | • Create a BIM model, including parametric enrichments to achieve LOD 300. | 1 | 1-5 |
| | • Comply with the exchange requirements (according to 6.2.1) | 2 | 1-5 |
| | • Fundamental knowledge of client's objectives. | 3 | 1-5 |

**Functional User and Content requirements (Cycle 1)**

| | **The engineer wants to be able to...** | **C** | **IP** |
|---|---|---|---|
| **My Project** | • Create and store a new project, add specific building data (e.g.: using IFC). | 4 | 1-3 |
| | • To receive the primary energy consumption, the related operational carbon emission, and the energy label. | 3 | 3-4/5 |
| | • See resulting values in the form of table view and Pie Charts. | 3 | 3-4/5 |
| | • See the 3D BIM model as-is (Based Model). | 1 | 5 |
| **Refurbishment** | • Receive information about national policy and governmental subsidy regulation regarding energy and carbon refurbishment. | 1 | 1-5 |
| | • Perform refurbishment packages and compare results towards the base model in an interactive way (including operational energy, carbon and cost performance). | 4 | 1-4 |
| | • See the affected building elements in the 3D BIM model. | 5+ | 1-3 |
| **Material Application** | • Gain knowledge about material application methods. | 1 | 1-5 |
| | • Gain knowledge about installation possibilities and receive information about material characteristics, containing thermal knowledge, embodied energy and carbon, costing. | 3 | 1-5 |
| | • See the affected building elements in the 3D BIM model. | 1 | 1-3 |

| | | | |
|---|---|---|---|
| **Life Cycle Assessment** | • Analyse embodied energy and carbon footprint per material package and in combination with operational energy and carbon performance. | 3 | 1-3 |
| | • Evaluate the LCA (embodied and operational performances) in the form of Pie Charts and on the 3D model. | 5 | 1-3 |

| | | | |
|---|---|---|---|
| **Costing** | • Analyse investment costing of material package and in relation to operational cost performances. | 3 | 1-3 |
| | • Evaluate the costing in the form of Pie Charts. | 5 | 1-3 |

| | | | |
|---|---|---|---|
| **Market Potential** | • Receive an overview of all performances established so far. | 2 | 1-5 |
| | • Find the trade off´s between sustainable key criteria based on insulation material. | 4 | 1-5 |
| | • Receive the market potential as the percentage probability of consumer preference. | 4 | 1-5 |

## System requirements (Cycle 1)

| | **To comply with the functional user and content requirements, the system must ...** | **C** | **IP** |
|---|---|---|---|
| **Web tool** | • Be hosted on a server and accessible via the web browser. | 3 | 1-5 |
| | • Allow a semantic enrichment and connection between graphical based and non-graphical based building information. | 5 | 1-3 |
| | • Allow a connection/an input to external Databases. | 4 | 1-5 |
| | • Allow a BIM-based evaluation system by querying and validating the 3D model with the predefined data model. | 5 | 1-3 |
| **UI/UX** | • Allow active user interaction, rather than submission of forms. | 3 | 1-5 |
| | • Allow the user to interactively add and query project related information in a reactive web environment. | 1 | 1-5 |
| | • Allow adapting layouts to a variety of screen and window sizes within a responsive web environment. | 1 | 1-4 |
| | • Indicate results within the 3D model viewer, table view and in the form of a report. | 1 | 1-4 |

**Table 41 Requirement evaluation**

In the first implementation cycle, the primary focus is to establish all components independently of each other. This has been successfully accomplished for the exchange requirements, three out of six web pages, and the UI and UX requirements. It is to mention that the components that are in place work independently and must be connected with each other in the second implementation cycle. For instance, the MySQL DB connection and the user interaction with the UI are implemented. **Chapter 6.5 Data Dictionary (data requirements)** shows thereby the proof of concept for SQL queries. Currently, hardcoded data are used that have to be replaced by a filter mechanism that derives the data from the DB´s. Moreover, the application of the tool is dominated by the use case of the Terrace House. Energy calculations were implemented in accordance with this archetype and the evaluation system. Also, material scenario application results from the use case definition.

# CHAPTER 7

# Conclusion & Reflection

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# 7 Conclusion & Reflection

*The final Chapter will provide an overview of the accomplishments of this research, in Section 7.1. It will then conclude and answer each research sub-question separately in Section 7.2. The relevance of the research and recommendations for future work is explained in Sections 7.3 and 7.4.*

## 7.1 Research overview

The European Union within its EU Green Deal policy packages aims to facilitate a 'Renovation Wave' for buildings across Europe. The residential building sector in the Netherlands is targeted by this transition and asks homeowners to refurbish their homes to achieve national ambitions (*Dutch Ministry of Economic Affairs and Climate, 2019).* Refurbishing homes is however a complex process. It includes multiple decision makers with different motives and multi-criteria objectives. In practice, decision support tools are scarce that include construction engineering design assessment with a consumer preferences model that accounts for the acceptance of the solutions for the homeowners *(Thorpe, 2017; Kamari et al., 2017; Taillandier et al., 2016).* To find a solution for this bottleneck the main research question was asked:

"Can we design a web-based decision support tool for sustainable refurbishment projects that brings together engineering evaluation methods and consumers´ preferences assessment?"

To answer the main question the research introduces a decision support system that is divided into three topics. Staring with the engineering evaluation methods, followed by the consumer preference model, and finally the integration of both within a web-based tool. The involved stakeholders as decision-makers in this thesis are construction engineers, homeowners and energy collectives.

The engineer evaluation method can infer the relevance that the building performance evaluation remains within the framework of sustainable development. Especially when focusing on insulation materials with a high complexity of characteristics. Building Information Modelling (BIM) in combination with such highly complex data requires a precise definition of the exchange requirements. Only then design scenarios can be created and compared with each other. The results for the design scenarios are used as the input for the second steps, the consumer preference modelling. Interactions with the end-users, the homeowners, were performed with a stated choice model. Dutch homeowners show a high acceptance rate to refurbish and attach high importance to considering all introduced attributes (reaching from technical installation, energy reduction, investment cost, $CO_2$ reduction and comfort improvement). This insight helps to conclude that the choice of materials is important to homeowners. Depending on the performance results of these attributes the acceptance rate changes. Finally, both methods were combined within one web-based tool. The web-based decision support tool ROTUNDORO [Latin: circular] is hosted on the Linked Building Data (LBD) sever and the functionalities are implemented on the frontend, the user dashboard. The value of the web-based tool is twofold. The inclusion and harmonization of the engineering evaluation method with the consumer research, as well as the emphasis on novel developments regarding linking BIM to online hosted databases that contain multi- and interdisciplinary information is addressed. The use of Industry Foundation Classes (IFC) in combination with national classification schemas, such as the NL-Sfb, can be used as data vocabulary to foster future database developments. This tool can be proposed for practical multi-criteria and multi-stakeholder collaborations in refurbishment projects, as well as encourages scientific research to combine discipline agnostics methods.

## 7.2 Reflection on research question

*This section will provide answer and conclusion per research question.*

**SQ1) What are the ambitions of Dutch policymakers regarding building refurbishment and what for role do insulation material measures play here? Chapter 2 Section 2.1**

To answer this question, firstly an analysis of the building stock in the Netherlands and of the refurbishment process explains the diversity in multiple aspects, including building owners, housing typology, construction period and expectation after the refurbishment. Local authorities and energy collectives consult homeowners in order to refurbish their houses, taking into account national policies. The Dutch policies The National Climate Agreement in the construction sector applies and is aligned to the EU Commission goals that seeks to refurbish existing building stock up to Energy Label B by 2030. These ambitions can be reached with minor and major refurbishments concepts *(Majcen, 2016).* In this research a step-wise approach (minor refurbishments) is recommended. Homes should start to refurbish the building envelope via insulation measures, followed by building integrated technical systems (BITS) improvements *(Dutch Ministry of Economic Affairs and Climate, 2019).* The installation of two measures, such as wall and roof insulation, is financially supported by the government and has the potential to be a no-regret investment. Further, an analysis about materials was conducted and shows the importance in multiple criteria. While materials are primarily chosen according to cost feasibility, multiple material studies stress the relevance to include besides thermal improvements also indoor comfort, health and safety aspects, as well as environmental footprint.

**SQ2) Which methodologies are currently used, that assess environmental performance of existing buildings, and evaluate possible refurbishment design scenarios?. Chapter 2 Section 2.2**

Introduced methods to evaluate building performances and possible refurbishment design scenarios are explained and show complexity. Official certifications such as the Energy Label, Energy Index and the Energy Performance Coefficient categorizes the energy consumption, however these measures differ from the actual household performances *(Majcen, 2016).* Instead, the International Energy Agency (IEA) introduces a holistic evaluation framework. It includes the primary energy calculation, in combination with the Life Cycle Assessment (LCA) and the Life Cycle Coting (LCC). The IEA EBC ANNEX 57 shows the structure of the building life cycle and highlights the operational impact and the increased importance of the embodied impacts *(Lützkendorf & Balouktsi, 2016).* In refurbishment projects, only newly added materials are considered, and compared via designs scenarios. Challenges remain as LCA and LCC require expert knowledge to establish database and make assessment on the existing building stock.

**SQ3) Which digital evaluation methods (tools) to assess building performances are currently on the market and what are the benefits of a BIM and web-based information exchange? Chapter 2 Section 2.3**

A study about tools that are available on the Dutch market concludes that they mainly differ in three aspects. Whether a tool is free of charge or not, has a graphical or non-graphical representation and lastly has a high level of complexity or not. Tools provided by the government (such as MPGcalc) show advantages as they are easy to use, are free of charge and can bring an approximate evaluation of a building performance. However, the results do not show the highest accuracy. On the contrary, advanced tools for building performances (such as GPRGebouw) show significant performance as they use certified LCA data (NMD). However, the tool is costly, and experts are needed. Both do not have a graphical representation in the form of a 3D model or chart visualisation. To make such assessment more attractive in the AEC industry, graphical tools (such as BIM and LCA) are developed and offer engineers to merge LCA data (or any other) to their local BIM project. While the data can be easily processed, human errors might risk messy data structures and wrong interpretation of results. Moreover, data loss is at risk when exchanging the result throughout multiple BIM platforms. This is why BIM and web-based information exchange becomes more important in the industry. The LBD method is an introduced method where data is linked with each other while using the single source of truth (SSOT). The LBD changes traditional working methods in the sector and allows to focus on the quality of the data, considering a structure for the data source from the author of the data. Schematic documentation and classification schemas, such as IFC ontologies, help to connect data of any sort. Optimizing such approaches can help to reduce the high number of communication channels and data duplication.

**SQ4) Which instruments for consumer preference modelling exist and how to translate multi-criteria objectives into a decision support system? Chapter 2 Section 2.4**

To answer this question, firstly the multi-criteria objectives of homeowners are analysed, secondly the instruments that are used to assess preferences of consumers, and thirdly, decisions making tools are introduced. The motives for end-users (such as homeowners) were introduced. Pro-environmental behaviour studies underlie behavioural economics, as introduced by Steg (2014). It can be concluded that Dutch homeowners' motives to refurbish harmonize with a sustainable framework (encompassing economic, environmental and social aspects). The improvement in living quality and the advantage of monetary benefits are highlighted. Moreover, pro-environmental actions can be encouraged when understanding to what extent people need to make sacrifices towards other criteria *(Steg et al., Ebrahimigharehbaghi et al., 2019; Broers et al., 2019).* Further, consumer research is supported by preference modelling. Multiple quantitative studies were found that focus on end users' preferred choices when facing energy refurbishments. The most commonly used method is the Stated Choice Modelling. It can be concluded that the economic component dominates the choices of homeowners. However, energy, carbon and comfort attributes become increasingly important *(Galassi & Madlener, 2017, Chau et al., 2010, Achtnicht 2011, Madlener, 2012).* Ways to encourage pro-environmental behaviour show success in information share *(Alberini et al., 2013, 2008, Ossokina et al., 2021).* A strong focus on inclusion and informing end-users is also shown in decision support tools. It was found that tools developed in practice tend to focus on qualitative rather than quantitative consumer engagement. The standard procedure of a decision support system is reflected and visible in the goal and criteria definition. The criteria weighting can be performed in different ways. Either on a personal level or accounting for a quantitative market scale, including a high number of people. The analysed tools do not include technical design scenario solutions that account for the preferences of the end-users. The harmonization of the engineering and behavioural methodologies within one decision-support tool is scarce in practice and has yet to be developed *(Thorpe, 2017).*

**SQ5) What can a program of requirements for a web-based assessment framework look like that contains multi-criteria objectives in an engineering evaluation system and takes consumers preferences into account? Chapter 3**

Based on the literate review a program of requirements could be formulated. Before naming the requirements, the stakeholders that play a major role are examined. These are the homeowners, energy collectives and construction engineers. Their motive is to refurbish sustainably using insulation materials. Next, a decision support system has been outlined that includes three major requirements that are then embedded within one web-based assessment framework. Firstly, the functional content and user requirements are defined. The evaluation system that helps engineers to assess existing building and design scenario performances are defined. It was found crucial to build upon existing engineering methods and make them more accessible to all stakeholders (more efficient to use). The second requirement represents the market potential. This includes the consumer preference model, in the form of a Stated Choice Model. This overcomes the challenge of the lacking role of end users when verifying the engineers design. Finally, the system design is introduced as the web application architecture. The iterative and incremental development cycle to build upon the LBD Server framework was found suitable to develop the listed functionalities.

**SQ6) How can an engineering evaluation method be designed that assesses insulation material measures according a sustainable evaluation framework? Chapter 4**

> Which insulation material parameters influence the buildings' sustainable performance?
> How to set up a use case and utilize BIM together with LCA, cost and comfort assessment to appraise design scenarios?

The engineering evaluation methods that are introduced in this thesis contain assessment methods that reach from a material level towards a building level. The use case of a Dutch terrace house (Rijwoning) was modelled as a 3D digital model using BIM software Autodesk Revit. The model was used throughout the performance assessments. The multi-criteria when choosing insulation materials can be evaluated within a sustainable assessment framework, including environment, economic and social criteria. A comparative assessment analysed material scenario and showed difference in thermal performance (Rc- and U-Value), cost, environmental footprint, health, comfort and safety parameters. It could be concluded that no material performs overall best. Therefore, two refurbishment packages that reduce the operational energy and five material packages were created. The packages were then applied on a building level, using the use case (Rijwoning). An energy model, a LCA analysis and a cost assessment was performed. The established approach stays in line with the IEA EBC ANNEX 57 (2014). It represents a sustainable building and refurbishment assessment methods, when working with BIM and insulation material.

**SQ7) How do homeowners value sustainable criteria of such design scenarios, including energy, carbon, cost, health and comfort attributes? Chapter 5**

> How to utilize the stated choice experiment to investigate trade-offs made by homeowners when choosing design scenarios in the form of insulation packages?
> How can criteria weighting be used to verify the likelihood of acceptance of design scenarios?

To answer this question, the design results from above were used to execute a stated choice experiment amongst 500 Dutch homeowners. It quantified the building owner's preferences regrading six attributes. (i) whether to inject insulate in existing construction or to make a second wall inside; (ii) investment cost; (iii) energy bill savings; (iv) $CO_2$ saving; (v) noise reduction level and (vi) comfort improvement. The resulting coefficients of the multinomial model show that all attributes are relevant when performing insulation measures. It can be concluded that homeowners have a high willingness to refurbish. The most important aspects are to insulate in the existing construction (cavity injection), followed by the high energy bill. The $CO_2$ reduction, noise reduction and comfort improvement were found as equally important. The trade-offs that homeowners make when refurbishing can be understood when creating insulation packages and analysing the probability of choosing one over the other. The initially created five material scenarios were applied. When homeowners choose to insulate with an inside layer a higher importance is dedicated on energy, carbon, noise reduction and indoor comfort improvement. The only material that allows to satisfy the latter attributes is the wood fibre. Otherwise, when materials can be injected, the homeowners prefer to choose the glass wool, as it performs throughout all criteria best. The results of this chapter are directly used and implemented within the web-based tool to calculate the probability of choosing one insulation package over the other (calculating the market potential of a package).

**SQ8) What can a web-based assessment framework look like that combines the evaluation system and the preference modelling together with BIM technology and semantic data enrichment? Chapter 6**

> How can the requirement engineering (RE) approach be used to elicit functional user and system requirements?
> How to create a relational database of multiple data sources and how to use React and JavaScript for frontend development?

The web-based assessment framework builds upon the LBD Server. The framework allows engineers to design refurbishment packages based on their BIM practice. The user of the tool, the engineer, is introduced to the assessment framework via six web pages. (i) My Project; the uploading and documentation of the current as-built performance, (ii) Refurbishment: creating packages to analyse the operational performance assessment; (iii) Material package definition: representing the informative aspect of materialisation scenarios; (iv) LCA performance; (v) cost assessment; (vi) Market potential: introducing the potential consumer adoption. The first five sections allow to semantically enrich the 3D geometry. The fifth page accesses the earlier defined performance results (step i to v) and calculates the likelihood that people will choose for either one of the packages. It was found important that engineers can go back and forth to amend performances, and thus increase the chance of acceptance. Moreover, semantic enrichment of BIM has great potential in such assessments. The externally held database was derived from the NMD data and manufacturing cost data, in a Dutch context. The ERD was used to create a relational database logic that supports the user queries from the dashboard. It is a great way to create logical data schemas to understand what is required to establish connectivity between materials, LCA and cost data. However, the connection of geometry data towards the externally held database was found difficult. The evaluation system is included via calculation algorithms, that are located on the frontend framework React, using JavaScript.

## 7.3 Research Relevance

The combination of engineering methods and consumer research has shown success and relevance in scientific aspects as well as in practical and societal aspects. The scientific contribution of this thesis shows a unique combination of specific methods within one decision-making support. It offers the possibility to combine two very different disciplines (namely construction engineers and urban research methods). So far, no tool has been found that includes this. Further, the combination of these professions improves communication on two levels, regarding human interaction and digital processes. As a knowledge platform, it helps to stimulate pro-environmental behaviour and raises awareness of the relevance of a sustainable refurbishment. A playful environment makes it possible to provide information and show the effect. Even small adjustments of the criteria can be seen immediately by the user. In return, this leads to a better understanding of the impact that certain criteria have on the insulation packages. Robust solutions can thus be formulated. Giving such insight among the decision-makers inevitably leads to a better understanding of multi- und interdisciplinarity. The quality of using engineering and web-based assessment methods can be better understood by clients. The demand of using such tools would therefore increase future developments. Overall, it could lead to a more dynamic and efficient process when refurbishing buildings.

## 7.4 Future work

*Finally, some words about future research and developments that are proposed.*

Regarding the evaluation system within the web-based assessment framework, more research is recommended in semantic data enrichments. The bottleneck of this thesis is that no connection and automatic assessment between the digital building model (BIM) and the externally held database could be established. Therefore, future work should continue to develop a data structure to enhance the connectivity of externally held databases towards BIM methods and open standards, such as IFC. Assuming that working with data from the web increases in practice, a stronger collaboration between software developers in the AEC sector, product and material manufacturers as well as creators of the LCA database would be needed. As a result, a free-to-use data policy could enable the connectivity of products and materials within the AEC industry. The downside remains in the competition of the market side when showing too much transparency on their data. Moreover, the tool should apply to multiple building typologies and socio-demographic groups, in the form of cluster groups. The tool could include a filter mechanism, selected by the users (engineers and energy collectives), that proposes refurbishment concepts according to the demands of the homeowners. To this end, an additional refurbishment concept should be included, that next to insulation material measures also BITS databases accesses. Finally, the market potential should apply to all cluster groups in the Netherlands. Therefore, multiple consumer preference models could be created in the future that focuses on building owner's acceptance rate for various refurbishment concepts. The scope of these preference models shall however remain the same to allow comparative results of coefficients. Those could be then implemented in the tool using the same filter mechanism as for the refurbishment concepts. The likelihood of accepting the solutions for a particular group of interest could be visualized.

# 8 References

## APA


Aditya, L., Mahlia, T. M. I., Rismanchi, B., Ng, H. M., Hasan, M. H., Metselaar, H. S. C., … Aditiya, H. B. (2017). A review on insulation materials for energy conservation in buildings, 73(January), 1352–1365. https://doi.org/10.1016/j.rser.2017.02.034

Achtnicht, M. (2011). Do environmental bene fits matter ? Evidence from a choice experiment among house owners in Germany. Ecological Economics, 70(11), 2191–2200. https://doi.org/10.1016/j.ecolecon.2011.06.026

Agentschap a NL. (2011). Voorbeeldwoningen 2011 Onderzoeksverantwoording.

Agentschap b NL. (2011). Bestaande bouw Voorbeeldwoningen 2011.

Alberini, A., Banfi, S., & Ramseier, C. (2013). Energy Efficiency Investments in the Home : Swiss Homeowners and Expectations about Future Energy Prices Author ( s ): Anna Alberini , Silvia Banfi and Celine Ramseier Published by : International Association for Energy Economics Stable URL : http://www.j. The Energy Journal, 34(1), 49–86.

Almeida, M., & Ferreira, M. (2015). IEA EBC Annex56 vision for cost effective energy and carbon emissions optimization in building renovation. Energy Procedia, 78, 2409–2414. https://doi.org/10.1016/j.egypro.2015.11.206

Almeida, M., & Ferreira, M. (2018). Ten questions concerning cost-e ff ective energy and carbon emissions optimization in building renovation, 143(June), 15–23.

Alonso, A., Patricio, J., Suárez, R., & Escandón, R. (2020). Acoustical retrofit of existing residential buildings: Requirements and recommendations for sound insulation between dwellings in Europe and other countries worldwide. Building and Environment, 174(February). https://doi.org/10.1016/j.buildenv.2020.106771

Aurum, A., & Wohlin, C. (n.d.). Engineering and Managing Software Requirements. https://doi.org/https://doi-org.dianus.libr.tue.nl/10.1007/3-540-28244-0

Ariyaratne, C. I., & Moncaster, A. M. (2014). Stand-alone calculation tools are not the answer to embodied carbon assessment. Energy Procedia, 62, 150–159. https://doi.org/10.1016/j.egypro.2014.12.376

BademliOğlu, A. H., Kaynakli, Ö., & Yamankaradeniz, N. (2018). The effect of water vapor diffusion resistance factor of insulation materials for outer walls on condensation. Isi Bilimi Ve Teknigi Dergisi/ Journal of Thermal Science and Technology, 38(2), 15–23.

Banfi, S., Farsi, M., Filippini, M., & Jakob, M. (2008). Willingness to pay for energy-saving measures in residential buildings ☆, 30, 503–516. https://doi.org/10.1016/j.eneco.2006.06.001

Bazerman & Moore (2012). Judgment in managerial decision making, Chapter 1, Introduction to managerial decision making, https://books.google.nl/books?hl=en&lr=&id=6HP4DwAAQBAJ&oi=fnd&pg=PA1&ots=pWa9KLVfc8&sig=V6Rhr0uoohLBhY_NgizONyMzCHE&redir_esc=y#v=onepage&q&f=false

Bonduel, M., Oraskari, J., Pauwels, P., Vergauwen, M., & Klein, R. (2018). The IFC to Linked Building Data Converter - Current Status, 34–43.

Bouw, C. A. O. (2020). Loonsverhoging per, 2020. Retrieved from https://www.scabadvies.nl/wp-content/uploads/2020/03/SCAB-Loon-en-loonkostenvergelijking-Bouw-2020-01-01.pdf

Berners-Lee, T., Hendler, J., & Lassila, O. (2018). The Semantic Web A new form of Web content that is meaningful to computers will unleash a revolution of new possibilities. Circulo de Linguistica Aplicada a La Comunicacion, 73(May), 303–314. https://doi.org/10.5209/CLAC.59071

Berggren, B., Hall, M., & Wall, M. (2013). LCE analysis of buildings - Taking the step towards Net Zero Energy Buildings. Energy and Buildings, 62, 381–391. https://doi.org/10.1016/j.enbuild.2013.02.063

Brejnrod, K. N., Kalbar, P., Petersen, S., & Birkved, M. (2017). The absolute environmental performance of buildings. Building and Environment, 119, 87–98. https://doi.org/10.1016/j.buildenv.2017.04.003

Broers, W. M. H., Vasseur, V., Kemp, R., Abujidi, N., Vroon, Z. A. E. P., Urban, S., … An, H. (2019). Energy Research & Social Science Decided or divided ? An empirical analysis of the decision-making process of Dutch homeowners for energy renovation measures. Energy Research & Social Science, 58(March), 101284. https://doi.org/10.1016/j.erss.2019.101284

Build Desk. (2002). Vapour resistances and μ -values, 1–6. https://builddesk.co.uk/wp-content/uploads/2013/01/vapourResistances.pdf

Bukhsh, Z. A., Sinderen, M. Van, & Singh, P. M. (2015). SOA and EDA : A Comparative Study - Similarities , Differences and Conceptual Guidelines on their Usage SOA and EDA : A Comparative Study Similarities , Differences and Conceptual Guidelines on their Usage, (September 2018). https://doi.org/10.5220/0005539802130220

Chau, C. K., Tse, M. S., & Chung, K. Y. (2010). A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. Building and Environment, 45(11), 2553–2561. https://doi.org/10.1016/j.buildenv.2010.05.017

Clark, T., & Barn, B. S. (2011). Event driven architecture modelling and simulation. Proceedings - 6th IEEE International Symposium on Service-Oriented System Engineering, SOSE 2011, (May 2014), 43–54. https://doi.org/10.1109/SOSE.2011.6139091

Clark, T., & Barn, B. S. (2012). A common basis for modelling service-oriented and event-driven architecture. Proceedings of the 5th India Software Engineering Conference, ISEC'12, (February), 23–32. https://doi.org/10.1145/2134254.2134258

Dutch Ministry of Economic Affairs (2016). Energy report, Transition to sustainable energy. IEEE Spectrum, 19(8), 12–13. https://doi.org/10.1109/mspec.1982.6366960

Dutch Ministry of Economic Affairs (2017). Energy Agenda. Retrieved from www.rijksoverheid.nl

Dutch Ministry of Economic Affairs and Climate. (2019). National Climate Agreement-The Netherlands, (June), 1–247. https://doi.org/10.1016/J.ENG.2016.04.009

D.Maskell, C. F. da Silva, K. Mower, C. Rana, A. Dengel, R. J. Ball, M. P. Ansell, P. J. Walker, A. S. (2020). PROPERTIES OF BIO-BASED INSULATION MATERIALS AND THEIR POTENTIAL IMPACT ON INDOOR AIR QUALITY.

Ebrahimigharehbaghi, S., Qian, Q. K., Meijer, F. M., & Visscher, H. J. (2019). Unravelling Dutch homeowners ' behaviour towards energy e ffi ciency renovations : What drives and hinders their decision-making ? Energy Policy, 129(June 2018), 546–561. https://doi.org/10.1016/j.enpol.2019.02.046

van Eck, H. (2018). EPBD Implementation in The Netherlands: Status in December 2016, (December). Retrieved from https://epbd-ca.eu/wp-content/uploads/2018/08/CA-EPBD-IV-The-Netherlands-2018.pdf

Esser, A., Dunne, A., Meeusen, T., Quaschning, S., & Denis, W. (2019). Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report, 87. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/1.final_report.pdf

Escalona, M. J., & Koch, N. (2004). Requirements Engineering for Web Applications - A Comparative Study ., (January).

EPISCOPE. (2016). Scenario Analyses Concerning Energy Efficiency and Climate Protection in Regional and National Residential Building Stocks Examples from Nine European Countries.

European Commission. (2015). Current Legal Requirements and Status of National NZEB Definition for Residential Buildings in the Netherlands NL. TU Delft Repositories, 213–224. Retrieved from http://repository.tudelft.nl/islandora/object/uuid:d7ceb03f-699e-4db6-9638-d1db98f8f2f1/datastream/OBJ/download

European Commission. (2017). Study to evaluate the need to regulate within the Framework of Regulation ( EU ) 305 / 2011 on the toxicity of smoke produced by construction products in fires Final Report.

European Commission. (2020) Renovation Wave, https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en

Filippidou, F., Nieboer, N., & Visscher, H. (2016). Energy efficiency measures implemented in the Dutch non-profit housing sector. Energy & Buildings, 132, 107–116. https://doi.org/10.1016/j.enbuild.2016.05.095

Filippidou, F., & Navarro, J. P. J. (2019). Achieving the cost-effective energy transformation of Europe ' s buildings Energy renovations via. https://doi.org/10.2760/278207

Galassi, V., & Madlener, R. (2017). The Role of Environmental Concern and Comfort Expectations in Energy Retrofit Decisions. Ecological Economics, 141, 53–65. https://doi.org/10.1016/j.ecolecon.2017.05.021

Gade, A. N., Jensen, R. L., Larsen, T. S., & Nissen, S. B. (2019). Value-based decision making in the pre-design stage of sustainable building renovation projects – exploring two methods for weighting criteria, 3599. https://doi.org/10.1080/15623599.2019.1578913

García-Martínez, A., & Sánchez-Montañés, B. (2016). Life cycle assessment ( LCA ) of building refurbishment : A literature review, (November). https://doi.org/10.1016/j.enbuild.2016.11.042

Giebeler, G., Fisch, R., Krause, H., Musso, F., Petzinka, K.-H., & Rudolphi, A. (2009). Refurbishment manual: maintenance, conversions, extensions. Basel: Birkhäuser. https://www.naibooksellers.nl/refurbishment-manual-maintenance-conversions-extensions-paperback-edition.html?___store=english&___from_store=default

Gomes, V., Loche, I., Saade, M. R. M., Pulgrossi, L. M., Paula, B., Rodrigues, L. L., … Doris, C. C. K. (2017). Operational and embodied impact assessment as retrofit decision-making support in a changing climate, 2011.
Habert, G., Röck, M., Steininger, K., Lupísek, A., Birgisdottir, H., Desing, H., … Lützkendorf, T. (2020). Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions. Buildings and Cities, 1(1), 429–452. https://doi.org/10.5334/bc.47
Harmelen;, D. A. K. van, & Koch;, I. W. W. R. (2002). CO 2 emission factors for fuels in the Netherlands. Retrieved from https://www.rvo.nl/sites/default/files/2013/10/Harmelen 2002 (EN) CO2 Emissionfactors for fuels in the Netherlands.pdf
Havinga;, D. ir. L., & Rijs;, I. A. (2020). Rekenkern ‘ Light ’ Verduurzaming Bestaande Woningen voor individuele woningen en de woningvoorraad, (november).
Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., & Bilec, M. M. (2019). Comparative whole-building life cycle assessment of renovation and new construction. Building and Environment, 161(May), 106218. https://doi.org/10.1016/j.buildenv.2019.106218
Haytink. T.G., B.J.H. Geurts, H. J. J. V. (2015). Onderzoek energiezuinige renovatiewoningen label B/A.
Hensher, D. A., Rose, J. M. A., & Greene, W. H. (2015). Getting started modeling : the workhorse – multinomial logit. Retrieved from https://www.cambridge.org/core/books/abs/applied-choice-analysis/getting-started-modeling-the-workhorse-multinomial-logit/9F985382B2ED50167F237EFF45A8FEC4
Hirsch, J., Lafuente, J. J., Spanner, M., Geiger, P., Haran, M., McGreal, S., … Brounen, D. (2020). Carbon Risk Real Estate Monitor STRANDING RISK & CARBON Science-based decarbonising of the EU commercial real estate sector THE CRREM TEAM GRATEFULLY ACKNOWLEDGES THE SUPPORT AND ADVICE RECEIVED FROM THE, (785058).
Hu, S., Wang, J., Hoare, C., Li, Y., Pauwels, P., & O’Donnell, J. (2021). Building energy performance assessment using linked data and cross-domain semantic reasoning. Automation in Construction, 124(November 2020), 103580. https://doi.org/10.1016/j.autcon.2021.103580
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings - A review of current trends. Energy and Buildings, 66, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026
IsoHemp, (n.d.). Case Study, Life Cycle Analysis of Hemp Blocks by Isohemp, Bouwen met Kalkhennep. Retrieved from http://ecodorpennetwerk.nl/wp-content/uploads/2017/02/Bouwen-met-Hennepkalk.april2015.pdf
Jusselme, T., Rey, E., & Andersen, M. (2020). Surveying the environmental life-cycle performance assessments : Practice and context at early building design stages. Sustainable Cities and Society, 52(September 2019), 101879. https://doi.org/10.1016/j.scs.2019.101879
Kappel, G.; Pröll, B.; Reich, S.; Retschitzegger, W. (2013). Web Engineering. Journal of Chemical Information and Modeling (Vol. 53). https://doi.org/10.1017/CBO9781107415324.004
Kamari, A., Corrao, R., & Henning, P. (2017). Sustainability focused decision-making in building renovation. International Journal of Sustainable Built Environment, 6(2), 330–350. https://doi.org/10.1016/j.ijsbe.2017.05.001
Kumar, D., Alam, M., Zou, P. X. W., Sanjayan, J. G., & Ahmed, R. (2020). Comparative analysis of building insulation material properties and performance. Renewable and Sustainable Energy Reviews, 131(July), 110038. https://doi.org/10.1016/j.rser.2020.110038
Kuijpers-Van Gaalen, I.M., Zeegers, A., Erdtsieck, P., (2017), "Bouwfysica", Technische Universiteit Delft, ISBN 9789006214994
Konstantinou, T. (2014). Supporting the Design of Residential Energy Upgrades. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:874ee906-6afa-4d5d-9af7-22b825976325/datastream/OBJ
Kuczenski, B., Davis, C. B., Rivela, B., & Janowicz, K. (2016). Semantic catalogs for life cycle assessment data. Journal of Cleaner Production, 137, 1109–1117. https://doi.org/10.1016/j.jclepro.2016.07.216
Lavagna, M., Baldassarri, C., Campioli, A., Giorgi, S., Dalla Valle, A., Castellani, V., & Sala, S. (2018). Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock. Building and Environment, 145(August), 260–275. https://doi.org/10.1016/j.buildenv.2018.09.008
Lindenberg, S., & Steg, L. (2007). Normative , Gain and Hedonic Goal Frames Guiding Environmental Behavior Normative , Gain and Hedonic Goal Frames Guiding Environmental Behavior, (March). https://doi.org/10.1111/j.1540-4560.2007.00499.x
Locher, B., Piquerez, A., Habermacher, M., Ragettli, M., Röösli, M., Brink, M., … Wunderli, J. M. (2018). Differences between outdoor and indoor sound levels for open, tilted, and closed windows. International

Journal of Environmental Research and Public Health, 15(1), 1–16. https://doi.org/10.3390/ijerph15010149

Lotteau, M., Loubet, P., Pousse, M., & Dufrasnes, E. (2015). Critical review of life cycle assessment ( LCA ) for the built environment at the neighborhood scale. Building and Environment, 93(December 2018), 165–178. https://doi.org/10.1016/j.buildenv.2015.06.029

Lützkendorf, T., & Balouktsi, M. (2016). IEA EBC ANNEX 57 - Guideline for Designers and Consultants – Part 1.

Malmgren, L., & Mjörnell, K. (2015). Application of a Decision Support Tool in Three Renovation Projects, 12521–12538. https://doi.org/10.3390/su70912521

Malcolm, A; Werbrouck, J; Pauwels, P. (2020). LBD server : Visualising Building Graphs in web-based environments using semantic graphs and glTF-models LBD server : Visualising Building Graphs in web-based environments using semantic graphs and glTF-models, (2020).

Majcen Daša. (2016). Predicting energy consumption and saving in the housing stock NL. A performance gap analysis in the Netherlands （2016）. Ccwg. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:00795500-6704-49c0-903f-6b6ba77dc544/datastream/OBJ

Majcen, D., Itard, L. C. M., & Visscher, H. (2013). Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. Energy Policy, 54, 125–136. https://doi.org/10.1016/j.enpol.2012.11.008

Mastrucci, A., Marvuglia, A., Leopold, U., & Benetto, E. (2017). Life Cycle Assessment of building stocks from urban to transnational scales: A review. Renewable and Sustainable Energy Reviews, 74, 316–332. https://doi.org/https://doi.org/10.1016/j.rser.2017.02.060

McFadden, D. (n.d.). Conditional logit analysis of qualitative choice behavior. Retrieved from https://eml.berkeley.edu/reprints/mcfadden/zarembka.pdf

Menzies, D. G. F. (2011). Technical Paper 13 Embodied energy considerations for existing buildings, (September). Retrieved from file:///C:/Users/jul/Downloads/techpaper13-embodied-energy.pdf

Michelsen, C. C., & Madlener, R. (2012). Homeowners ' preferences for adopting innovative residential heating systems : A discrete choice analysis for Germany. Energy Economics, 34(5), 1271–1283. https://doi.org/10.1016/j.eneco.2012.06.009

Milieu centraal. (2018). Energieneutrale woning. Retrieved from https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/energieneutrale-woning/

Miyamoto, A., Allacker, K., & Troyer, D. F. (2019). Visual tool to integrate LCA and LCC in the early design stage of housing Visual tool to integrate LCA and LCC in the early design stage of housing. https://doi.org/10.1088/1755-1315/323/1/012161

Nielsen, A. N., Jensen, R. L., Larsen, T. S., & Nissen, S. B. (2016). Early stage decision support for sustainable building renovation e A review. Building and Environment, 103, 165–181. https://doi.org/10.1016/j.buildenv.2016.04.009

Nault, E., Jusselme, T., & Andersen, M. (2018). Sustainable Design of the Built Environment SDBE 2018. International Conference for Sustainable Design of the Built Environment - SDBE London 2018.

Oregi, X., Hernandez, P., Gazull a, C., & Isasa, M. (2015). Integrating simplified and full life cycle approaches in decision making for building energy refurbishment: Benefits and Barriers. *Buildings*, *5*(2), 354–380. https://doi.org/10.3390/buildings5020354

Ortiz, M., Itard, L., & Bluyssen, P. M. (2020). Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. Energy and Buildings, 221. https://doi.org/10.1016/j.enbuild.2020.110102

Ossokina, I. V, Arentze, T. A., Gameren, D. Van, & Heuvel, D. Van Den. (2019). Best living concepts for elderly homeowners : combining a stated choice experiment with architectural design. Journal of Housing and the Built Environment, (0123456789). https://doi.org/10.1007/s10901-019-09716-5

Ossokina, I. V., Kerperien, S., & Arentze, T. A. (2021). Does information encourage or discourage tenants to accept energy retrofitting of homes? Energy Economics, 103(August), 105534. https://doi.org/10.1016/j.eneco.2021.105534

Österbring, M., Mata, É., Thuvander, L., & Wallbaum, H. (2019). Explorative life-cycle assessment of renovating existing urban housing- stocks. Building and Environment, 165(May), 106391. https://doi.org/10.1016/j.buildenv.2019.106391

Passer, A., Balouktsi, M., Lützkendorf, T., & Kreiner, H. (2016). Iea Ebc Annex 57. https://doi.org/10.3217/978-3-85125-519-5

Passer, A., Ouellet-Plamondon, C., Kenneally, P., John, V., & Habert, G. (2016). The impact of future scenarios on building refurbishment strategies towards plus energy buildings. Energy and Buildings, 124, 153–163. https://doi.org/10.1016/j.enbuild.2016.04.008

Passer, A., Röck, M., & Saade, M. R. M. (2017). Systematic literature review, 1–23. https://doi.org/10.1007/978-3-319-53351-3_1
Pont, U. (2014). A comprehensive approach to web-enabled, optimization-based decision support in building design and retrofit, (August). https://doi.org/10.13140/RG.2.1.3115.9521
Rasmussen, M. H., Pauwels, P., Hviid, C. A., & Karlshøj, J. (2017). Proposing a Central AEC Ontology That Allows for Domain Specific Extensions, I(July), 237–244. https://doi.org/10.24928/jc3-2017/0153
Rasmussen, M. H., Lefrançois, M., Schneider, G. F., & Pauwels, P. (2020). BOT : the Building Topology Ontology of the W3C Linked Building Data Group, (November). https://doi.org/10.3233/SW-200385
Ramírez-Villegas, R., Eriksson, O., & Olofsson, T. (2019). Life cycle assessment of building renovation measures–trade-off between building materials and energy. Energies, 12(3). https://doi.org/10.3390/en12030344
Rijksdienst voor Ondernemend Nederland. (2013). Infoblad Trias Energetica, 4–5. Retrieved from http://www.rvo.nl/sites/default/files/Infoblad Trias Energetica en energieneutraal bouwen-juni 2013.pdf
RVO. (2014). Technieken voor een energieneutrale woning. Retrieved from https://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/energieneutrale-woning/
Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM : Visualization of environmental potentials in building construction at early design stages, 140(May), 153–161. https://doi.org/10.1016/j.buildenv.2018.05.006
Röck, M., Ruschi, M., Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., … Lützkendorf, T. (2020). Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation ☆. Applied Energy, 258(October 2019), 114107. https://doi.org/10.1016/j.apenergy.2019.114107
Santos, R., Pyl, L., & Silvestre, J. D. (2018). A VALIDATION STUDY OF A SEMI-AUTOMATIC BIM-LCA TOOL, (March 2019).
SBK, Stichting Bouwkwaliteit. (2014). Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken, (November), 1–52. Retrieved from http://www.rijksoverheid.nl/documenten-en-publicaties
SBK. Stichting Bouwkwaliteit. (2017). Gids Milieuprestatieberekeningen, 17. Retrieved from https://www.milieudatabase.nl/imgcms//Gids_milieuprestatieberekening_V2.1.pdf
SBK. Stichting Bouwkwaliteit. (2019). Determination Method Environmental performance Buildings and civil engineering works, 31(January), 1–83.
Schiavoni, S., D'Alessandro, F., Bianchi, F., & Asdrubali, F. (2016). Insulation materials for the building sector: A review and comparative analysis. Renewable and Sustainable Energy Reviews, 62, 988–1011. https://doi.org/10.1016/j.rser.2016.05.045
Schilder, F. (2020). Woonlastenneutraal koopwoningen verduurzamen. Retrieved from https://www.pbl.nl/sites/default/files/downloads/pbl-2020-woonlastenneutraal-koopwoningen-verduurzamen-4152.pdf
Seghezzi, E., Masera, G., & Cecconi, R. F. (2019). Decision Support for existing buildings : an LCC-based proposal for facade retrofitting technological choices. https://doi.org/10.1088/1755-1315/296/1/012032
Slavkovic, K., Nault, E., Jusselme, T., & Andersen, M. (2019). Life-Cycle Assessment as a decision-support tool for early phases of urban planning : evaluating applicability through a comparative approach. https://doi.org/10.1088/1755-1315/323/1/012030
Stec, A. A., & Hull, T. R. (2011). Assessment of the fire toxicity of building insulation materials. Energy and Buildings, 43(2–3), 498–506. https://doi.org/10.1016/j.enbuild.2010.10.015
Somanathan, E., Sterner, T., & Sugiyama, T. (2012). IPCC Chapter 15 : National and Sub - national Policies and Institutions Contents, (July).
Steg, L., Bolderdijk, J. W., Keizer, K., & Perlaviciute, G. (2014). An Integrated Framework for Encouraging Pro-environmental Behaviour : The role of values , situational factors and goals. Journal of Environmental Psychology, 38, 104–115. https://doi.org/10.1016/j.jenvp.2014.01.002
Steffen, W., Richardson, K., Rockström, J., Cornell, S., Fetzer, I., Bennett, E., … Carpenter, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science (New York, N.Y.), 348(6240), 1217. https://doi.org/10.1126/science.aaa9629
Shukla, V. (2015). Requirements Engineering : A Survey Requirements Engineering : A Survey, (November), 27–31. https://doi.org/10.5120/cae2015651947
Tao, X., Das, M., Liu, Y., & Cheng, J. C. P. (2021). Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design. Automation in Construction, 130(June), 103851. https://doi.org/10.1016/j.autcon.2021.103851
Taillandier, F., Mora, L., & Breysse, D. (2016). Decision support to choose renovation actions in order to reduce house energy consumption – An applied approach. Building and Environment, 109(September), 121–134. https://doi.org/10.1016/j.buildenv.2016.09.019

Thayer, R. H., & Thayer, M. C. (n.d.). Software Requirements Engineering Glossary, 489–528.
Thorpe, C. (2017). Sustainable Home Design. ISBN 978-1-55092-645-3
Toma, I., &  Komazec, S., (2013). Requirements Engineering for Web Applications, 1–27. Retrieved from https://www.sti-innsbruck.at/sites/default/files/courses/WE-02-Requirements.pdf
UN, United Nation. (2013). Sustainable Development Challenges. United Nations, Department for Economic and Social Affairs.
Veen, L. E. (2014). Efficient querying and updating of XML data : the Rainforest data structure Efficient Querying and Updating of XML Data The Rainforest Data Structure Lourens Veen Master ' s Thesis in Computer Science, (February).
Veit, M., & Herrmann, S. (2003). Model-view-controller and object teams, (February 2003), 140–149. https://doi.org/10.1145/643603.643618
VIBE. (2007). VIBE -fiches Bouwmaterialen / isolatiematerialen, 1–13. Retrieved from https://www.vibe.be/wp-content/uploads/2019/12/KF_isolatiematerialen.pdf
Visser, C. De, Wijk, K. Van, & Voort, M. Van Der. (2015). Health, comfort, energy use and sustainability issues related to the use of biobased building materials, (February), 1–46. https://doi.org/10.13140/RG.2.1.1081.2645
Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. Energy and Buildings, 135, 286–301. https://doi.org/10.1016/j.enbuild.2016.11.042
WCED, World Commission on Environment and Development. (1987). Our Common Future. Retrieved from https://www.are.admin.ch/are/en/home/media/publications/sustainable-development/brundtland-report.html
Weißenberger, M., Jensch, W., & Lang, W. (2021). The convergence of life cycle assessment and nearly zero-energy buildings : The case of Germany. Energy & Buildings, 76(2014), 551–557. https://doi.org/10.1016/j.enbuild.2014.03.028
Werbrouck, J., Pauwels, P., & Beetz, J. (2019). Towards a Decentralised Common Data Environment using Linked Building Data and the Solid Ecosystem, (September).
Wilson, C., Pettifor, H., & Chryssochoidis, G. (2018). Quantitative modelling of why and how homeowners decide to renovate energy e ffi ciently. Applied Energy, 212(June 2017), 1333–1344. https://doi.org/10.1016/j.apenergy.2017.11.099
WHO. (n.d.). 4 . Guideline Values, 55–65. Retrieved from https://www.who.int/docstore/peh/noise/Comnoise-4.pdf
ZAVADSKAS, Edmundas Kazimieras &Arturas KAKLAUSKAS, S. R. (2004). Evaluation of investments into housing renovation, 177–190.
Zijlstra, H. (2009). Analysing buildings from context to detail in time. ABCD research method. Analysing Buildings from Context to Detail in Time. ABCD Research Method. Retrieved from http://homepage.tudelft.nl/20j9u/ABCD (in time) Research Method/Zijlstra 2009 Analysing Buildings from Context to Detail in Time.pdf

## Internet

Fire Safety in Buildings. (2020). Retrieved from http://fr.polymerinsights.com/flame-retardants/fire-safety-in-buildings)
Loonen, Online article, accessed on 22.09.2020, https://www.cursor.tue.nl/nieuws/2020/september/week-2/profpraat-toch-maar-geen-duurzame-woning/
MilieuCentral, 2020, accessed on 22.09.2020, https://www.milieucentraal.nl/energie-besparen/zonnepanelen/zonnepanelen-kopen/
MilieuCentral b, 2020 accessed on 28.09.2020 https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen/alles-over-isoleren/#Kosten%20en%20besparingen
Dutch Kennisbank, 2020, accessed on 10.09.2020, Kennisbank https://kennisbank.isso.nl/publicatie/energievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen/2017/bijlage-3
VolkerWessels, 2015, accessed on 26.10.2020, https://www.youtube.com/watch?v=I3WBT2eAArI&t=1s
Layman Matt, n.d, accessed on 31.10.2020,  https://www.mattlayman.com/understand-django/browser-to-django/
VisualParadigm n.d, accessed on 15.04.2021, https://www.visual-paradigm.com/scrum/agile-development-iterative-and-
.incremental/#:~:text=An%20incremental%20development%20process%20works,of%20what%20has%20

gone%20before.&text=Iterative%20development%20is%20the%20process,of%20working%20(an%20iteration).
NEN 8800, 2020, accessed on 24.10.2020, https://www.nen.nl/en/nta-8800-2020-nl-272896
Stockholm Resilience Centre, Planetary boundaries, accessed on 18.February 2020, https://www.stockholmresilience.org/research/planetary-boundaries.html
IPCC, accessed 15.04. 2021, https://www.ipcc.ch/
Pauwels, 2021, accessed on 13.10.2021, https://github.com/pipauwel/IFCtoRDF
IEA EBC Annex56, accessed on 20.01.2021, http://www.iea-annex56.org/index.aspx?MenuID=1
IEA EBC ANNEX 57, EN 15978:2011, accessed on 20.01.2021, http://www.iea-ebc.org/Data/publications/EBC_Annex_57_Guideline_for_Designers_Part_1.pdf
TABULA, accessed on 20.04.2021, https://webtool.building-typology.eu/#bm
SBR kennisplatform voor de bouw (2011), https://open.isso.nl/

## Interviews

Broers, W. (2020, September 18), personal interview [online call interview]
Lünenschloß, H. (2020, September 4), personal interview [phone interview]
Richert, M. (2020, September 7), personal interview [personal interview]
Spithoven, A. (2020, September 9), personal interview [phone interview]
Gauvin, F. (2020, October 13), personal interview [online call interview]
Gauvin, F. (2020, October 20), personal interview [email conversation]
Rovers, R. (2020, October 1), personal interview [online call interview]
Rijs, A. (2020, December 3), personal interview [online call simulation evaluation]
Boer, Tom de. (2021, February 18), personal interview [phone call]
Werbrouck, J. and Rasmussen, M. (2020, October 29) [personal interview]
Leusden energy collective, Riemersma de Feyter, Maaike. and Van Dam, Nico. (2021, April 15) [personal interview]
Hier Opgewekt, Jan (2021, April 28) [personal interview]
040Energie, Vlot. M., Raaijmakers. L, (2021, March 3) [personal interview]
Best Duurzaam, Lambert van den Hoven, (2021, April 28) [personal interview]
INDU ZERO, 2021 [personal interview]
Isovwer, Glass wool (2021, January 9) [phone interview]
IsoVlas Flaxwool (2021, January 10) [phone interview]
Kalkhennepbouw Nederland, (2021, January 18) [phone interview]
Dijksta draaisma, (2021, January 25) [phone interview]
John Egan, AECHive, (2020, November 21) [personal interview]

## Tool overview

SimaPro, accessed on 9.10.2020, https://simapro.com/
GPRGebouw, accessed on 9.10.2020, https://www.gprsoftware.nl/gpr-gebouw/
MPG calc, accessed on 9.10.2020, https://dgmrsoftware.nl/producten/gebouw-en-installatie/mpgcalc/
DGBC, accessed on 9.10.2020, https://www.dgbc.nl/dgbc-materialentool-voor-milieuprestatieberekening-67
Tally, accessed on 9.10.2020, https://bimchapters.blogspot.com/2018/04/tally-life-cycle-assessment-by.html
One-Click LCA, accessed on 9.10.2020, https://www.oneclicklca.com/
H\B:ERT, accessed on 9.10.2020, https://www.hawkinsbrown.com/services/hbert

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# APPENDIXES

# ROTUNDORO. A web-based decision support tool for building refurbishment.

Insulation material assessment using engineering evaluation method

and potential consumer adoption,

for owner-occupied Dutch housing refurbishment

Julia Katharina Kaltenegger – 1337602

Eindhoven University of Technology - Architecture, Building and Planning

Urban Systems and Real Estate (USRE) &
Construction Management Engineering (CME)
Combined Graduation Project 7CZ60M0 – 60 ECTS
October 2021

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# Appendix A

## A.1 Use Case – Plans

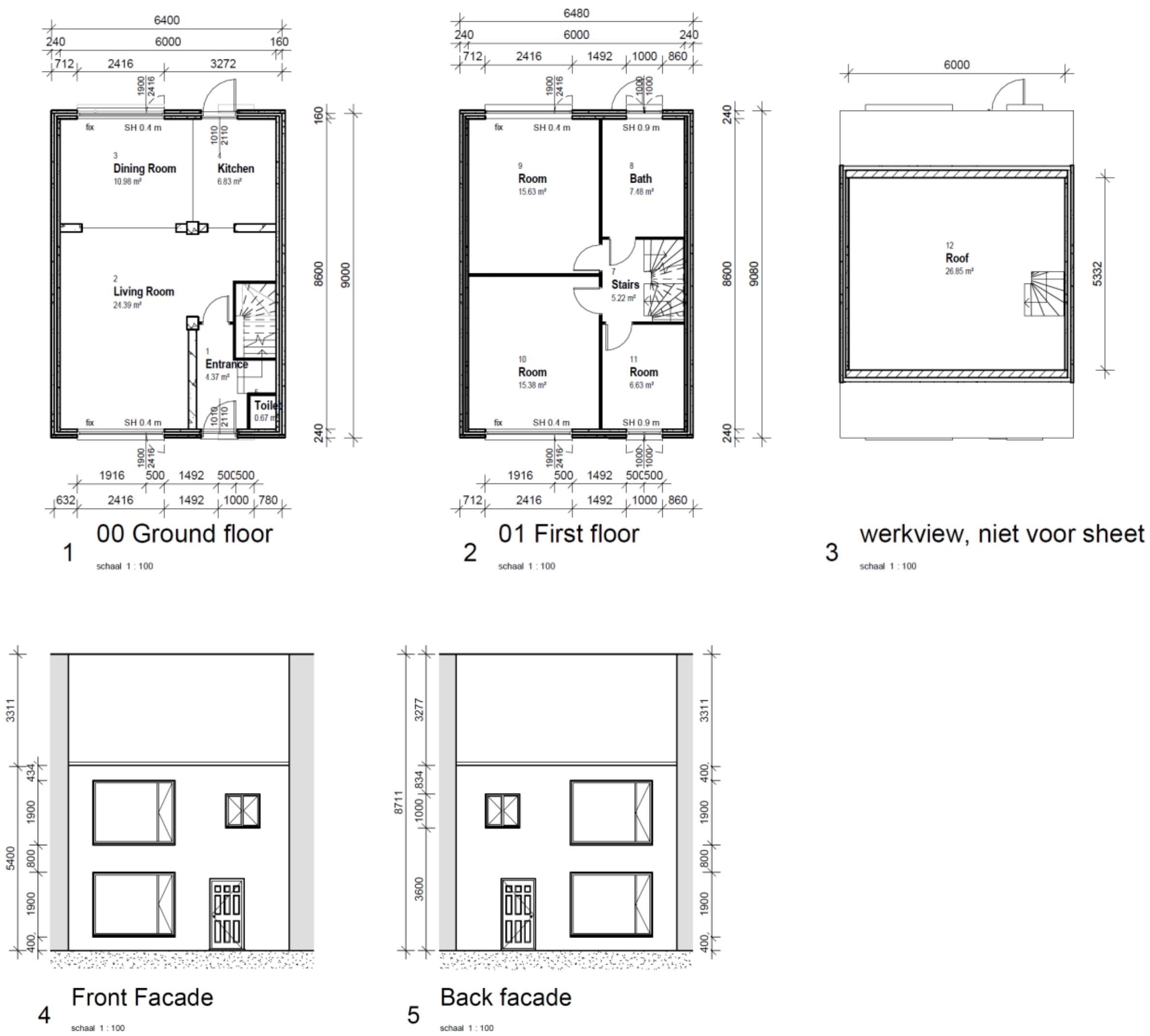



**Figure 74 Use Case plan Rijwoning**

## A.2 Case Study - Quantity

### Walls

| Count | Family and Type | Area | RC | U | NL-SfB | Thickness | Cost |
|---|---|---|---|---|---|---|---|
| 1 | Basic Wall: NLRS_21_WA_80mm | 60.74 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 20.52 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 22.68 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 60.30 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 20.09 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 22.68 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 62.97 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| 1 | Basic Wall: NLRS_21_WA_80mm | 62.97 m² | 0.4444 (m²·K)/W | 2.2500 | 21 | 80 | 0 |
| **8** | | **332.95 m²** | | | | | |
| 1 | Basic Wall: NLRS_22_WA_250mm | 6.91 m² | 0.3151 (m²·K)/W | 3.1735 | 22 | 250 | 0 |
| 1 | Basic Wall: NLRS_22_WA_250mm | 2.83 m² | 0.3151 (m²·K)/W | 3.1735 | 22 | 250 | 0 |
| 1 | Basic Wall: NLRS_22_WA_250mm | 3.68 m² | 0.2331 (m²·K)/W | 4.2902 | 22 | 250 | 0 |
| **3** | | **13.42 m²** | | | | | |
| 1 | Basic Wall: NLRS_22_WA_350mm | 0.88 m² | 0.4107 (m²·K)/W | 2.4348 | 22 | 350 | 0 |
| 1 | Basic Wall: NLRS_22_WA_350mm | 0.88 m² | 0.4107 (m²·K)/W | 2.4348 | 22 | 350 | 0 |
| **2** | | **1.75 m²** | | | | | |
| 1 | Basic Wall: NLRS_41_AIR_60mm | 24.62 m² | | | 21 | 60 | 0 |
| 1 | Basic Wall: NLRS_41_AIR_60mm | 24.62 m² | | | 21 | 60 | 0 |
| **2** | | **49.25 m²** | | | | | |
| 1 | Basic Wall: NLRS_41_IN_80mm | 65.18 m² | 0.1159 (m²·K)/W | 8.6250 | 41 | 60 | 0 |
| 1 | Basic Wall: NLRS_41_IN_80mm | 24.41 m² | 0.1159 (m²·K)/W | 8.6250 | 41 | 60 | 0 |
| 1 | Basic Wall: NLRS_41_IN_80mm | 64.71 m² | 0.1159 (m²·K)/W | 8.6250 | 41 | 60 | 0 |
| 1 | Basic Wall: NLRS_41_IN_80mm | 24.41 m² | 0.1159 (m²·K)/W | 8.6250 | 41 | 60 | 0 |
| **4** | | **178.71 m²** | | | | | |
| 1 | Basic Wall: NLRS_42_WA_75mm | 4.03 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 4.03 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 18.12 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 9.09 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 0.69 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 2.50 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 5.53 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 1.81 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 2.81 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| 1 | Basic Wall: NLRS_42_WA_75mm | 2.81 m² | 0.3000 (m²·K)/W | 3.3333 | 22 | 75 | 0 |
| **10** | | **51.43 m²** | | | | | |
| **29** | | **625.66 m²** | | | | | |

**Table 42 Case Study Quantity Wall**

## Roof

| Family and Type | Area | Thermal Resistance (R) | NL-SfB | Thickness | Cost |
|---|---|---|---|---|---|
| Basic Roof: NLRS_27_structure-120mm | 65.87 m² | 0.4800 (m²·K)/W | 27 | 120 | 0.00 |
| Basic Roof: NLRS_27_IN-80mm | 72.78 m² | 0.1870 (m²·K)/W | 47 | 80 | 0.00 |

**Table 43 Case Study Quantity Roof**

## Floor

| Family and Type | Area | Thermal Resistance (R) | NL-SfB | Thickness | Cost |
|---|---|---|---|---|---|
| Floor: NLRS_23_FL_150mm | 49.48 m² | 0.6522 (m²·K)/W | 23 | 150 | |
| Floor: NLRS_23_FL_150mm | 52.50 m² | 0.6522 (m²·K)/W | 23 | 150 | |
| **Floor: NLRS_23_FL_150mm: 2** | **101.97 m²** | | | | |
| Floor: NLRS_23_FL_250mm | 53.96 m² | 1.0870 (m²·K)/W | 13 | 250 | |
| **Floor: NLRS_23_FL_250mm: 1** | **53.96 m²** | | | | |
| Floor: NLRS_23_FL_Finish 15mm | 50.44 m² | 0.0052 (m²·K)/W | 23 | 30 | |
| Floor: NLRS_23_FL_Finish 15mm | 51.60 m² | 0.0052 (m²·K)/W | 23 | 30 | |
| Floor: NLRS_23_FL_Finish 15mm | 50.29 m² | 0.0052 (m²·K)/W | 23 | 30 | |
| **Floor: NLRS_23_FL_Finish 15mm: 3** | **152.33 m²** | | | | |
| Floor: NLRS_23_FL_Insulation 35mm | 40.00 m² | 0.0507 (m²·K)/W | 43 | 20 | |
| Floor: NLRS_23_FL_Insulation 35mm | 40.00 m² | 0.0507 (m²·K)/W | 43 | 20 | |
| Floor: NLRS_23_FL_Insulation 35mm | 40.00 m² | 0.0507 (m²·K)/W | 43 | 20 | |
| **Floor: NLRS_23_FL_Insulation 35mm:** | **120.00 m²** | | | | |
| Floor: NLRS_23_IN_80mm | 56.20 m² | 0.1159 (m²·K)/W | 23 | 80 | |
| **Floor: NLRS_23_IN_80mm: 1** | **56.20 m²** | | | | |

**Table 44 Case Study Quantity Roof**

## Window

| Count | Family and Type | Area | Glas Area | Frame Area | Rough Height | Rough Width | NL-SfB | Heat Transfer Coefficient (U) |
|---|---|---|---|---|---|---|---|---|
| 1 | Windows_Concept_Plain_Dbl: 1000x1000mm | 1 | 0.9 | 0.1 | 1000 | 1000 | 31 | 2.9000 |
| 1 | Windows_Concept_Plain_Dbl: 1000x1000mm | 1 | 0.9 | 0.1 | 1000 | 1000 | 31 | 2.9000 |
| **2** | | 2.00 | 1.80 | 0.20 | | | | |
| 1 | Windows_Concept_Plain_Sgl: 2416x1900mm | 4.5904 | 4.13136 | 0.45904 | 1900 | 2416 | 31 | 2.9000 |
| 1 | Windows_Concept_Plain_Sgl: 2416x1900mm | 4.5904 | 4.13136 | 0.45904 | 1900 | 2416 | 31 | 2.9000 |
| 1 | Windows_Concept_Plain_Sgl: 2416x1900mm | 4.5904 | 4.13136 | 0.45904 | 1900 | 2416 | 31 | 2.9000 |
| 1 | Windows_Concept_Plain_Sgl: 2416x1900mm | 4.5904 | 4.13136 | 0.45904 | 1900 | 2416 | 31 | 2.9000 |
| **4** | | 18.36 | 16.53 | 1.84 | | | | |
| **SUM** | | **20.36** | **18.33** | **2.04** | | | | |

**Table 45 Case Study Quantity Window**

# Appendix B

## B.1 Comparative Material Performance Rc 1.7

**Materials for Rc 1.7 ($m^2K/W$)**

| | | | | **Thermal Characteristics** | | | | **Environment** | | | | **Economic** | **Lifetime** | **Health, Safety & Comfort** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Materials | Functionality and applicability | | Thermal Conductivity Lambda | Thickness | Density | Weight (Mass Per Unit Area) | *Embodied Energy* | | | *Embodied Carbon* | *Material Costing* | Expected material lifetime | Fire rating | Toxic Hazards g/m³ | dB drop | VDRF |
| | | *Panels, Rolls* | *Flocks, Injectable* | *λ (W/mK)* | *(cm)/1m²* | *ρ (kg / m³)* | *(kg)/1m²* | *EE (MJ/m2)* | *EE nonrenewable* | *EE renewable* | *EC (kgCO2eq/m²)* | *€/m2* | *years* | *A-F* | *g/m³* | *dB* | *μ-value* |
| **1** | Glass wool | x | x | 0.034 | 6 | 18.4 | 1.06 | *51.50* | *44.10* | *7.40* | *1.60* | *6.80* | 75 | A2 | 129.5 | 8.52 | 0.29 |
| **2** | Rock wool | x | x | 0.035 | 6 | 45 | 2.68 | *48.90* | *42.48* | *6.42* | *2.90* | *7.40* | 75 | A1 | 172.1 | 7.85 | 0.36 |
| **3** | PUR (air) | x | x | 0.026 | 4 | 33 | 1.44 | *179.30* | *177.40* | *1.90* | *11.60* | *7.86* | 75 | E | 11.4 | 11.54 | 22.10 |
| **4** | EPS | x | x | 0.0325 | 6 | 23 | 1.24 | *117.50* | *118.67* | *-1.17* | *8.70* | *5.85* | 75 | E | 27.6 | 2.16 | 15.19 |
| **5** | XPS | x | | 0.027 | 5 | 35 | 1.61 | *178.20* | *179.80* | *-1.60* | *24.80* | *8.11* | 75 | E | ≤ 27.6 | 4.81 | 26.39 |
| **6** | Flax wool | x | | 0.041 | 7 | 31 | 2.16 | *86.30* | *45.50* | *40.70* | *2.60* | *24.08* | 40 | C | ≥ 129.5 | 10.17 | 0.52 |
| **7** | Wood fiber | x | | 0.038 | 6 | 45 | 21.96 | *23.50* | *7.50* | *15.90* | *0.62* | *6.91* | 100 | C-D | ≥ 129.5 | 21.00 | 0.97 |
| **8** | Cellulose roof | x | x | 0.04 | 7 | 70 | 4.76 | *8.80* | *2.70* | *6.10* | *0.29* | *55.50* | 30 | C | ≥ 129.5 | 10.90 | 0.85 |
| **9** | Sheep wool | x | | 0.0412 | 7 | 25 | 1.75 | *21.54* | *n.a* | *n.a* | *-2.10* | *13.48* | 100 | E | ≥ 129.5 | 6.52 | 0.70 |
| **10** | Hemp lime | x | x | 0.067 | 11 | 340 | 38.73 | *152.63* | *n.a* | *n.a* | *-8.59* | *23.92* | 100 | B | ≥ 129.5 | 16.48 | 1.59 |

**Table 46 Material for Rc 1.7**

## B.2 Comparative Material Performance Rc 2.5

| | Materials for Rc 2.5 (m²K/W) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Thermal Characteristics** | | | | **Environment** | | | | **Economic** | **LIFETIME** | **Health, Safety & Comfort** | | | |
| | Materials | Functionality and applicability | | Thermal Conductivity Lambda | Thickness | Density | Weight (Mass Per Unit Area) | *Embodied Energy* | | | *Embodied Carbon* | *Material Costing* | Expected material lifetime | Fire rating | Toxic Hazards g/m³ | dB drop | VDRF |
| | | *Panels, Rolls* | *Flocks, Injectable* | *λ (W/mK)* | *(cm)/1m²* | *ρ (kg / m³)* | *(kg)/1m²* | *EE (MJ/m2)* | *EE non renewable* | *EE renewable* | *EC (kgCO2eq/m²)* | *€/m2* | *years* | *A-F* | *g/m³* | *dB* | *μ-value* |
| **1** | Glass wool | x | x | 0.034 | 9 | 18.4 | 1.56 | *75.74* | *64.85* | *10.88* | *2.35* | *8.00* | 75 | A2 | 129.5 | 8.52 | 0.43 |
| **2** | Rock wool | x | x | 0.035 | 9 | 45 | 3.94 | *70.80* | *61.50* | *9.30* | *4.10* | *10.70* | 75 | A1 | 172.1 | 7.85 | 0.53 |
| **3** | PUR (air) | x | x | 0.026 | 7 | 33 | 2.11 | *259.80* | *257.10* | *2.80* | *16.80* | *10.00* | 75 | E | 11.4 | 11.54 | 32.50 |
| **4** | EPS | x | x | 0.0325 | 8 | 23 | 1.83 | *170.30* | *172.00* | *-1.70* | *12.70* | *7.80* | 75 | E | 27.6 | 2.16 | 22.34 |
| **5** | XPS | x | | 0.027 | 7 | 35 | 2.36 | *258.20* | *260.50* | *-2.40* | *36.47* | *13.87* | 75 | E | ≤ 27.6 | 4.81 | 38.81 |
| **6** | Flax wool | x | | 0.041 | 10 | 31 | 3.18 | *125.00* | *66.00* | *59.00* | *3.70* | *31.07* | 40 | C | ≥ 129.5 | 10.17 | 0.77 |
| **7** | Wood fiber | x | | 0.038 | 10 | 45 | 32.30 | *34.20* | *11.00* | *23.30* | *0.90* | *10.61* | 100 | C-D | ≥ 129.5 | 21.00 | 1.43 |
| **8** | Cellulose roof | x | x | 0.04 | 10 | 70 | 7.00 | *12.70* | *3.90* | *8.80* | *0.42* | *65.50* | 30 | C | ≥ 129.5 | 10.90 | 1.25 |
| **9** | Sheep wool | x | | 0.0412 | 10 | 25 | 2.58 | *31.67* | *n.a* | *n.a* | *-3.09* | *19.83* | 100 | E | ≥ 129.5 | 6.52 | 1.03 |
| **10** | Hemp lime | x | x | 0.067 | 17 | 340 | 56.95 | *224.45* | *n.a* | *n.a* | *-12.63* | *35.18* | 100 | B | ≥ 129.5 | 16.48 | 2.35 |

**Table 47 Material for Rc 2.5**

## B.3 Comparative Material Performance Rc 4.0

| | Materials for Rc 4.0 (m²K/W) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Thermal Characteristics** | | | | **Environment** | | | | **Economic** | **LIFETIME** | **Health, Safety & Comfort** | | | |
| | Materials | Functionality and applicability | | Thermal Conductivity Lambda | Thickness | Density | Weight (Mass Per Unit Area) | *Embodied Energy* | | | *Embodied Carbon* | *Material Costing* | Expected material lifetime | Fire rating | Toxic Hazards g/m³ | dB drop | VDRF |
| | | *Panels, Rolls* | *Flocks, Injectable* | *λ (W/mK)* | *(cm)/1m²* | *ρ (kg / m³)* | *(kg)/1m²* | *EE (MJ/m2)* | *EE non renewable* | *EE renewable* | *EC (kgCO2eq/m²)* | *€/m2* | *years* | *A-F* | *g/m³* | *dB* | *μ-value* |
| **1** | Glass wool | x | x | 0.034 | 14 | 18.4 | 2.50 | *119.80* | *102.59* | *17.21* | *3.70* | *12.30* | 75 | A2 | 129.5 | 8.52 | 0.68 |
| **2** | Rock wool | x | x | 0.035 | 14 | 45 | 6.30 | *113.70* | *98.76* | *14.94* | *6.70* | *16.55* | 75 | A1 | 172.1 | 7.85 | 0.84 |
| **3** | PUR (air) | x | x | 0.026 | 10 | 33 | 3.38 | *417.20* | *412.80* | *4.40* | *26.90* | *14.96* | 75 | E | 11.4 | 11.54 | 52.00 |
| **4** | EPS | x | x | 0.0325 | 13 | 23 | 2.93 | *273.40* | *276.20* | *-2.80* | *20.30* | *13.60* | 75 | E | 27.6 | 2.16 | 35.75 |
| **5** | XPS | x | | 0.027 | 11 | 35 | 3.78 | *414.50* | *418.19* | *-3.69* | *57.80* | *31.44* | 75 | E | ≤ 27.6 | 4.81 | 62.10 |
| **6** | Flax wool | x | | 0.041 | 16 | 31 | 5.08 | *200.70* | *105.82* | *94.80* | *6.00* | *42.53* | 40 | C | ≥ 129.5 | 10.17 | 1.23 |
| **7** | Wood fiber | x | | 0.038 | 15 | 45 | 51.68 | *55.10* | *17.70* | *37.50* | *1.45* | *17.28* | 100 | C-D | ≥ 129.5 | 21.00 | 2.28 |
| **8** | Cellulose roof | x | x | 0.04 | 16 | 70 | 11.20 | *20.40* | *6.20* | *14.20* | *0.68* | *72.50* | 30 | C | ≥ 129.5 | 10.90 | 2.00 |
| **9** | Sheep wool | x | | 0.0412 | 16 | 25 | 4.12 | *50.68* | *n.a* | *n.a* | *-4.94* | *31.72* | 100 | E | ≥ 129.5 | 6.52 | 1.65 |
| **10** | Hemp lime | x | x | 0.067 | 27 | 340 | 91.12 | *359.12* | *n.a* | *n.a* | *-20.21* | *56.28* | 100 | B | ≥ 129.5 | 16.48 | 3.75 |

**Table 48 Material for Rc 4.0**

## B.4 Comparative Material Performance Rc 6.5

**Materials for Rc 6.5 ($m^2K/W$)**

| | | | | **Thermal Characteristics** | | | | **Environment** | | | | **Economic** | **LIFETIME** | **Health, Safet & Comfort** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Materials | Functionality and applicability | | Thermal Conductivity Lambda | Thickness | Density | Weight (Mass Per Unit Area) | *Embodied Energy* | | | *Embodied Carbon* | *Material Costing* | Expected material lifetime | Fire rating | Toxic Hazards $g/m^3$ | dB drop | VDRF |
| | | *Panels, Rolls* | *Flocks, Injectable* | *λ (W/mK)* | *(cm)/1m²* | *ρ (kg / m³)* | *(kg)/1m²* | *EE (MJ/m2)* | *EE non renewable* | *EE renewable* | *EC (kgCO2eq/m²)* | *€/m2* | *years* | *A-F* | *g/m³* | *dB* | *µ-value* |
| **1** | Glass wool | x | x | 0.034 | 22 | 18.4 | 4.07 | *196.91* | *168.62* | *28.29* | *6.12* | *20.00* | 75 | A2 | 129.5 | 8.52 | 1.11 |
| **2** | Rock wool | x | x | 0.035 | 23 | 45 | 10.24 | *186.97* | *162.41* | *24.56* | *11.09* | *26.00* | 75 | A1 | 172.1 | 7.85 | 1.37 |
| **3** | PUR (air) | x | x | 0.026 | 17 | 33 | 5.49 | *680.70* | *673.50* | *7.20* | *43.90* | *23.00* | 75 | E | 11.4 | 11.54 | 84.50 |
| **4** | EPS | x | x | 0.0325 | 21 | 23 | 4.75 | *449.26* | *453.75* | *-4.48* | *33.26* | *21.00* | 75 | E | 27.6 | 2.16 | 58.09 |
| **5** | XPS | x | | 0.027 | 18 | 35 | 6.14 | *681.35* | *687.42* | *-6.07* | *94.82* | *39.92* | 75 | E | ≤ 27.6 | 4.81 | 100.91 |
| **6** | Flax wool | x | | 0.041 | 27 | 31 | 8.26 | *329.97* | *173.97* | *156.00* | *9.94* | *67.25* | 40 | C | ≥ 129.5 | 10.17 | 2.00 |
| **7** | Wood fiber | x | | 0.038 | 25 | 45 | 83.98 | *89.40* | *28.60* | *60.70* | *2.35* | *30.17* | 100 | C-D | ≥ 129.5 | 21.00 | 3.71 |
| **8** | Cellulose roof | x | x | 0.04 | 26 | 70 | 18.20 | *33.30* | *10.20* | *23.10* | *1.11* | *90.00* | 30 | C | ≥ 129.5 | 10.90 | 3.25 |
| **9** | Sheep wool | x | | 0.0412 | 27 | 25 | 6.70 | *82.35* | *n.a* | *n.a* | *-8.03* | *51.55* | 100 | E | ≥ 129.5 | 6.52 | 2.68 |
| **10** | Hemp lime | x | x | 0.067 | 44 | 340 | 148.07 | *583.57* | *n.a* | *n.a* | *-32.84* | *91.46* | 100 | B | ≥ 129.5 | 16.48 | 6.10 |

**Table 49 Material for Rc 6.5**

# Appendix C

## C.1 Building Elements and System boundaries

| | Related building elements | Included |
|---|---|---|
| **Shell (substructure and superstructure)** | | |
| Foundation_Substructure | Piles | no |
| | Basements | no |
| | Retaining walls | no |
| Load_bearing_structural_frame | Frame (beams, columns and slabs) | no |
| | Upper floors | no |
| | External wall | no |
| | Balconies | no |
| Non_load_bearing_elements | Ground floor slab | yes |
| | Internal walls, partitions and doors | no |
| | Stairs and ramps | no |
| Facades | External wall systems, cladding and shading devices | yes |
| | Façade openings (including windows and external doors) | yes |
| | External paints, coatings and renders | no |
| Roof | Structure | no |
| | Weatherproofing | yes |
| Parking_facilities | Above ground and underground (within the curtilage of the building and servicing the building occupiers) | no |
| Core (fittings, furnishings and services) | | |
| Fittings_and_furnishings | Sanitary fittings | no |
| | Cupboards, wardrobes and worktops (where provided in residential property) | no |
| | Ceilings | no |
| | Wall and ceiling finishes | yes |
| | Floor coverings and finishes | yes |
| In_built_lighting_system | Light fittings | no |
| | Control systems and sensors | no |
| Energy_system | Heating plant and distribution | yes |
| | Cooling plant and distribution | n.a |
| | Electricity generation and distribution | yes |
| Ventilation_system | Air handling units | n.a |
| | Ductwork and distribution | n.a |
| Sanitary_systems | Cold water distribution | no |
| | Hot water distribution | no |
| | Water treatment systems | no |
| | Drainage system | no |
| Other_systems | Lifts and escalators | no |
| | Firefighting installations | no |
| | Communication and security installations | no |
| | Telecoms and data installations | no |
| External works | | |
| Utilities | Connections and diversions | no |
| | Substations and equipment | no |
| Landscaping | Paving and other hard surfacing | no |
| | Fencing, railings and walls | no |
| | Drainage systems | no |

**Table 50 LCA Building Elements and System boundary**

# Appendix D

## D.1 Result heat Load Demand VABI

Results for net surface 100m² building

| **Concept** | | | | | **Heat Load Demand kWh/m²** | **Energy Saving** |
|---|---|---|---|---|---|---|
| Package As Built | WA_R0.68 | R_R1.12 | F_R0.17 | WI_U4.5 | 106.00 | *0%* |
| Package 1 | | | | | | |
| WALL | WA_R1.7 | R_R1.12 | F_R0.17 | WI_U4.5 | 92.00 | *8.10%* |
| WALL+ROOF | WA_R1.7 | R_R2.5 | F_R0.17 | WI_U4.5 | 83.00 | *13.30%* |
| WALL+WINDOW | WA_R1.7 | R_R1.12 | F_R0.17 | WI_U1.2 | 56.00 | *29.04%* |
| WALL+ROOF+WINDOW | WA_R1.7 | R_R2.5 | F_R0.17 | WI_U1.2 | 45.00 | *35.43%* |
| Package P2+P3 | | | | | | |
| WALL | WA_R4.0 | R_R1.12 | F_R0.17 | WI_U4.5 | 87.00 | *11.03%* |
| WALL+ROOF | WA_R4.0 | R_R6.5 | F_R0.17 | WI_U4.5 | 71.00 | *20.33%* |
| WALL+WINDOW | WA_R4.0 | R_R1.12 | F_R0.17 | WI_U0.7 | 45.00 | *35.43%* |
| WALL+ROOF+WINDOW | WA_R4.0 | R_R6.5 | F_R0.17 | WI_U0.7 | 29.00 | *44.72%* |

**Table 51 Heat load demand simulation, according to VABI**

## D.2 Embodied Impact Wall

| **Wall** | | **EPS (1.7)** | **Glass wool (1.7)** | **Glass wool (4.0)** | **Rock wool (4.0)** | **Wood fibre (4.0)** |
|---|---|---|---|---|---|---|
| Material EC | kgCO2eq/m² | 8.7 | 1.6 | 3.7 | 6.7 | 1.45 |
| Wall insulation | kgCO2eq/BE | 424.64 | 78.09 | 127.20 | 230.34 | 49.85 |
| Wall sub structure | kgCO2eq | - | - | 289.65 | 289.65 | 289.65 |
| Sub-total Wall | kgCO2eq | 424.64 | 78.09 | 416.85 | 519.99 | 339.5 |

**Table 52 EC for Wall insulation**

## D.3 Embodied Impact Roof

| Roof | | EPS (2.5) | Glass wool (2.5) | Glass wool (6.5) | Rock wool (6.5) | Wood fibre (6.5) |
|---|---|---|---|---|---|---|
| Insulation EC | kgCO2eq/m² | 12.70 | 2.35 | 6.12 | 11.09 | 2.35 |
| Roof insulation | kgCO2eq/BE | 924.30 | 171.03 | 395.78 | 717.19 | 151.97 |
| Roof sub structure | kgCO2eq | - | - | 537.14 | 537.14 | 537.14 |
| Sub-total Roof | kgCO2eq | 924.30 | 171.03 | 932.92 | 1,254.33 | 689.11 |

**Table 53 EC for Roof insulation**

## D.4 Embodied Impact Window

The Window frame and the glass was handled separately. Thus, embodied carbon values for wood, aluminium and PVC and for HR++ and triple glass was collected and multiplied with the case study window frame and glass area. More information can be added in a second step.

| **Window** | **Wood HR ++ (U 1.2)** | **Aluminium HR++ (U 1.2)** | **PVC HR ++ (U 1.2)** | **Wood Triple (U 0.7)** | **Aluminium Triple (U 0.7)** | **PVC Triple (U 0.7)** |
|---|---|---|---|---|---|---|
| Window EE (MJ/m²) | 512.20 | 602.80 | 539.30 | 644.90 | 735.50 | 672.00 |
| Window EE (MJ) | 7,003.17 | 7,187.64 | 7,058.35 | 9,434.95 | 9,619.43 | 9,490.13 |
| Window EC (kgCO2eq/m²) | 24.26 | 36.90 | 36.50 | 37.56 | 50.20 | 49.80 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Window BE (kgCO2eq) | 441.96 | 467.71 | 466.89 | 685.69 | 711.43 | 710.62 |

**Table 54 EC for Windows**

## D.5 Embodied Impact Sub Structure

As for the secondary construction, soft wooden beams are used, see **Table 55**. For the inside wool, we use wood for the sub construction. Wood beams with a cross section is 0.07 x 0.15 m and Length is 62.5 m = 0.656 $m^3$ * 4,673.00 $MJ/m^3$ = 3,066.66 MJ & and 0.656 $m^3$ * 92.0 $kgCO2eq/m^3$ = 60.352 kgCO2eq. Add gypsum boards with an area of 34.38 $m^2$ multiplied with the embodied energy of 66.10 $MJ/m^2$ = 2,272.552 MJ and carbon footprint of 6.67 $kgCO2eq/m^2$ yields 229.3 kgCO2eq. Sum for the wall secondary constructions is therefore 5,339.17 MJ and 289.65 kgCO2eq. For the inside rood, we use wood beams with a cross section of 0.075 x 0.25 cm and a length of 61.54 m = 1.15 $m^3$ * 4,673.00 $MJ/m^3$ = 5,392.06 MJ & 1.15 $m^3$ * 92.0 $kgCO2eq/m^3$ = 106.16 kgCO2eq. Add gypsum boards with an area of 64.67 $m^2$ multiplied with the embodied energy of 66.10 $MJ/m^2$ = 4,274.69 MJ and the carbon footprint of 6.67 $kgCO2eq/m^2$ yields 431.34 kgCO2eq. Sum for the roof secondary constructions is therefore 9,666.74 MJ and 537.14 kgCO2eq.

| **Sub Structure** | **Embodied Energy** | | | **Embodied Carbon** | | |
|---|---|---|---|---|---|---|
| | EE ($MJ/m^2$) EE ($MJ/m^3$) | Wall inside (MJ) | Roof inside (MJ) | EC ($kgCO2eq/m^2$) | Wall inside (kgCO2eq) | Roof inside (kgCO2eq) |
| Wood | 4,673.00 | 3,066.66 | 5,392.06 | 92.00 | 60.38 | 106.16 |
| Plaster board | 66.10 | 2,272.52 | 4,274.69 | 6.67 | 229.31 | 431.35 |
| Pe folie | | | | | | |
| Total | | 5,339.17 | 9,666.74 | | 289.69 | 537.51 |

**Table 55 Embodied Emission Secondary Construction P2**

# Appendix E

## E.1 Investment Cost (IC) Wall

| Wall investment | | EPS (1.7) | Glass wool (1.7) | Glass wool (4.0) | Rock wool (4.0) | Wood fibre (4.0) |
|---|---|---|---|---|---|---|
| Material Cost | €/m² | 5.85 | 6.8 | 12.3 | 16.55 | 17.28 |
| Wall insulation | € | 285.73 | 331.91 | 422.87 | 568.99 | 594.09 |
| Sub Construction Cost | € | - | - | 646.45 | 646.45 | 646.45 |
| Installation Cost | € | 628.36 | 500.95 | 429.75 | 429.75 | 429.75 |
| Sub-Wall IC | € | 914.09 | 832.86 | 1,499.07 | 1,645.19 | 1,670.29 |

**Table 56 Wall IC**

## E.1 Investment Cost (IC) Roof

| Roof investment | | EPS (2.5) | Glass wool (2.5) | Glass wool (6.5) | Rock wool (6.5) | Wood fibre (6.5) |
|---|---|---|---|---|---|---|
| Material Cost | €/m² | 7.80 | 8.00 | 20.00 | 26.00 | 30.17 |
| Roof insulation | € | 567.68 | 582.24 | 1,293.4 | 1,681.42 | 1,951.09 |
| Sub Construction Cost | € | - | - | 968.18 | 968.18 | 968.18 |
| Installation Cost | € | 1,455.6 | 1,455.6 | 1,293.4 | 1,293.4 | 1,293.4 |
| Sub-Roof IC | € | 2,023.28 | 2,037.84 | 3,554.98 | 3,943.00 | 4,212.68 |

**Table 57 Roof IC**

## E.2 Investment Cost (IC) Window

Windows were calculated but are not part of the experiment, however are calculated. Source were taken from Verbouwcosten.com.[99]

| Window | Wood HR ++ (U 1.2) | Aluminium HR++ (U 1.2) | PVC HR ++ (U 1.2) | Wood Triple (U 0.7) | Aluminium Triple (U 0.7) | PVC Triple (U 0.7) |
|---|---|---|---|---|---|---|
| Glass Cost | 135.00 | 135.00 | 135.00 | 180.00 | 180.00 | 180.00 |
| Frame Cost | 527.50 | 590.00 | 502.50 | 502.38 | 566.75 | 476.63 |
| IC Window (€/m²) | 662.50 | 725.0 | 637.50 | 682.38 | 746.75 | 656.63 |
| Sub-total IC (€) | 13,489.56 | 14,762.16 | 12,980.52 | 13,894.25 | 15,205.02 | 13,369.94 |

**Table 58 IC Windows**

## E.3 Investment Cost (IC) Wall and Roof Sub Structure

For the inside wall we apply a secondary construction out of soft wood columns (0.07 x 0.15 m). The price for the wall wooden columns area 6.59 €/m [100] multiplied by a total length of 62.5 m yields 411.8 €. To cover the inside walls, we use a gypsum plate 1.25 cm. The gypsum plate is 2.46 €/m² [101] and multiplied by a total area of 34.38 m² which yields 84.57 €. Total secondary construction cost for wall is 496.37 €. For the inside roof we also apply a secondary construction out of wooden columns (0.075

[99] https://www.verbouwkosten.com/kozijnen/aluminium/prijs/
[100] https://www.houthandelgorinchem.nl/product/douglas-balk-70-x-150-mm/
[101] https://www.hornbach.de/shop/Gipskartonplatte-KNAUF-GKB-2000x1250x12-5mm-die-Standardplatte/3286520/artikel.html

x 0.25 m). The price for the roof wooden column is 10.71 €/m [102] multiplied by a total length of 61.54 m yields 659.09 €. The cover of the inside roof insulation, we will use a gypsum plate 1.25 cm. The gypsum plate is 2,46 €/m² [103] and multiplied by a total area of 64.67 m² yields 159.08 €. Total secondary construction cost for roof is 818.17 €. Second layer wall add PE Foil[104] to the pricing with 2.0€/m², so for a surface for 100m² (walls 35m² and roof 65m²) it yields 299.98€ (approx. 300€). Because the manufacture of the PE Foil delivers in certain quantities, 100m² must be covered with 2 roles and yields therefore a higher value.

| **Sub Structure** | | **Investment Cost** | |
|---|---|---|---|
| | | Wall inside €/BE | Roof inside €/BE |
| Wood (0.07x0.15m) [€/m] | 6.59 | 411.88 | - |
| Wood (0.075x0.25m) [€/m] | 10.71 | - | 659.09 |
| Plaster board [€/m²] | 2.46 | 84.57 | 159.09 |
| Pe folie [€/m²] | 1,32 | 150.00 | 150.00 |
| Total [€] | | 646.45 | 968.18 |

**Table 59 Investment Cost Package 2**

## E.4 Subsidy

The subsidy regulation has been derived from the RVO.[105]

| | **Subsidy amount and insulation values** | | | |
|---|---|---|---|---|
| | Grant amount per m² | Minimum m² | Maximum m² | Minimum Rc-Value |
| Façade insulation | € 25 | 15 | 170 | 3.5 |
| Cavity wall insulation | € 5 | 15 | 170 | 1.1 |
| Roof insulation | € 20 | 25 | 200 | 3.5 |
| Attic/loft floor | € 5 | 25 | 130 | 3.5 |
| Floor insulation | € 7 | 25 | 130 | 3.5 |
| Bottom insulation | € 4 | 25 | 130 | 3.5 |

**Table 60 Subsidy amount for envelop insulation**

| | **Subsidy amount and insulation values** | | | |
|---|---|---|---|---|
| | Grant amount per m² | Minimum m² | Maximum m² | Minimum Rc-Value |
| Façade HR++ glass | € 35 | 10 | 45 | 1.2 |
| Frame panels | € 15 | | | 1.2 |
| Insulating doors | € 35 | | | 1.5 |
| Triple glass | € 100 | 10 | 45 | 0.7 |
| Frame panels | € 75 | | | 0.7 |
| Insulating doors | € 100 | | | 1.0 |

**Table 61 Subsidy amount for window insulation**

[102] https://www.dehoutgroothandel.nl/vurenhout/vuren-balken/vuren-balk-c24-geschaafd-75x250mm
[103] https://www.hornbach.de/shop/Gipskartonplatte-KNAUF-GKB-2000x1250x12-5mm-die-Standardplatte/3286520/artikel.html
[104] https://www.obi.at/daemmstoffzubehoer/ursa-seco-pro-sd2-dampfbremse-50-m-x-1-5-m/p/5951843
[105] https://www.rvo.nl/subsidie-en-financieringswijzer/isde/woningeigenaren/voorwaarden-woningeigenaren/isolatiemaatregelen

# Appendix F

## F.1 Factorial Design

| Profil | A1 | A2 | A3 | A4 | A5 | A6 |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 1 | 1 | 1 |
| 3 | 0 | 1 | 1 | 0 | 0 | 1 |
| 4 | 0 | 1 | 1 | 1 | 1 | 0 |
| 5 | 1 | 0 | 1 | 0 | 1 | 1 |
| 6 | 1 | 1 | 0 | 0 | 1 | 0 |
| 7 | 1 | 0 | 1 | 1 | 0 | 0 |
| 8 | 1 | 1 | 0 | 1 | 0 | 1 |

**Table 62 Orthogonal and a simple fractional factorial design**

## F.2 Package creation for Lime Survey,

28 choice tasks were created.

| |
|---|
| id,package1,package2 |
| q0r182, 000111,101011 |
| q0r321, 000000,110010 |
| q0r387, 000111,110101 |
| q0r564, 011001,101011 |
| q0r565, 011001,110010 |
| q0r568, 011001,110101 |
| q0r569, 011110,000000 |
| q0r570, 011110,000111 |
| q0r571, 011110,011001 |
| q0r572, 011110,110101 |
| q0r573, 101011,000000 |
| q0r574, 101011,011110 |
| q0r575, 101011,101100 |
| q0r576, 101011,110101 |
| q0r577, 101100,000111 |
| q0r578, 101100,011001 |
| q0r579, 101100,011110 |
| q0r580, 101100,110010 |
| q0r581, 101100,110101 |
| q0r582, 110010,000111 |
| q0r583, 110010,011110 |
| q0r584, 110010,101011 |
| q0r585, 110010,110101 |
| q0r624, 000111,011001 |
| q0r667, 000000,011001 |
| q0r688, 000000,101100 |
| q0r828, 000000,000111 |
| q0r829, 000000,110101 |

**Table 63 Choice tasks (combined packages)**

## F.3 Lime Survey Stated Choice Set up

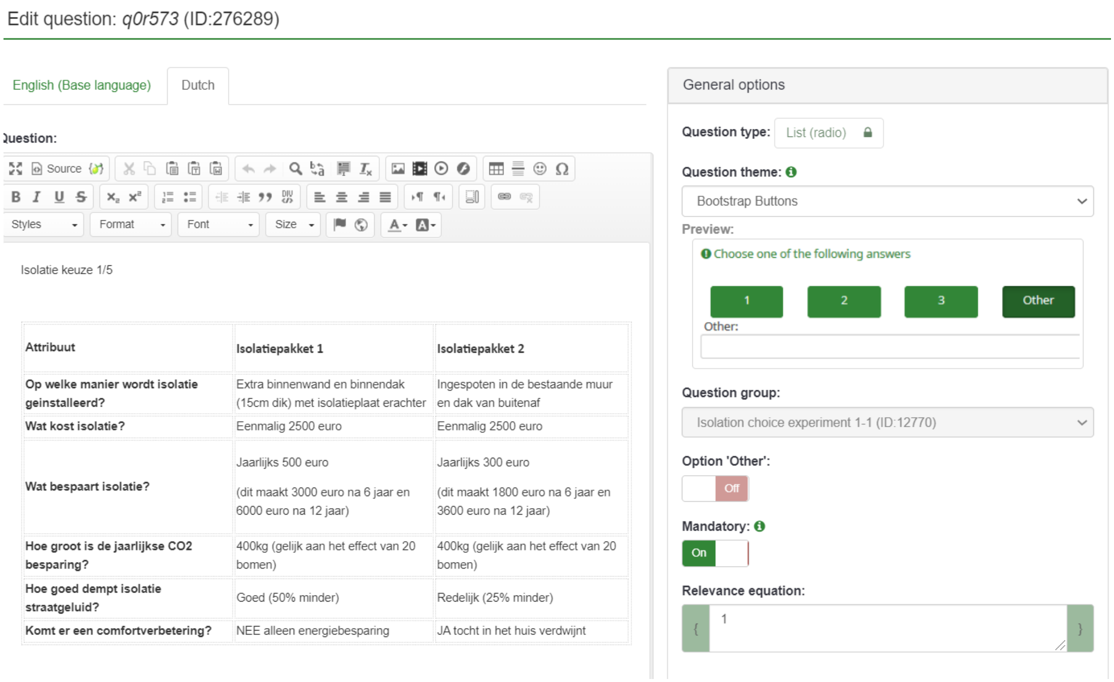


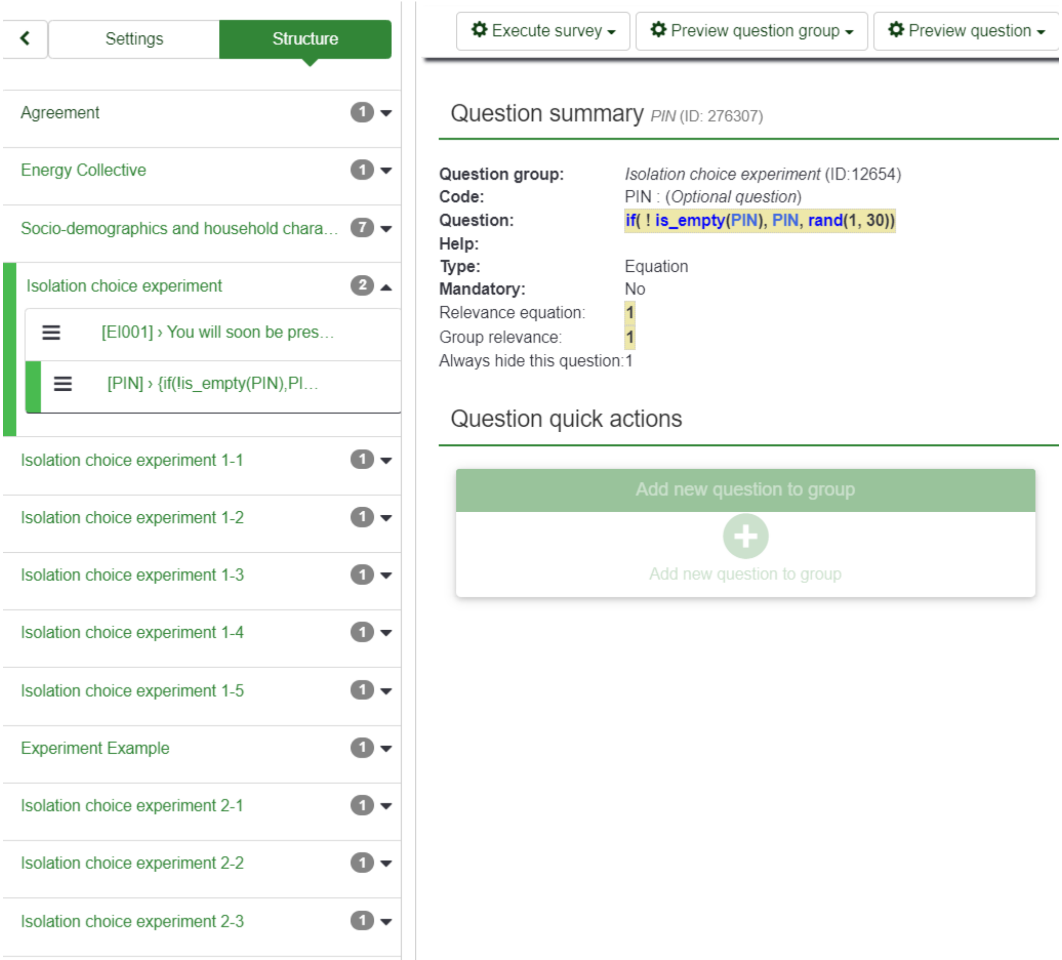

**Figure 75 Lime Survey Choice set up**

## F.4 HTML Code in Lime Survey

```
<p><!--Profiles: 101011, 000000-->Isolatie keuze 1/5</p>

<p> </p>

<table class="table table-condensed">
	<tbody>
		<tr class="success">
			<th style="text-align: left;" width="300px">Attribuut</th>
			<th style="text-align: left;" width="300px">
			<p style="margin-bottom:13px"><span style="font-size:11pt"><span style="line-height:115%"><span style="font-family:Calibri,sans-serif"><em><span lang="EN-GB" style="font-family:&quot;Calibri&quot;,sans-serif"><span style="font-style:normal">Isolatiepakket 1</span></span></em></span></span></span></p>
			</th>
			<th style="text-align: left;" width="300px">
			<p style="margin-bottom:13px"><span style="font-size:11pt"><span style="line-height:115%"><span style="font-family:Calibri,sans-serif"><em><span lang="EN-GB" style="font-family:&quot;Calibri&quot;,sans-serif"><span style="font-style:normal">Isolatiepakket 2</span></span></em></span></span></span></p>
			</th>
		</tr>
		<tr>
			<td><strong>Op welke manier wordt isolatie geinstalleerd?</strong></td>
			<td>Extra binnenwand en binnendak (15cm dik) met isolatieplaat erachter</td>
```

```
                    <td>Ingespoten in de bestaande muur en dak van buitenaf</td>
          </tr>
          <tr>
                    <td><strong>Wat kost isolatie?</strong></td>
                    <td>Eenmalig 2500 euro</td>
                    <td>Eenmalig 2500 euro</td>
          </tr>
          <tr>
                    <td><strong>Wat bespaart isolatie?</strong></td>
                    <td>
                    <p>Jaarlijks 500 euro</p>

                    <p>(dit maakt 3000 euro na 6 jaar en 6000 euro na 12 jaar)</p>
                    </td>
                    <td>
                    <p>Jaarlijks 300 euro</p>

                    <p>(dit maakt 1800 euro na 6 jaar en 3600 euro na 12 jaar)</p>
                    </td>
          </tr>
          <tr>
                    <td><strong>Hoe groot is de jaarlijkse CO2 besparing?</strong></td>
                    <td>400kg (gelijk aan het effect van 20 bomen)</td>
                    <td>400kg (gelijk aan het effect van 20 bomen)</td>
          </tr>
          <tr>
                    <td><strong>Hoe goed dempt isolatie straatgeluid?</strong></td>
                    <td>Goed (50% minder)</td>
                    <td>Redelijk (25% minder)</td>
          </tr>
          <tr>
                    <td><strong>Komt er een comfortverbetering?</strong></td>
                    <td>NEE alleen energiebesparing</td>
                    <td>JA tocht in het huis verdwijnt</td>
          </tr>
     </tbody>
</table>
```

## F.5 PIN code



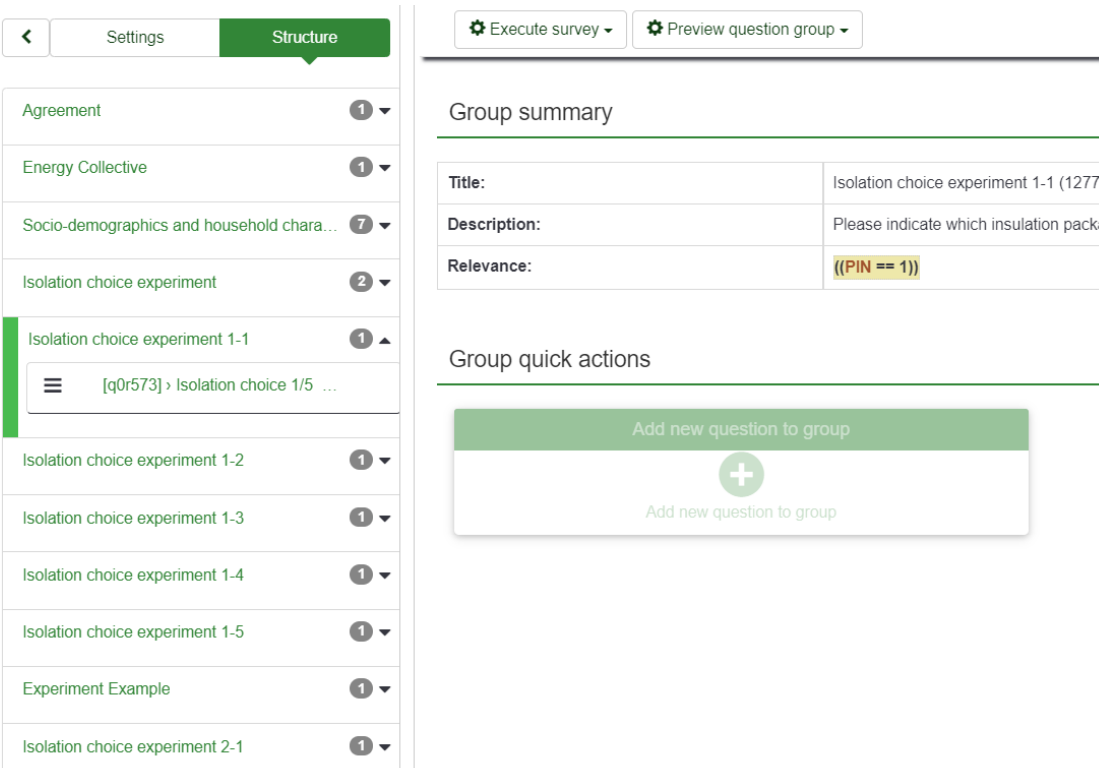




**Figure 76 Lime Survey PIN Code for random combination**

## F.5 Cross Effect per energy collective

| Attributes | General | | | |
|---|---|---|---|---|
| | Coef. (β) | | Std. Error | |
| No renovation | -0.500 | | 0.086*** | |
| + 040energie | | -0.568 | | 0.096*** |
| + Best Duurzaam | | 0.200 | | 0.260 |
| + Individual | | 0.396 | | 0.389 |
| Installation technique | -1.143 | | 0.062*** | |
| + 040energie | | -1.178 | | 0.068*** |
| + Best Duurzaam | | 0.002 | | 0.190 |
| + Individual | | 0.567 | | 0.254* |
| Investment Cost | -0.230 | | 0.061*** | |
| + 040energie | | -0.237 | | 0.067*** |
| + Best Duurzaam | | 0.119 | | 0.185 |
| + Individual | | -0.040 | | 0.256 |
| Energy reduction | 0.530 | | 0.063*** | |
| + 040energie | | 0.552 | | 0.069*** |
| + Best Duurzaam | | -0.153 | | 0.190 |
| + Individual | | -0.024 | | 0.253 |
| CO2 reduction | 0.321 | | 0.064*** | |
| + 040energie | | 0.345 | | 0.071*** |
| + Best Duurzaam | | -0.019 | | 0.198 |
| + Individual | | -0.359 | | 0.260 |
| Noise reduction | 0.341 | | 0.066*** | |
| + 040energie | | 0.345 | | 0.073*** |
| + Best Duurzaam | | -0.031 | | 0.203 |
| + Individual | | -0.020 | | 0.268 |
| Comfort improvement | 0.345 | | 0.063*** | |
| + 040energie | | 0.329 | | 0.070*** |
| + Best Duurzaam | | -0.018 | | 0.194 |
| + Individual | | 0.297 | | 0.267 |
| #respondents | 478 | | | |
| | | 389 | | |
| | | 59 | | |
| | | 31 | | |

**Table 64 Relative importance of coefficient for energy collective groups**

## F.6 Cross effect Gender

| **Attributes** | **Men** | |
|---|---|---|
| | Coef. (β) | Std. Error |
| No refurbishment | -0.407 | 0.094*** |
| + women | -0.521 | 0.239* |
| + nonbinary | -1.026 | 0.742 |
| Installation technique | -1.175 | 0.068*** |
| + women | 0.256 | 0.166 |
| + nonbinary | -8.465 | 1287.045 |
| Investment Cost | -0.175 | 0.067** |
| + women | -0.351 | 0.165* |
| + nonbinary | -8.010 | 1287.04 |
| Energy reduction | 0.531 | 0.069*** |
| + women | -0.014 | 0.170 |
| + nonbinary | 7.701 | 1287.045 |
| $CO_2$ reduction | 0.320 | 0.070*** |
| + women | 0.110 | 0.174 |
| + nonbinary | -0.606 | 0.924 |
| Noise reduction | 0.366*** | 0.072*** |
| + women | 0.026 | 0.184 |
| + nonbinary | -1.205 | 0.917 |
| Comfort improvement | 0.396*** | 0.069*** |
| + women | -0.275 | 0.173 |
| + nonbinary | -1.068 | 0.718 |
| #respondents | 397 | |
| | 74 | |
| | 7 | |

**Table 65 Cross-effect per gender group**

## F.7 Cross effect Age

| **Attributes** | **Older (> 50years)** | |
|---|---|---|
| | Coef. (β) | Std. Error |
| No refurbishment | -0.419 | 0.096*** |
| + younger (<50yrs) | -0.475 | 0.223* |
| Installation technique | -1.137 | 0.069*** |
| + younger (<50yrs) | -0.053 | 0.152 |
| Investment Cost | -0.197 | 0.068** |
| + younger (<50yrs) | -0.130 | 0.150 |
| Energy reduction | 0.459 | 0.070*** |
| + younger (<50yrs) | 0.330 | 0.155* |
| $CO_2$ reduction | 0.244 | 0.072*** |
| + younger (<50yrs) | 0.356 | 0.159* |
| Noise reduction | 0.378 | 0.074*** |
| + younger (<50yrs) | -0.114 | 0.163 |
| Comfort improvement | 0.307 | 0.070*** |
| + younger (<50yrs) | 0.180 | 0.159 |
| #respondents | 375 | |
| | 103 | |

**Table 66 Cross effect per age group**

## F.8 Cross effect Income level

| Attributes | High income (>50,000€/yr) | |
|---|---|---|
| | Coef. (β) | Std. Error |
| No refurbishment | -0.645 | 0.113*** |
| Low income (<50,000€/yr) | 0.338 | 0.198. |
| Income n.a. | 0.479 | 0.269. |
| Installation technique | -1.353 | 0.081*** |
| Low income (<50,000€/yr) | 0.531 | 0.141*** |
| Income n.a. | 0.360 | 0.200. |
| Investment Cost | -0.193 | 0.079* |
| Low income (<50,000€/yr) | -0.074 | 0.139 |
| Income n.a. | -0.066 | 0.198 |
| Energy reduction | 0.593 | 0.081*** |
| Low income (<50,000€/yr) | -0.097 | 0.144 |
| Income n.a. | -0.226 | 0.203 |
| CO2 reduction | 0.398 | 0.083*** |
| Low income (<50,000€/yr) | -0.282 | 0.146. |
| Income n.a. | 0.174 | 0.211 |
| Noise reduction | 0.418 | 0.086*** |
| Low income (<50,000€/yr) | -0.049 | 0.152 |
| Income n.a. | -0.429 | 0.209* |
| Comfort improvement | 0.465 | 0.083*** |
| Low income (<50,000€/yr) | -0.225 | 0.145 |
| Income n.a. | -0.348 | 0.204. |
| #respondents | 295<br>127<br>56 | |

**Table 67 Cross effect per income level**

## F.9 Cross effect Noise level

| Attributes | Higher noise disturbance | |
|---|---|---|
| | Coef. (β) | Std. Error |
| No refurbishment | -0.527 | 0.120*** |
| + lower noise disturbance | 0.066 | 0.177 |
| Installation technique | -1.191 | 0.086*** |
| + lower noise disturbance | 0.095 | 0.123 |
| Investment Cost | -0.326 | 0.085*** |
| + lower noise disturbance 1-2 | 0.212 | 0.122. |
| Energy reduction | 0.615 | 0.087*** |
| + lower noise disturbance | -0.174 | 0.126 |
| CO2 reduction | 0.251 | 0.089** |
| + lower noise disturbance | 0.146 | 0.128 |
| Noise reduction | 0.424 | 0.091*** |
| + lower noise disturbance | -0.167 | 0.132 |
| Comfort improvement | 0.461 | 0.088*** |
| + lower noise disturbance | -0.243 | 0.126. |
| #respondents | 252<br>226 | |

**Table 68 Cross effect per noise level**

## F.10 Cross effect Gas consumption

| Attributes | Gas consumption <100€/month | |
|---|---|---|
| | Coef. (β) | Std. Error |
| No refurbishment | -0.588 | 0.122*** |
| >100€/month | 0.300 | 0.182. |
| Not applicable | -0.425 | 0.306 |
| Installation technique | -1.046 | 0.085*** |
| >100€/month | -0.255 | 0.132. |
| Not applicable | 0.058 | 0.208 |
| Investment Cost | -0.274 | 0.084** |
| >100€/month | 0.137 | 0.130 |
| Not applicable | -0.140 | 0.213 |
| Energy reduction | 0.445 | 0.086*** |
| >100€/month | 0.213 | 0.135 |
| Not applicable | 0.001 | 0.209 |
| CO2 reduction | 0.294 | 0.089** |
| >100€/month | -0.008 | 0.137 |
| Not applicable | 0.303 | 0.222 |
| Noise reduction | 0.236 | 0.092* |
| >100€/month | 0.296 | 0.141* |
| Not applicable | -0.153 | 0.228 |
| Comfort improvement | 0.333 | 0.088*** |
| >100€/month | 0.022 | 0.135 |
| Not applicable | -0.007 | 0.219 |
| #respondents | 239 | |
| | 192 | |
| | 47 | |

**Table 69 Cross effect per gas consumption**

# Appendix G

## G.1 Shared Parameter

```
# This is a Revit shared parameter file.
# Do not edit manually.
*META	VERSION	MINVERSION
META	2	1
*GROUP	ID	NAME
GROUP	1	Archetype
*PARAM	GUID	NAME	DATATYPE	DATACATEGORY	GROUP	VISIBLE	DESCRIPTION	USERMODIFIABLE	HIDEWHENNOVALUE
PARAM	d744eb49-fa03-4b51-830c-4708e7cb5971	NLSFB	TEXT		1	1		1	0
PARAM	cfd3ac4a-07a8-498d-85c6-5b800447f516	RC	NUMBER		1	1		1	0
PARAM	f31cc551-e3c4-4f5b-8f52-c67463dbd30b	Area	AREA		1	1		1	0
PARAM	bdbd995a-acdb-42b5-8b7f-92ec07dba404	Cost	NUMBER		1	1		1	0
PARAM	c261847f-2ee2-4cbb-b738-3b7a01c1a52b	Frame Area	AREA		1	1		1	0
PARAM	e0c269ba-6e25-4ec6-aae2-8bfc7af0982f	Thickness	LENGTH		1	1		1	0
PARAM	b715d7cb-3b6d-4ff5-b42f-20916f2ae44d	Glass Area	AREA		1	1		1	0
```

**Figure 77 Shared Parameter in Autodesk Revit**

## G.2 NL-SfB and NMD merge

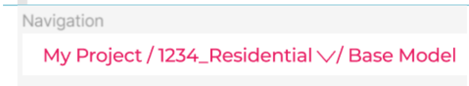
| Element name | NL-SfB (version: 2020-03-13 - Correctie codes 54.6x) | NMD (version 2.3) |
|---|---|---|
| Foundation (funderingen) | | |
| Fundament Floor (Vloeren op grondslag) | 13.0 | n.a |
| Non-load bearing (niet constructief) | 13.1 | n.a |
| Load bearing (constructief) | 13.2 | n.a |
| Shell (ruwbouw) | | |
| External Wall (Façade) (Buitenwand) | 21.0 | - |
| Non-load bearing (niet constructief) | 21.1 | 21.01.001-21.01.019; |
| Load bearing (constructief) | 21.2 | 21.02.001-21.02.008;<br>21.03.001-21.03.011;<br>21.04.001-21.04.005; |
| Internal Wall (Binnenwanden) | 22 | n.a |
| Non-load bearing (niet constructief) | 22.1 | n.a |
| Load bearing (constructief) | 22.2 | n.a |
| Inside Floor (Vloeren) | 23 | n.a |
| Non-load bearing (niet constructief) | | n.a |
| Load bearing (constructief) | | n.a |
| Roof Construction (Daken) | 27.0 | - |
| Non-load bearing (niet constructief) | 27.1 | 27.01.001-27.01.026 |
| Load bearing (constructief) | 27.2 | 27.02.002-27.02.033 |
| Finishes (afbouw) | | |
| Exterior Wall windows (Buitenwandopeningen) | 31 | |
| Window frame (Buitenramen) | 31.1 | 31.02.001-31.02.020.<br>31.03.004-31.03.015; |
| Window Ramen (Buitenbeglazing) | 31.2 | 31.07.001-31.07.026 |
| Exterior Doors (Buitendeuren) | 31.3 | 31.04.002-31.04.010; |
| Finishes (afwerkingen) | | |
| Façade insulation (Buitenwandafwerkingen) | 41.0 | 41.02.038-41.02.046;<br>41.04.001-41.04.0046; |
| Floor insulation (Vloerafwerkingen) | 43.0 | 43.03.001-43.03.024; |
| Roof insulation (Isolatielagen plat dak) | 47.0 | 47.07.002-47.07.024; |
| Roof insulation (Isolatielagen hellend dak) | 47.0 | 47.08.001-47.08.038 |

**Table 70 NL-SfB and NMD verification**

## G.3 Legend of user interface component

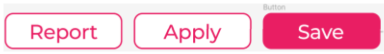
**Hamburger Menu**
Type: “Button”
Function: extendable and responsive side bar drawer


**Main Menu**
Type: “Button”
Function: Routing through UI site view definition
Example: “My Project” (activated)
“Refurbsihment” (deactivated)



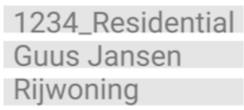

**Navigation Bar**
Type: Nav Bar, included “Drop Down Button”
Function: Navigation through project (including building model and defined package definition)


**View components**
Type: “Button”
Function: Routing within one UI site view definition through 5 view components.
Example:
“Dashboard” (activated): Project general knowledge and information.
“Calculation Performance” (deactivated): Table view calculation, via drop down.
“Pie Chart” (deactivated): results shown in pie charts in %.
“3D Model view” (deactivated): illustrates the 3D BIM model.



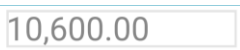

“Reporting” contains three types “Button”
“Report”; “Apply” and “Save”: Stores the decision.


**3D View – View component**
Type: “Button”
“Information” (deactivated)
“tree element view” (deactivated)
3D View component “Cube”




**User input**
Type: “Text field” (Numeric/Alphanumeric)
Function: Create and read using GET operation.
Example: Project number and Client and building name.


**User selection**
Type: “Drop Down” (List)
Function: read and update using POST operation
Depending on user input, API model renders list.
Example: list all possible material application for building element (using m:n relation)




**Computed Field**
Type: “Text Field” (Numeric/Alphanumeric)
Function: render computed results by API mode.
Example: numeric field to show computed energy in kWh.

**Table 71 UI legend**

## G.4 Basic UI and View Components

The previously created pages are further analysed and structured into reusable components and the basic layout in which the components are fed. The Grid components are used and filled with multiple functional components.

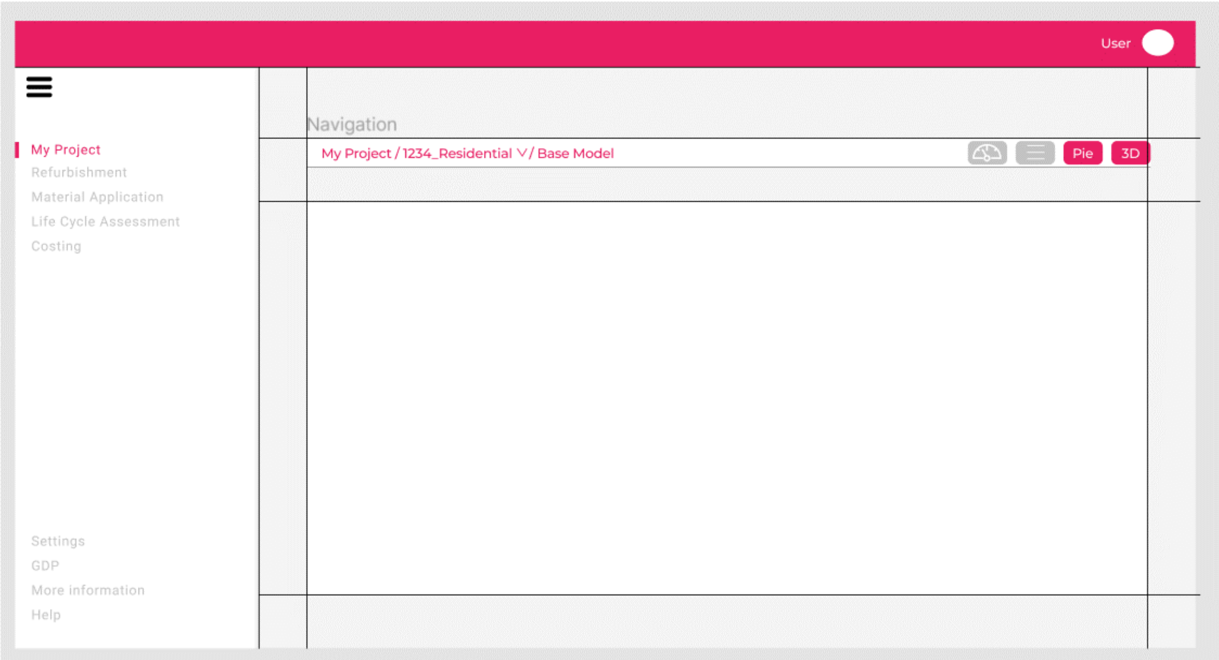



**Figure 78 UI Basic Grid Layout**

## Hamburger Menu (Drawer)

```
export default function MyPlugin() {
  const classes = useStyles();
  const { context, setContext } = useContext(AppContext);

  function setState(state) {
    setContext({...context, states: {...context.states, [context.plugin]: state}})
  }
```

```
 const state = context.states[context.plugin]

  return (
    <div className={classes.root}>
      {context.currentProject ? (
        <div>
          <Drawer
           className={classes.drawer}
           drawe with="20%"
           variant="permanent"
           anchor="left"
           classes={{
             paper: classes.drawerPaper,
           }}>
           <div className={classes.drawerHeader}></div>
           <div>
            <p><Button color="inherit" className={classes.hover} component={ Link } to="/myprojects"> M
y Projects </Button></p>

            <p><Button color="inherit" className={classes.hover} component={ Link } to="/refurbishments
"> Refurbishments </Button></p>

            <p><Button color="inherit" className={classes.hover} component={ Link } to="/materials"> Ma
terials </Button></p>
            <p><Button color="inherit" className={classes.hover} component={ Link } to="/lifecycleasses
sment"> Life Cycle Assessment </Button></p>
```

```
          <p><Button color="inherit" className={classes.hover} component={ Link } to="/costs"> Costs
</Button></p>
          <p><Button color="inherit" className={classes.hover} component={ Link } to="/marketpotentia
l"> Market Potential </Button></p>
          </div>
        </Drawer>{" "}
      </div>
              ) : (
      <div></div>
    )}
  </div>
 );
}
```

**Listing 15 Hamburger Menu**

## Component MPTable

```
function createData(ProjectName, ClientName, BuildingType) {
  return { ProjectName, ClientName, BuildingType };
}
```

```
export default class MyProjectTable extends Component {
    classes = {
      table: {
        minWidth: '900px',
      }
    }
    constructor(props) {
      super(props)
      this.state = {}
    }
    componentDidUpdate = () => {
      console.log('updated!')
    }
    render() {
      return (
        <div>
        <TableContainer component={Paper}>
          <Table className={this.classes.table}>
            <Divider/>
              <TableBody> {this.props.rows.map((row) => (
                <TableRow key={row.projectName}>
                <TableCell> {row.projectName} </TableCell>
                <TableCell> {row.clientName} </TableCell>
                <TableCell> {row.buildingType} </TableCell>
                <TableCell>
                  <Button variant="contained" color="primary" size="medium" > Edit </Button>
                </TableCell>
                <TableCell>
                  <Button variant="contained" color="primary" size="medium" > Save </Button>
                </TableCell>
              </TableRow>
               ))}
            </TableBody>
          </Table>
      </TableContainer>
    </div>
      )
    }
  }
```

**Listing 16 Component MPTable**

## G.5 Web Environment

### My Projects

### /Dashboard

Components imported are NavbarMinMP and MPTable.

The const MyProjects is created to set any created new project via the UseState function as true. The variable myProjectTableKey allows to save each newly created project with an unique ID. In that way we can store the projects as records and refer to the myProjects constant as object that defines the content of the projects. To be filled in values are projectName, clientName and buildingType, and are defined via the useRef hook that will be logged when activating the onSaveClicked event.

```
// MAIN function to create a new project -> const [array of myProjects setmyProjects]

function MyProjects(props) {
  var myProjectsTableKey = 0
    const classes = useStyles()
    const {context, setContext} = useContext(AppContext);
    const [collapse, setCollapse] = useState(true);
    const [myProjects, setmyProjects] = useState([])
    // const [myProjects, setmyProjects] = useState([projectName, clientName, buildingType])

//adding the myProject constant elements and referencing it to the textfield input
const projectNameTextFieldRef = useRef()
const clientNameTextFieldRef = useRef()
const buildingTypeTextFieldRef = useRef()

//Click on Save and add the values into a new project
//complex variable:. current.firstChild ... -> go to consol and redirect where to find the value
function onSaveClicked() {
  console.log('projectname', projectNameTextFieldRef.current.firstChild.firstChild.value)
  console.log('clientname', clientNameTextFieldRef.current.firstChild.firstChild.value)
  console.log('buildingtype', buildingTypeTextFieldRef.current.firstChild.firstChild.value)

//set the complex variable equal to easy var
  var typedInProjectName = projectNameTextFieldRef.current.firstChild.firstChild.value
  var typedInClientName = clientNameTextFieldRef.current.firstChild.firstChild.value
  var typedInBuildingType = buildingTypeTextFieldRef.current.firstChild.firstChild.value
```

**Listing 17 Function myProjects**

To define the objects content, we create a global variable namely const newProject. It allows to predefine all included objects' attributes that can later be filled in when performing through the web tool. A default render of all possible variables as 0 is done in advance to allow starting any page even when not yet defined by the user.

The setmyProjects function allows to add new projects (set via var myProjectTableKey) in a follow up series of the previously created project.

```
 // //Define variable for newProject -> create newProject when all three elements are entered.
 //return: is used to return the value of the function that returns the new projects
  const newProject = {
    projectName : typedInProjectName,
    clientName : typedInClientName,
    buildingType : typedInBuildingType,
    spaceHeating : 0,
    DHOW : 0,
    Electricity : 0,
    PrimaryEnergy : 0,
    EnergyLabel : 0,
    CO2op : 0,
    constructionYear: 0,
    refurbishmentYear: 0,
    refurbishmentLife: 0,
  }
  // rerender only added projects (see ToDoList tutorial)
```

```
  setmyProjects(prevProject => {
    return [...prevProject, newProject]
  })

  //adds a new key for each project -> not for each value added
  myProjectsTableKey++
  console.log('myProjects', myProjects)}
```
**Listing 18 Const newProject**

The newly created project must be stored, to remember the dependencies of all further user inputs towards this one particular project. While usually, we would access an externally hosted DB for storing, this thesis will use the web browsers local storage. The useEffect hook allows to access the localStorage, and enables to store the object as JSON string on the local web storage. Storing on local storage has the advantage that we can call the data on any other page, and thus parse on values from performance step to performance step.

Looking at the second useEffect function, we need to setItem my Project to the local storage, which stringifies the objects in a JSON format. After setting the item we call getItem to let the local storage remember the objects even after refreshing the web browser. The if function calls the constant TableData that encompasses the parsed project data information and checks if the table length is bigger than 0 (meaning if not empty), then we setmyProjects to the tableData.

```
//Save State On Page Refresh
 useEffect(() => {
   const myProjectData = localStorage.getItem('myProjects')
   if (myProjectData) {

   const TableData = JSON.parse(myProjectData);
   if (TableData.length > 0) {
     setmyProjects (TableData);
     }
   }
 }, [])


useEffect(() => {
  localStorage.setItem('myProjects', JSON.stringify(myProjects));
}, [myProjects]);
```
**Listing 19 useEffect newProject**

In the return function we define the UI in alignment to the basic UI grids and fill in the required components plus user input definitions. Textfields will be entered by the user that refer back to the earlier defined project objects (project name, client name, building type, etc). The onClick event is called within the add button and refers back to the onSavedClick function, that logs the user input.

The component MyProjectTable is called in the return function. The key refers to the in the very beginning defined variable encompassing the created project as row of the table component.

### / Performance

In the function MyProjectsPerformance, we define the constant currentSelectedProjects, as well as define the constant that is used to save all related objects stored in one created project array.

```
function MyProjectsPerformance() {

  const classes = useStyles()
  const {context, setContext} = useContext(AppContext)


//Read data from browser cash and write in variables //add global contaxt variable {MyProject}
   const [myProjects, setmyProjects] = useState([]);
```

```
   const [currentSelectedProject, setcurrentSelectedProject] = useState({})

//Define User input for energy calculaiton
    const [Spaceheating, setSpaceHeating] = useState(0)
    const [DHOW, setDHOW] = useState(0)
    const [Electricity, setElectricity] = useState(0)

//Perform Primary Energy wit user input from above
    const [PrimaryEnergy, setPrimaryEnegery] = useState(0)
    const [EnergyLabel, setEnergyLabel] = useState("")
    const [CO2op, setCO2op] = useState(0)

    const [ConversionFactorGas, setConversionFactorGas] = useState(35.17)
    const [ConversionFactorEle, setConversionFactorEle] = useState(3.6)
    const [TransfereeEle, setTransfereeEle] = useState(0.39)

//Refurbishment time
    const [constructionYear, setconstructionYear] = useState(0)
    const [refurbishmentYear, setrefurbishmentYear] = useState(0)
    const [refurbishmentLife, setrefurbishmentLife] = useState(0)
```

**Listing 20 Function MyProjects Performance**

The earlier stored projects listed as array are stored in the local storage and is called with the useEffect function. It calls a new constant storedProject and parses the list of all create projects early on and sets the myProjects to the storedProject. Then we call the const storedProject that calls the first project (object) from the list and sets the currentSelectedProject to the (storedProject). So, the first project created will always appear to be the selected one for further performances. Note that this process shall be optimized in the future. Every created project should be editable independently from each other. For demonstration purposes, we use the firstly entered project as the project which we want to further assess.

In the setcurrentSelectedProject (storedProjects) we already have the project name, client name and building typology saved, thus we can directly pass on these values to the text field in the return function, using `{currentSelectedProject.projectName}.` Further, we set the variables that will be assigned to the selected project below. These are space heating, DHOW, Electricity, Primary Energy, Energy Label, $CO_2$ operational, Construction year, refurbishment year and refurbishment life.

```
//Store ProjectS in one arry, and select first project as current project &
setSpaceheating and all the other variables.
   useEffect(() => {
    const storedProjects = JSON.parse(localStorage.getItem('myProjects'))
    setmyProjects (storedProjects)
    const storedProject = storedProjects[0]

    setcurrentSelectedProject (storedProject)
    setSpaceHeating (storedProject.spaceHeating)
    setDHOW (storedProject.DHOW)
    setElectricity (storedProject.Electricity)
    setPrimaryEnegery (storedProject.PrimaryEnergy)
    setEnergyLabel (storedProject.EnergyLabel)
    setCO2op (storedProject.CO2op)
    setconstructionYear (storedProject.constructionYear)
    setrefurbishmentYear (storedProject.refurbishmentYear)
    setrefurbishmentLife (storedProject.refurbishmentLife)
    },
    []);

  useEffect(() => {
     localStorage.setItem('myProjects', JSON.stringify(myProjects));
   }, [myProjects]);
```

**Listing 21 useEffect myProject Performance**

Next to this information, the code above, parses the set statements per attribute, towards the stored project object definition. The performance of the values are defined in the following function(s):

The constant variables for Spaceheating, DHOW, and Electricity are created and refer to the input text fields that the user has to enter. Remember, the space heating and DHOW is entered in $m^3$/yr, and electricity in kWh/yr. While entering these values, the code is supposed to log these values to the new project (first in the row) and parse it on to calculate the Primary Energy consumption. Simultaneously, while entering the values, the user wants to find the resulting primary energy computed automatically. To avoid a handleChange event (including a onClick event) we add the function calculatePrimaryEnergy inside the functions of the getSpaceHeating, getDHOW, and getElectricty, and define the variables which are needed additionally to the active created function. For instance, from spaceHeating we call the numeric (+) target value, with the DHOW, and the electricity.

```
//Get user input (+ means translate to numbers)
//calculatePrimarEnergy: +value... updates the user imput of all 3 value sat them same time

  function getSpaceHeating(val)
  {
    setSpaceHeating(+val.target.value)

    const newProject = currentSelectedProject
    newProject.spaceHeating = +val.target.value
    setcurrentSelectedProject (newProject)
    const newMyProject = [...myProjects]
    newMyProject [0] = newProject
    setmyProjects (newMyProject)

    console.log(val.target.value)
    calculatePrimaryEnergy(+val.target.value, DHOW, Electricity )
  }

  function getDHOW(val)
  {
    setDHOW(parseFloat(val.target.value))

    const newProject = currentSelectedProject
    newProject.DHOW = +val.target.value
    setcurrentSelectedProject (newProject)
    const newMyProject = [...myProjects]
    newMyProject [0] = newProject


    console.log(val.target.value)
    calculatePrimaryEnergy(Spaceheating, +val.target.value, Electricity)
  }

  function getElectricity(val)
  {
    setElectricity(parseFloat(val.target.value))

    const newProject = currentSelectedProject
    newProject.Electricity = +val.target.value
    setcurrentSelectedProject (newProject)
    const newMyProject = [...myProjects]
    newMyProject [0] = newProject


    console.log(val.target.value)
    calculatePrimaryEnergy(Spaceheating, DHOW, +val.target.value)
  }
```

**Listing 22 myProject Performance**

Next, we focus on the primary energy calculation using the values as defined in the step before. Six constant variables are created. The first three are PrimaryEnergy, EnergyLabel, CO2op, and the next three are the conversation factors required to transport energy and electricity.

The function calculatePrimaryEnergy uses the former three user input values (Spaceheating, DHOW, electricity) as variables to define the constant PrimaryEnergyValue which includes the formular (7) from **Section 4.4.2.** The math.round is used to limit the decimals to two. The result is set in the variables value PrimaryEnergyValue with setPrimaryEnergy.

Further, the energy label and the operational CO2 should be shown instantly too. It should be computed at the same time as the Primary energy; thus we call next to setPrimaryEnergy, also the calculateEnergyLable and calculateCO2op, while using the primary energy value as property. Both will be performed in the following step.

```
  //when Primary energy is calculated, render Energy lable and CO2op (based on primary energy)
  function calculatePrimaryEnergy(SpaceHeating, Dhow, electricity) {

    const PrimaryEnergyValue = Math.round((((((SpaceHeating + Dhow) * ConversionFactorGas) + ((electric
ity * ConversionFactorEle) / TransfereeEle))*0.277777) + Number.EPSILON) * 100) / 100
    localStorage.setItem('PrimaryEnergy', PrimaryEnergy)

    setPrimaryEnegery (PrimaryEnergyValue)
    calculateEnergyLabel(PrimaryEnergyValue)
    calculateCO2op (PrimaryEnergyValue)

    //redo line 89 to 99
    // assign the PrimaryEnergyValue towrds the fisrt project in the record.
    const newProject = currentSelectedProject
    newProject.PrimaryEnergy = PrimaryEnergyValue
    newProject.EnergyLabel = EnergyLabel
    newProject.CO2op =CO2op
    setcurrentSelectedProject (newProject)
    const newMyProject = [...myProjects]
    newMyProject [0] = newProject
    setmyProjects (newMyProject)
  }
```

**Listing 23 myProject calculate Primary Energy**

For the energy label, the two main constants are the buildingArea and the resulting primary energy Value. The function calculateEnergyLabel uses the PrimaryEnergyValue as variable input to define the constant EnergyLabelValue. It is a simple calculation of the resulting primary energy divided by the building gross area, see literature study **Section 2.1.1** table 1. The logic is that the energy label A to G yields if the resulting value of primary energy divided by building area is lower or equal the corner value X. *(Find more information about energy labelling in Majcen, 2016).*

```
// Energy Lable calc. define value, then translate to alph.num. value
  const [buildingArea, setbuildingArea] = useState(100)

  function calculateEnergyLabel(PrimaryEnergyValue) {
    const EnergyLabelValue = PrimaryEnergyValue/buildingArea
      switch (true) {
        case (EnergyLabelValue <= 138.84):
          setEnergyLabel ("A")
          break;
        case (EnergyLabelValue <= 162.08):
          setEnergyLabel ("B")
          break;
        case (EnergyLabelValue <= 174.27):
          setEnergyLabel ("C")
          break;
        case (EnergyLabelValue <= 195.60):
          setEnergyLabel ("D")
          break;
        case (EnergyLabelValue <= 211.55):
          setEnergyLabel ("E")
          break;
        case (EnergyLabelValue <= 223.83):
          setEnergyLabel ("F")
          break;
        case (EnergyLabelValue <= 232.10):
          setEnergyLabel ("G")
          break;
```

```
        default:
          setEnergyLabel ("need to improve")
          break;
      }
  }
```
**Listing 24 myProject calculate Energy Label**

The operational CO2opValue is performed with the function calculateCO2op with input of PrimaryEnergyValue. The formula is used from Section 4.4.2 where the CO2 coefficient is multiplied with the primary energy.

```
  //CO2 operational
  const [CO2coef, setCO2coef] = useState(0.2019)

  function calculateCO2op(PrimaryEnergyValue) {
    const CO2opValue = Math.round((PrimaryEnergyValue * CO2coef + Number.EPSILON) * 100) / 100
    setCO2op (CO2opValue)
  }
```
**Listing 25 myProject calculate $CO_2$ operational**

Finally, each of the performed calculations above are put into the basic layout of the user interface. Inside the basic Grid layout, a Box class was used to split the view in two (left and right). In the left hand side, we find the typography that states the content of the right hand side located user input as text field or computed results as typography. The return function as well as the full code can be found in **Appendix G**.

### Refurbishment

In the Refurbishment section the user wants to:

- ➔ To receive information about national policy and governmental subsidy regulation regarding energy and carbon refurbishment. -> **/ Dashboard**
- ➔ To perform refurbishment packages and compare results towards the base model in an interactive way (including operational energy, carbon and cost performance). -> **/ Performance**
- ➔ To see the affected building elements in the 3D BIM model.

### / Performance

Component imported are NavbarMinRP, ButtonSelect and ControlledOpenSelect.

To start with, the function RefurbishmentPerformance is called. Firstly, we create an ID key to identify refurbishment packages stored as listed objects in an array. Furthermore, we create the constant variables for RCValueWall and RCValueRoof. In there we define the class with attribute ID, name and two actual values per building components. As for this use case we use for the wall improvement an RC of 1.7, and RC 4.0, for roof improvement an RC of 2.5 and RC 6.5. The object definitions need to stay in line with the component used, the ControlledOpenSelect (defined with ID, name, value).

```
function RefurbishmentsPerformance() {
  const NEWPACKAGES_KEY = "newPackages"
    const classes = useStyles()
    const {context, setContext} = useContext(AppContext)

// define RC values and define list as option for ControlledOpenSelect
    const [RCValueWall, setRCValueWall] = useState([{id:uuidv4(), name:"RC 1.7", value:1.7 }, {id:uuidv
4(), name:"RC 4.0", value:4.0 }])
    const [RCValueRoof, setRCValueRoof] = useState([{id:uuidv4(), name:"RC 2.5", value:2.5 }, {id:uuidv
4(), name:"RC 6.5", value:6.5 }])
```
**Listing 26 Function Refurbishment Performance**

Furthermore, Package1 and Package2 is predefined as object definition and initialized attributes. In both we use multiple variables inputs, reaching from RC-Values for Wall, Roof and Space heating, towards energy saving values and material names that are used in a later stage. For future purpose, it would be ideal to create an empty arry of package objects, that can automatically be adjusted by the users' input (adding and deleting of packages).

```
//define var for package 1, and package 2
const [Package1, setPackage1] = useState({RCValueWall:0, RCValueRoof:0, Spaceheating:0, DHOW:0, Electri
city:0, PrimaryEnergy:0, EnergyLabel:0, CO2op:0, costSaving:0, gasSaving:0, materialname:0})
const [Package2, setPackage2] = useState({RCValueWall:0, RCValueRoof:0, Spaceheating:0, DHOW:0, Electri
city:0, PrimaryEnergy:0, EnergyLabel:0, CO2op:0, costSaving:0, gasSaving:0, materialname:0})
```

**Listing 27 Const Refurbishment Package 1 and 2**

The idea of this page is to let the user modify packages by selecting improvement scenarios per Rc-Values of Wall and Roof measure. While the selection process happens, the code is supposed to compute and update operational energy and carbon performances of the improved packages. We rely on the useEffect and useState hooks to let the computing be updated and saved on local storage. Again, the current selected project is called from local storage. Next, the stored packages are defined as the first two [0 && 1] objects in the list. The function not update both packages reads the existing package (…Package1) and overwrites changes in the variable listed next to it. Also in this step, optimization in the future can be made.

```
//initialize, get values from local storage and update UI
useEffect(() => {
    const storedProjects = JSON.parse(localStorage.getItem('myProjects'))
    setmyProjects (storedProjects)
    const storedProject = storedProjects[0]

    setcurrentSelectedProject (storedProject)

    const storedPackage = JSON.parse(localStorage.getItem(NEWPACKAGES_KEY))
    console.log(storedPackage)
    if (storedPackage && storedPackage.length > 1 ) {
      console.log(storedPackage[0])
      updatePackage1 (storedPackage[0])
      updatePackage2 (storedPackage[1])
    }
 }, []);

//update of complete package, by calling ...Package1, and overwrite, all values, as listed next to it.
function updatePackage1(updatedPackage){
  setPackage1({...Package1, RCValueWall:updatedPackage.RCValueWall, RCValueRoof:updatedPackage.RCValueR
oof, Spaceheating: updatedPackage.Spaceheating, DHOW:updatedPackage.DHOW, Electricity:updatedPackage.El
ectricity, PrimaryEnergy:updatedPackage.PrimaryEnergy, EnergyLabel:updatedPackage.EnergyLabel, CO2op:up
datedPackage.CO2op, costSaving:updatedPackage.costSaving, gasSaving:updatedPackage.gasSaving, materialn
ame:updatedPackage.materialname})
}
function updatePackage2(updatedPackage){
  setPackage2({...Package2, RCValueWall: updatedPackage.RCValueWall, RCValueRoof:updatedPackage.RCValue
Roof, Spaceheating: updatedPackage.Spaceheating, DHOW:updatedPackage.DHOW, Electricity:updatedPackage.E
lectricity, PrimaryEnergy:updatedPackage.PrimaryEnergy, EnergyLabel:updatedPackage.EnergyLabel, CO2op:u
pdatedPackage.CO2op, costSaving:updatedPackage.costSaving, gasSaving:updatedPackage.gasSaving, material
name:updatedPackage.materialname})
}

// save packages to local storage, which is calledn in earlier functions
function saveDataToLocalStorage(){
  localStorage.setItem(NEWPACKAGES_KEY, JSON.stringify([Package1, Package2]));
}
```

**Listing 28 useEffect update Refurbishment Package 1 and 2**

Computed values are defined as a conditional value for both packages. Depending on the user selection the resulting space heat must change. So, we create four functions, one per user input (the OpenControlled Select is used as drop down menu) that define each package with a set of building component (in this case Wall and Roof for Package1 and Package2). The functions are selectPackage1wall, selectPackage2wall, and selectPackage1roof selectPackage2roof. For the sake of demonstration, selectPackage1wall is elaborated.

The computed results are supposed to be rendered when activating the function. The function is called when the user activates the drop down. For instance, the calculation of the primary energy, gas and cost saving is rendered at the same time while the package definition is updated and stored on local storage. The calculation process and for primary energy is performed in the same way as for the my project page.

```
//Functions to P1 set wall, P1 set roof => Package 1
//Functions to P2 set wall, P2 set roof => Package 2
function selectPackage1wall(value) {
  let newPackage = Package1
  newPackage.RCValueWall = value
  newPackage.Spaceheating = selectSpaceheating(newPackage.RCValueWall,newPackage.RCValueRoof)

  newPackage.DHOW = currentSelectedProject.DHOW
  newPackage.Electricity = currentSelectedProject.Electricity

  newPackage = calculatePrimaryEnergy (newPackage.Spaceheating, newPackage.DHOW, newPackage.Electricity
, newPackage)

  newPackage.gasSaving = calculateGasSaving (newPackage.Spaceheating)
  newPackage.costSaving = calculateCostSaving (newPackage.gasSaving)

  updatePackage1(newPackage)
  saveDataToLocalStorage()
}
```

**Listing 29 Refurbishment Performance calculate**

The additional information on this page is the operational gas and cost saving. The engineers want to compare the value between base model and the refurbishment improvements. So, we call the stored projects operational space heating as constant and subtract the space heating per package, returning the gas saving value. The gas cost saving is a simple multiplication of the saving times constant gas price. Also here, future development could allow accessing the energy and electric price indices from the Dutch government.

```
//Calculate Gas Saving
function calculateGasSaving (Spaceheating){
  const currentSpaceheating = currentSelectedProject.spaceHeating
  const gasSavingValue = Math.round((currentSpaceheating - Spaceheating))
  console.log(gasSavingValue)
  return gasSavingValue
}

//Calculate Cost Saving
const [gasPrice, setgasPrice] = useState(0.814)

function calculateCostSaving (gasSavingValue) {
  const costSavingValue = Math.round(gasSavingValue*gasPrice)
  return costSavingValue
}
```

**Listing 30 Refurbishment Performance calculate savings**

### Market Potential

In the Market Potential page, the user wants to:

➔ Receive an overview of all performances established so far.

➔ Find the trade off´s between sustainable key criteria based on refurbishment package and per defined material selection.

➔ Receive the market potential as the percentage probability of consumer preference.

### / Performance

In this part we focus on the performance page, in which we identify all three user requirements. Firstly, we are using the same use state definitions as in the earlier pages. This are the current project definition and the package definition. In the packages we add the material definitions, with the material name.

```
function MarketPotentialPerformance() {
  const NEWPACKAGES_KEY = "newPackages"
    const classes = useStyles()
    const {context, setContext} = useContext(AppContext)
    // const [RCValueWall, setRCValueWall] = useState([{id:uuidv4(), name:"RC 1.7", value:1.7 }, {id:uu
idv4(), name:"RC 4.0", value:4.0 }])

//access current selected Project (myProject)
const [myProjects, setmyProjects] = useState([])
const [currentSelectedProject, setcurrentSelectedProject] = useState({})

//var for package 1, and package 2
const [Package1, setPackage1] = useState({RCValueWall:0, RCValueRoof:0, Spaceheating:0, DHOW:0, Electri
city:0, PrimaryEnergy:0, EnergyLabel:0, CO2op:0, costSaving:0, gasSaving:0, materialname:0})
const [Package2, setPackage2] = useState({RCValueWall:0, RCValueRoof:0, Spaceheating:0, DHOW:0, Electri
city:0, PrimaryEnergy:0, EnergyLabel:0, CO2op:0, costSaving:0, gasSaving:0, materialname:0})
```

**Listing 31 Function Market Potential Performance**

Furthermore, this page enriches the packages with possible material definitions, as assigned with the material name. We identify two scenarios, which are material for injection and material for secondary wall inside. Depending on the user´s selection process regarding on the Rc-Values, we highlight the installation possibilities. For wall RC 1.7 and roof RC 2.5 it yields material injection, for Wall RC 4.0 and Roof 6.5 it yields inside insulation. Note, that this scenario definition is limited as we assume one material for both measures, wall and roof. Future implementations are supposed to let the user assign multiple RC-Values with multiple material scenarios. In this proof of concept phase we focus on these two predefinitions. The utility and probability constants are defined in the use state hook and will be explained later on.

```
//Selection possibilities for drop down
const [materialInject, setmaterialInject] = useState([{id:uuidv4(), name:"EPS", value:1}, {id:uuidv4(),
 name:"Glass Wool", value:2}])
const [materialInside, setmaterialInside] = useState([{id:uuidv4(), name:"Rock Wool", value:3}, {id:uui
dv4(), name:"Wood Fiber", value:4}])

const [p1Utility, setp1Utility] = useState(0)
const [p2Utility, setp2Utility] = useState(0)

const [ProbabilityNoren, setProbabilityNoren] = useState(0)
const [Probability1, setProbability1] = useState(0)
const [Probability2, setProbability2] = useState(0)
```

**Listing 32 Market Potential define Material in drop down**

Also, the constants for both material packages are to define as objects containing the relevant key criteria, used to perform the trade off tables. We initialize the values via numbers and strings.

```
//Selection of material scenarios for package 1 and 2
const [selectedP1Material, setSelectedP1Material] = useState({
  name : "",
  installation : "",
  investment : 0,
```

```
  CO2saving : 0,
  Noise : 0,
  Comfort : "",
})

const [selectedP2Material, setSelectedP2Material] = useState({
  name : "",
  installation : "",
  investment : 0,
  CO2saving : 0,
  Noise : 0,
  Comfort : "",
})
```

**Listing 33 Const select Material Package 1 and 2**

Again, the use Effect hook accesses the local storage, retrieving the current project and the applied refurbishment package information. In this page, it adds the relevant information regarding the material application, selected by the user. By calling the function updatePackage1 and updatePackage2 the chosen material by the user will be called and additionally stored. The updatePackage1 and 2 function is the same as in the previous page.

```
//call My stored project, packag1 and package2 from local storage, and add material name selection by update package with material name, list 0 and 1.
useEffect(() => {
      const storedProjects = JSON.parse(localStorage.getItem('myProjects'))
      setmyProjects (storedProjects)
      const storedProject = storedProjects[0]

      setcurrentSelectedProject (storedProject)

      const storedPackage = JSON.parse(localStorage.getItem(NEWPACKAGES_KEY))
      console.log(storedPackage)
      if (storedPackage && storedPackage.length > 1 ) {
        console.log(storedPackage[0])
        updatePackage1 (storedPackage[0])
        updatePackage2 (storedPackage[1])
        if (storedPackage[0].materialname){
          updateP1Values(storedPackage[0].materialname)
        }
        if (storedPackage[1].materialname){
          updateP2Values(storedPackage[1].materialname)
        }
      }
},[]);
```

**Listing 34 useEffect update Package 1 and 2**

The user selection for the materials is done via the drop down selection and is called with selectMaterialPackage1 and 2. In fact, again two functions are called, one for each drop down and calls the embedded function to assign the material values.

```
//make user selection function from selection drop down
function selectMaterialPackage1(value){
  const newPackage = Package1
  newPackage.materialname = value

    updatePackage1(newPackage)
    updateP1Values(value)
    saveDataToLocalStorage()
  }

function selectMaterialPackage2(value){
  const newPackage = Package2
  newPackage.materialname = value

  updatePackage2(newPackage)
  updateP2Values(value)
  saveDataToLocalStorage()
}
```

**Listing 35 Function select Market Potential Package 1 and 2**

The material values are hardcoded as can be seen below. In fact, this information is aimed to be retrieved from the previously executed performances pages, such as LCA and Costing. For example, the operational gas saving is not included in here, since this could already be retrieved from the current selected project, accessed via use Effect hook. In future development, this represents one of the first steps to implement.

```
//If wall RC 1.7 && roof RC 2.5 =>
const EPS = {
  name : "EPS",
  installation : "Cavity Injection",
  investment : 2700,
  CO2saving : 330,
  Noise : 25,
  Comfort : "no",
}
const GlassWool ={
  name : "Glass Wool",
  installation : "Cavity Injection",
  investment : 2630,
  CO2saving : 440,
  Noise : 50,
  Comfort : "no",
}
//If wall RC 4.0 && roof RC 6.5 =>
const WoodFiber = {
  name : "Wood Fiber",
  installation : "Inside Layer",
  investment : 3730,
  CO2saving : 605,
  Noise : 75,
  Comfort : "yes",
}
const RockWool = {
  name : "Rock Wool",
  installation : "Inside Layer",
  investment : 3500,
  CO2saving : 530,
  Noise : 50,
  Comfort : "yes",
}
```

**Listing 36 Const material definition**

Knowing the performance values per material and having the function in place that allows to update the materials information per drop down selection, the function to understand with which value/material it has to be updated follows. For showcasing purpose, only updateP1Values is used.

A if else loop is created that loops through the user selection and automatically assigned the requested material. We identify each material with an ID code and match the call the related information when matching. Instead of using 1..4, this ID could be based on the NL-SfB and filters per measure all possible materials. For instance, when Wall injection is required, then we call NL-SfB=41 and possible to inject.

Also, when none is selected, an empty object will be returned, meaning 0.

```
//function to update all values, called in useEffect, and in selection drop down functions
function updateP1Values (value) {
  const copyP1 = Package1
  if (value == 1) {
    setp1Utility(calcUtility(EPS, copyP1))
    calcProb()
    setSelectedP1Material({...selectMaterialPackage1,
    name: EPS.name,
    installation: EPS.installation,
    investment: EPS.investment,
```

```
    CO2saving: EPS.CO2saving,
    Noise: EPS.Noise,
    Comfort: EPS.Comfort})
  } else if(value == 2){
    setp1Utility(calcUtility(GlassWool, copyP1))
    calcProb()
    setSelectedP1Material({...selectMaterialPackage1,
      name: GlassWool.name,
      installation: GlassWool.installation,
      investment: GlassWool.investment,
      CO2saving: GlassWool.CO2saving,
      Noise: GlassWool.Noise,
      Comfort: GlassWool.Comfort})
  }
  else {
    setSelectedP1Material({...selectMaterialPackage1,
      name : "",
      installation : "",
      investment : 0,
      CO2saving : 0,
      Noise : 0,
      Comfort : ""})
  }
}
```

**Listing 37 Function update material package values**

So far, we can allow the user to make material selection in a drop down that retrieves all related performance values per choice. The follow-up step will focus on the probability calculation, deriving from the stated choice experiment. The selected material attribute definitions are called and shall be used in the utility formular from Chapter 3, Section 3.4.1 and 3.4.2. The logic of the implementing is the follow up of **Chapter 5.**

Firstly, the coefficients, resulting from the quantitative research are defined in the use state. We must note that out of six attributes, four are numeric and two are strings. The numeric values can increase/decrease on a linear function, while the string values differentiate only between two states (L0, and L1).

```
//set coefficients
//exp(p) -> constant value for no renovation
const [norenovation, setnorenovation] = useState(0.42323318)
//installation coef: is using only two levels. Injection=0, SecondLayer=-1.145371
const [installationcoef, setinstallationcoef] =useState({L0:0, L1:-1.145371})
//(IC value-L0)*slope in Euro
const [investmentCostcoef, setinvestmentCostcoef] =useState({L0:2500, slope: -0.000248969})
//energy reduction in Euro
const [energycoef, setEenergycoef] = useState({L0:300, slope: 0.00267716})
//CO2 saving in kgCO2
 const [CO2coef, setCO2coef] = useState({L0:400, slope: 0.000823145})
 //Noise reduction coef
 const [noisecoef, setnoisecoef] = useState({L0:25, slope:0.01291908})
 //comfort coef: is using only two levels. yes:0, no: -0.333178
 const [comfortcoef, setcomfortcoef] = useState ({L0:0, L1: -0.333178})
```

**Listing 38 Const Set Utility coefficient**

The function calcUtility calls the material and the packages (p). Both inputs allow the function to access the selected material definitions, as well as the gas reduction value form the earlier defined refurbishment package definition.

Now, we know the statistical base models' value (L0), the slope per coefficient (Δx/Δy) and can access the performance values per materials attribute (L1). The following will explain the utility calculation per materials level. For the installation and comfort utility, we write an if statement, querying weather "cavity injection", or "inside layer" is called, as well as weather "yes" or "no" is called. Regarding that the constant value L0 or L1 is used. For all numeric values, we apply the following **Formula 22**. where U is the utility of the alternative A for a particular level. L1 will be the analysed level subtracting the in the stated choice model used base model definition, where the constant coefficient yields 0. The slope has to be used as explained above.

$$U_{A,l} = (L_1 - L_0) * slope_{coef} \quad (22)$$

The constant sumUtility, adds up the utility per package, and return the mathematical exponents.

```
//let = initialize first to 0 the overwrite
function calcUtility(material, p){
  let installationUtility = 0
  let comfortUtility = 0

  if (material.installation == 'Cavity Injection'){
    installationUtility = (installationcoef.L0)
  }
  if (material.installation == 'Inside Layer'){
    installationUtility = (installationcoef.L1)
  }
  const investmentUtility = ((material.investment-investmentCostcoef.L0)*investmentCostcoef.slope)
  const energyUtility = ((p.costSaving-energycoef.L0)*energycoef.slope)
  console.log(p.costSaving)
  const CO2Utility = ((material.CO2saving-CO2coef.L0)*CO2coef.slope)
  const noiseUtility = ((material.Noise-noisecoef.L0)*noisecoef.slope)
  if (material.Comfort == 'yes'){
    comfortUtility = (comfortcoef.L0)
  }
  if (material.Comfort == 'no'){
    comfortUtility = (comfortcoef.L1)
  }
  const sumUtility = (installationUtility+investmentUtility+energyUtility+CO2Utility+noiseUtility+comfo
rtUtility)

  return Math.exp(sumUtility)
}
```

**Listing 39 Function calculate Utility per package**

Last but not least, the utilities will have to be translated into the probability performance. To do this, the sum of the exponents of all three packages, the base models (no renovation), the Package1, and Package2 is created. The use state hook to set the probabilities per package is then used. It puts the sum of the exponents in the denominator and the related utility in the nominator. Eventually the use effect hook allows the state to update while the user interferes with the UI.

```
//calculate based on the sum sof the exponants the probability percentage
function calcProb (){
  const SumExp = (p1Utility + p2Utility + norenovation)

  setProbabilityNoren(Math.round((norenovation/SumExp)*100))
  setProbability1(Math.round((p1Utility/SumExp)*100))
  setProbability2(Math.round((p2Utility/SumExp)*100))
}

//set state hasn't finished yet before calcprob is called, thus after initializing all values, and perf
orming the calcProp, we call one more time the useEffect.
useEffect (() => {
  calcProb()
 }, [norenovation, p1Utility, p2Utility])
```

**Listing 40 Function calculate Probability**