“EMPOWERING CIRCULARITY IN CONSTRUCTION: STAKEHOLDER-INFORMED SUSTAINABLE RENOVATION ASSESSMENT”

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Declaration

I hereby, declare that this manuscript, entitled “title of thesis”, is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Date: 21.02.2015

Abstract

The construction industry is the largest consumer of natural resources and is responsible for producing 13 to 30 percent of global waste due to the linear economy “take, make, dispose” model. Today shifting towards circular economy is essential to decrease material consumption and waste generation. Building renovation is a part of building construction when the existing building is enhanced due to different reasons and receiving increasing attention in many countries. The following thesis presents the framework for assessing circularity in building renovation using the factors and indicators of circularity and their weights obtained from different categories of stakeholders (academy, public and construction industry sector) based on their perception. It covers the 6 different factors: “material type and flow”, “water and energy”, “construction and demolition waste (C&DW) management”, “cost and benefits”, “building functions and services”, and “renovation service provision”. The evaluations of factors and indicators were collected from stakeholders by survey. Results show that stakeholders rated the importance of factors and indicators differently by their categories. All stakeholder categories rated “cost and benefits” and “material type and flow” factor as the most important factors in assessing circularity during building renovation. Based on the responses of stakeholders the weights for each of the indicators were identified, analyzed using SHAP value analysis, and framework was created based on the ranking of the factors and indicators. The originality of the work is that the framework was created based on a stakeholder survey and is aimed specifically at the principles of circularity, since previous research was aimed at the principles of sustainability.

Keywords: building renovation, circularity assessment tool, stakeholder opinion, circularity ranking.

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List of Abbreviations

CE	Circular economy
C&DW	Construction and demolition waste
MS	Mean score
SLR	Systematic literature review

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Chapter 1 - Introduction

The master's thesis on the topic “Stakeholder-Informed Sustainable Renovation Assessment: Empowering Circularity in Construction” is presented in this document. It includes the primary research questions, a literature review, methodology of the research work and the output and discussion of the thesis. Based on the opinions and experiences of stakeholders, it discusses the principles of the circular economy in construction, particularly during building renovation operations. A survey of stakeholders with renovation experience was conducted to develop a framework for evaluating circularity in building renovations. The literature review and quantitative research approach for framework creation are the main topics of the thesis. The research focuses on developing an effective and efficient framework for managing the circular economy (CE) in building renovation projects by gathering and analysing the opinions and perceptions of various stakeholders.

1.1 Research problem

The construction industry is the largest consumer of natural resources and is responsible for producing 13 to 30 percent of global waste, as well as 39 percent of all global greenhouse gas emissions (Jemal et al., 2023). Buildings alone account for 50% of global material use, consuming 42.4 billion tons of material annually (Wong et al., 2024). Waste can be generated at any stage of the building construction process, including design, planning, procurement, transportation, jobsite operations, service stages, and end-of-life disposal. Additionally, construction and demolition waste (C&DW) contributes to 40% of global waste, much of which is disposed of in landfills, causing significant environmental, economic, and social challenges (De Silva et al., 2023a; Ginga et al., 2020). Therefore, identifying effective strategies for recycling and reusing debris from buildings and demolitions is essential (De Silva et al., 2023a).

In recent years, circular economy research has gained traction due to growing concerns over preserving and restoring the value of building materials and minimizing C&DW. The CE model plays a crucial role in achieving sustainable development by promoting the recycling and disassembly of building materials at the end of their useful lives, creating material banks for future construction and ensuring that materials and components are kept within a closed loop (Benachio et al., 2020).

Building rehabilitation/renovation refers to the process of repairing or remodelling an existing structure to improve its condition, functionality, safety, and aesthetics. Renovation aims to extend the lifespan of a building and enhance its overall state. This process typically involves a combination of repair, refurbishing, retrofitting, and restoration techniques to address structural issues, modernize building systems, and meet contemporary standards. Renovating old buildings is key to achieving sustainability goals related to material reduction, clean energy, climate change mitigation, and resource efficiency (Foster et al., 2020). A sustainable building renovation project aims to improve comfort levels and quality of life while minimizing negative environmental impacts and enhancing the economic sustainability of construction (Kylili et al., 2016).

Building rehabilitation is a significant source of waste that can be managed through CE principles. To effectively implement CE practices during building rehabilitation, it is necessary to develop a framework for assessing circularity based on stakeholder input.

The findings of this study can contribute to the development of a successful CE strategy model for construction companies, not only in Kazakhstan but also in other Central Asian countries. This model can also improve existing strategies, promoting the sustainability of future construction operations. By following the proposed recommendations, construction companies can modify their internal policies, and the state can implement supportive measures, which would positively impact the transition to a CE in waste management within the construction sector.

1.2 Research statement

Incorporating stakeholder perspectives into circular renovation assessments is essential for promoting sustainability in the construction industry. This approach not only fosters inclusive decision-making but also drives innovation in CE practices, thereby enhancing the environmental, social, and economic sustainability of construction projects.

1.3 Research objectives

The main goal of this research work is to develop a comprehensive understanding of the needs and expectations of different stakeholders to create a framework that can meet their requirements. To achieve this goal, it is necessary to carry out the following tasks, which are the main objectives of this research work:

- To identify existing sustainable/circular renovation practices.
- To identify the main circularity factors and indicators in building assessment for renovation projects.
- To prepare a framework for stakeholder-informed assessment.

Chapter 2 - Literature Review

2.1 Circular economy concept

The prevailing global direction urges the international community to explore pathways for transitioning from linear to circular economy models. In a linear economy, materials flow unidirectionally through the industrial process, from raw materials to final products and eventually to recyclable waste. This model of the linear economy is shown in Figure 2.1. The traditional linear economy is based on the concept of "take, make, dispose," which makes it unsustainable. However, in an era focused on sustainability and global greening initiatives, the new circular economy model is gaining significant attention from various sectors.

Figure 2.1. Linear economy concept

Conversely, in the emerging circular economy paradigm, the recovery and valorisation of waste allow materials to re-enter the supply chain, effectively decoupling economic advancement from environmental degradation (Morseletto, 2020). The conceptual model of the circular economy is shown in Figure 2.2, which clearly illustrates the closed-loop system, as this model aims to keep products within the cycle for as long as possible. Additionally, the circular economy emphasizes improved resource management by rethinking consumption patterns and minimizing unnecessary use.

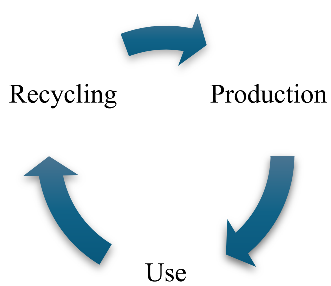

Figure 2.2. Circular economy concept

One significant benefit of the circular economy is its potential to promote sustainable development by decoupling economic growth from the negative effects of resource depletion and environmental degradation (Morseletto, 2020). In today's world, where sustainability is crucial, transitioning to a circular economy across various industries can have a positive impact not only on the environment but also on society and the economy in the future. Figure 2.3 summarizes the core objectives of the circular economy as defined by (Morseletto, 2020), with an emphasis on sustainability and efficiency. The targets highlighted in the figure likely include strategies to minimize the extraction of virgin materials, design products for durability and reparability, and promote closed-loop recycling systems.

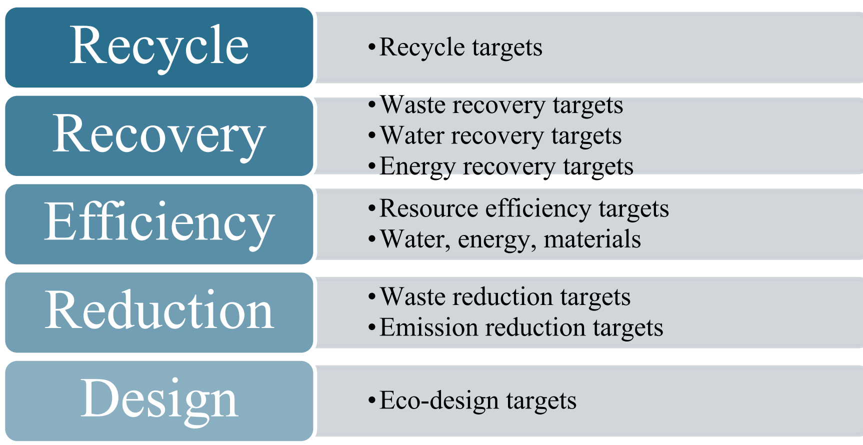

Figure 2.3. Circular economy targets

2.2 Construction industry in Kazakhstan

Kazakhstan is experiencing rapid urbanization, which is driving an increased demand for housing. Over the past two decades, the growth of the construction industry has been a significant factor in the more than threefold increase in the production of building materials (Torgautov et al., 2021). There are approximately 4,000 landfills in Kazakhstan, with 500 of them located near the capital city. However, only 10 percent of these landfills are legally authorized (Turkyilmaz et al., 2019a). This widespread landfilling has led to environmental and social problems, such as air and water pollution, soil contamination, resource waste, and habitat destruction. While 95 percent of construction industry waste can be recycled or repurposed, much of it continues to be disposed of in landfills.

The rapid growth of Kazakhstan's economy, reflected in the increase in Gross Domestic Product (GDP) from US$18.3 billion in 2000 to US$225 billion in 2022, is largely driven by the thriving construction sector. However, insufficient waste management practices and the anticipated increase in waste production due to growing GDP highlight the urgent need to address the specific challenges and obstacles faced in the region. It is crucial to propose optimal strategies for improving construction and demolition waste management, considering the region's unique needs. This situation demonstrates that while the construction industry in Kazakhstan is expanding rapidly, businesses are still struggling to meet circular economy standards and effectively implement reuse, reduction, and recycling practices (Turkyilmaz et al., 2019a).

Moreover, a review of the existing literature reveals gaps in circular economy research within Kazakhstan, with limited studies conducted in the actual construction environment and without stakeholder engagement. Specific improvement solutions for current construction and demolition waste management practices in Kazakhstan have yet to be explored. Therefore, it is essential to study the circular economy situation in Kazakhstan and develop sustainable construction solutions.

2.3 Circular economy in construction industry

The circular economy in the construction industry is a conceptual model aimed at optimizing resource flow within defined boundaries to ensure maximum efficiency. Described as a regenerative system, the circular economy seeks to minimize waste, emissions, and energy loss, while maximizing the utilization of resources. Achieving this requires the adoption of practices such as long-term design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (De Silva et al., 2023a).

In the construction industry, the circular economy is applied in several key areas, including material supply chain management, material inventory, recovery and reuse processes, material data documentation, as well as design considerations such as dismantling practices and ensuring the longevity of buildings and their components (Hossain et al., 2020).

In their literature review, Butković et al. identified that most research on the circular economy in construction focuses on waste management. The next most common areas of research include building design, material, and product design. This highlights that the core principles of the circular economy in the construction industry revolve around the proper management of waste and the efficient use of materials and products (Lovrenčić Butković et al., 2023). The findings of Butković et al. shows that waste management is leading category of CE in CI, it is followed by reducing the impact on the environment, material and product design, then building design and other.

The application of CE principles in the construction industry will help reduce industry costs, eliminate negative environmental impacts, and improve the liveability, productivity, and convenience of urban areas (Ahmed et al., 2023). Therefore, it is crucial to emphasize the need for implementing CE principles in the construction industry currently.

2.3.1 Circular economy challenges in construction industry

The integration of the circular economy into the value chain of the construction industry presents challenges due to the inherent characteristics of the model. Major obstacles include technical complexities, policy and legislative constraints, ambiguity surrounding the definition of CE in construction, and insufficient funding (Superti et al., 2021). Additionally, Yu argues that the construction industry lacks a CE framework that guarantees economic benefits for all stakeholders (Yu et al., 2021).

Another critical factor is that construction firms primarily focus on their own business models, showing limited collaboration with other stakeholders. However, successful implementation of CE requires collaboration across the entire stakeholder chain, which fosters the necessary environment for the concept's success (Guerra et al., 2021).

The challenges outlined above create an unfavourable atmosphere for implementing a circular economy in the capital market. Moreover, it is important to recognize that the circular models developed in research may not always be suitable for practical application (Leising et al., 2018), highlighting the need for further refinement of this concept within the construction sector.

Table 2.1 summarizes the challenges of integrating circular economy concepts into the construction industry in developing countries.

Table 2.1. Circular economy integration challenges in developing countries

Aspects	***Factors***	***References***
Political	- Regulations concerning resource utilization and waste management may be limited or vary inconsistently. - Political priorities may favor short-term economic benefits over longer-term sustainability objectives. - Circular economy initiatives may suffer from inadequate government funding or subsidies. - There may be restricted collaboration and coordination among government bodies, industry participants, and other stakeholders.	(De Silva et al., 2023b), (Turkyilmaz et al., 2019b)
Socio-cultural	- Limited understanding - Lack of awareness and comprehension of the concept - Diminished motivation to implement circular economy practices	
Economic	- Landfilling costs less than employing circular economy strategies - Absence of a stable and adaptable market for recycling - The implementation of circular economy practices necessitates investment in specialized techniques	
Technological	- Absence of recycling facilities - Inadequate availability of specialized equipment	
Environmental	- Current practices involving waste disposal in landfills	
Legal	- Absence of stringent regulations and policies - Absence of standardized practices	

2.4 Building renovation

Building renovation/rehabilitation, which involves repairing or remodelling an existing structure to enhance its state, functionality, safety, and appearance, is currently receiving increasing attention in many countries (Ástmarsson et al., 2013). Renovation primarily focuses on improving a building's appearance, with the goal of enhancing its overall condition by making aesthetic modifications to the interior or exterior, such as upgrading or adding new elements to the building. The need for renovation of existing buildings can arise from various factors. Renovating old buildings is essential for meeting targets related to reducing material use, clean energy, climate change, and resource efficiency (Foster et al., 2020).

2.4.1 The need for building renovation

Indoor climate issues can be a significant reason for the necessity of building renovation. Today, people spend approximately 70% of their time indoors, making it important to ensure that buildings are healthy and fully functional (Jensen & Maslesa, 2015). Poor indoor microclimates can lead to health issues and productivity challenges for both regular occupants and visitors of the building (Mujan et al., 2019). This highlights the necessity for buildings to provide comfortable conditions and an optimal design, allowing both users and visitors to seamlessly adjust to the environment and vice versa.

As buildings age, their energy efficiency tends to decline, emphasizing the importance of maintaining and operating them appropriately to prolong their lifespan and retain property value. Timely and proper maintenance and operation are essential because external factors and the deterioration of building materials and components can cause the building to become outdated and less efficient. Therefore, it can be concluded that the renovation of buildings becomes necessary as they age due to the degradation of materials and external factors such as weather conditions (Ástmarsson et al., 2013). Figure 2.4 shows the main common reasons for building renovation/rehabilitation. The reasons vary from the age of the building, its condition, safety, environmental reasons, energy or cultural value.

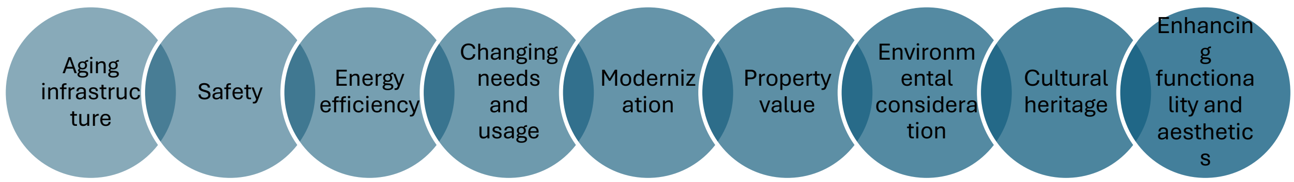

Figure 2.4. Building renovation reasons

The increasing emphasis on building renovation is equally important as new building construction and should be addressed within the circular economy framework, as renovation processes can produce construction waste and require the use of new virgin materials, highlighting the importance of implementing sustainable practices. A sustainable building renovation project is anticipated to increase comfort levels and quality of life, while minimizing negative environmental impacts and enhancing the economic sustainability of construction (Kylili et al., 2016).

2.4.2 Building renovation stages

The process of renovating a building closely resembles the process of designing a new one, yet the primary distinction lies in the constraints imposed by the existing structure and construction site, as well as the occupants of the building.

During and before renovation, making the right decisions is very important, as all subsequent work depends on them. Nielsen et al. identified six areas where decision-making influences the renovation process, including goal setting, criteria weighting, building diagnosis, design alternatives generation, performance estimation and design alternative estimation (Nielsen et al., 2016). There are many challenges when making decisions regarding the selection, extent, and timing of building repairs. Planning rehabilitation work encounters several issues when determining the rehabilitation needs of buildings, such as:

- Which building element needs immediate rehabilitation and should be prioritized?

- Is it feasible to wait and rehabilitate several building elements together?

Decision-making depends on several criteria (Nowogońska, 2020):

- The degree of technical condition of the elements;
- Type of element in the building structure;
- Durability of the element;
- Impact of the technical condition of the element on damage to other elements;
- Interdependence of the rehabilitation of the element with that of another;
- The value of the building due to its location;
- The heritage value of the building.

By using these criteria, it is possible to select the building elements that need to be rehabilitated based on the objectives of the renovation project, as setting objectives is the main and first phase of the renovation.

Proposing a categorization method for building elements enables the assessment of rehabilitation requirements based on their priority. This framework suggests dividing elements into four groups (Nowogońska, 2020):

- - Elements requiring mandatory rehabilitation;
- - Elements where rehabilitation holds significant importance;
- - Elements where rehabilitation proves beneficial;
- - Elements currently not requiring rehabilitation.

Konstantinou et al. identified five phases of the renovation process with tasks (Konstantinou et al., 2021). Table 2.2 illustrates these phases along with their respective tasks.

Table 2.2. Renovation process phases and tasks overview

Phases	Name	Tasks
1	Pre-project	- Setting objective and criteria - Diagnosis of existing conditions - Definition of client requirements - Cost initial estimate
2	Concept design	- Identification of renovation measures - Decision industrialized components design concept - Assessment and optimization - Preparation of permit applications
3	Final design	- Detailed design for industrialized renovation - Survey of existing building - Engineering of the components
4	Execution and hand over	- Manufacturing - Transport - Mounting - Site - Construction - Construction quality control - Hand-over
5	Post-construction	- Building operation optimization - Monitoring

2.4.3 Circularity/Sustainability assessment tools during building renovation

Multiple research studies have previously been conducted, proposing various methods for assessing circularity and sustainability during renovation. González et al. identified five essential pillars – Energy, Materials, Water, Social Value, and Economic Value – that should be integrated into circularity assessments for building construction and refurbishment activities (González et al., 2021a). The study suggested a methodology that requires the calculation of these five pillars for circularity measurement. Four parameters such as Stakeholders, Environment, Organization, and Economy were covered in the RENO-EVALUE tool, which mainly focuses on the assessment of sustainability for decision-making in renovation, as suggested by Jensen P. A. (Jensen & Maslesa, 2015).

Moreover, in other studies on sustainable construction, key environmental, economic, and social factors, along with their corresponding indicators, were identified and discussed (Calvo-Serrano et al., 2020; Gilani et al., 2017; Habibi et al., 2020; Kylili et al., 2016; Masseck et al., 2024; Nielsen et al., 2016; Sanchez et al., 2019). However, the concept of sustainability is defined as development that meets current needs without compromising the ability of future generations to meet theirs, while the circular economy advances this objective by preventing resource depletion and closing energy and material cycles (Alarcón et al., 2020; Kirchherr et al., 2023). This highlights the necessity of identifying specific factors and indicators for evaluating circularity, particularly in the context of this study, which focuses on assessing circularity during building renovation to create a quick and easy-to-implement framework. Table 2.2 summarized the papers from literature review related to the topic.

Table 2.3. Literature review summary on existing frameworks and tools

Source	***Object***	***Factors***	***Methodology***
(Calvo-Serrano et al., 2020)	Sustainable rehabilitatuon	Environment, Economy, Social	Review
(Habibi et al., 2020)	Sustainable refurbishment	Economic, Environmental, Social	Survey
(Kylili et al., 2016)	Sustainable renovation	Environment, Economy, Social	Review
(González et al., 2021a)	Circular refurbishment	Energy, Materials, Water, Social Value, Economic Value	Calculation based on approaches
(Jensen & Maslesa, 2015)	Sustainable renovation	Environment, Economy, Social, Project Organization	Interview survey

2.5 Stakeholder and experts' importance

The key participants in the sustainable retrofitting and renovation of buildings include the stakeholders, facility managers, and occupants of the buildings. The stakeholder is responsible for financing the renovation but stands to gain from the enhanced value of the property. Occupants benefit from reduced energy consumption, leading to lower energy bills, as well as potential improvements in indoor air quality and comfort, which will positively influence the health condition of occupants (Ástmarsson et al., 2013).

The integration of various disciplines complicates building renovations, necessitating interdisciplinary expertise for most renovation projects, as these projects usually address several different issues in the building at the same time (Jensen & Maslesa, 2015). That is why, for this research work, the workshop with experts and survey with stakeholders who have renovation experience are crucial components of the research, as the framework was developed based on the information gathered. The list of possible stakeholders who will be involved in the survey in this study can be seen in Figure 2.5.

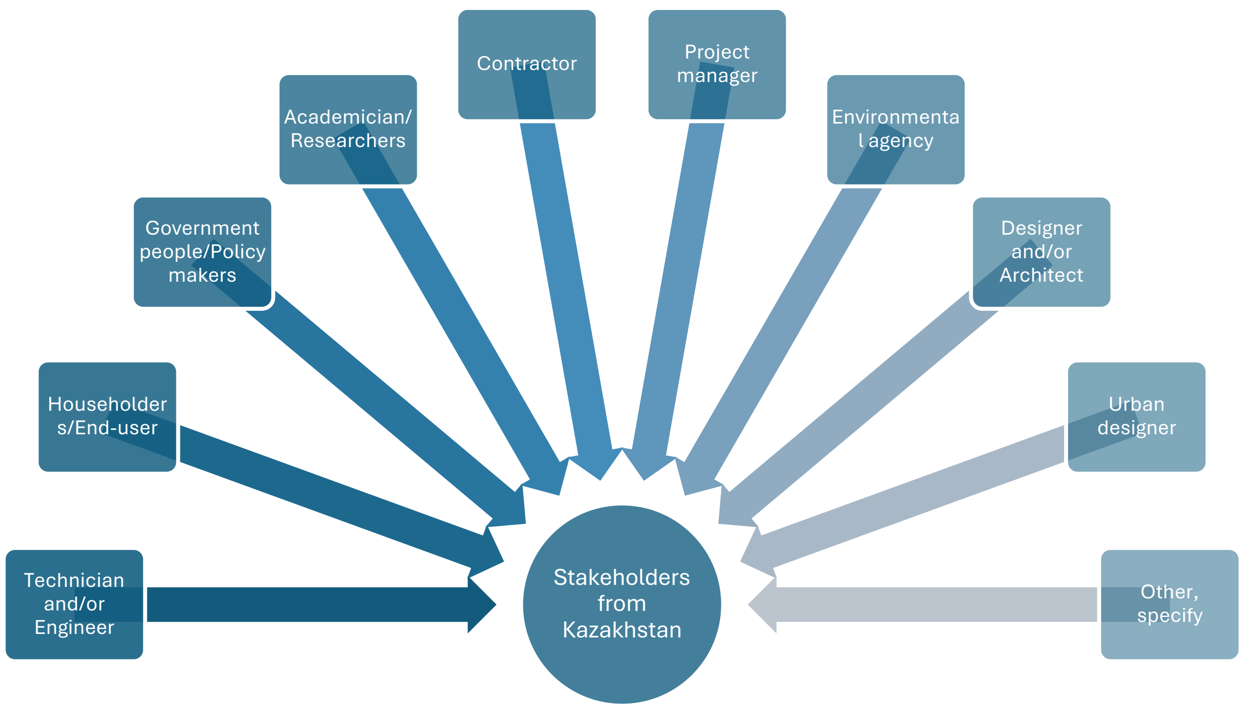

Figure 2.5. Stakeholders' categories

Chapter 3 - Methodology

The methodology steps of the research work are illustrated in Figure 3.1. The flowchart presents a structured methodology for developing a Renovation Circularity Assessment Framework, combining literature review, stakeholder input, and expert workshops which was proposed in the beginning of the research. This process identifies, evaluates, and prioritizes indicators for assessing circularity in renovation projects.

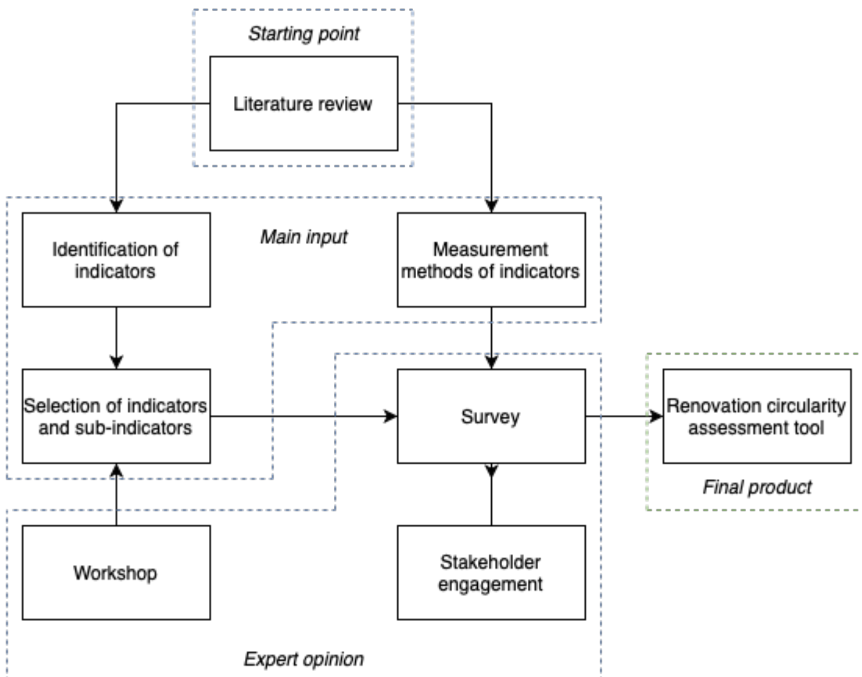

Figure 3.1. The methodology of the development of renovation circularity assessment framework

Figure 3.2 shows sequence of the tasks for this methodology. As it can be seen the research starts with systematic literature review to identify indicators of circularity. To categorize identified indicators by factors workshop was held with circularity experts. This was followed by conducting of the survey. In the end, obtained results from the survey were analysed to propose framework.

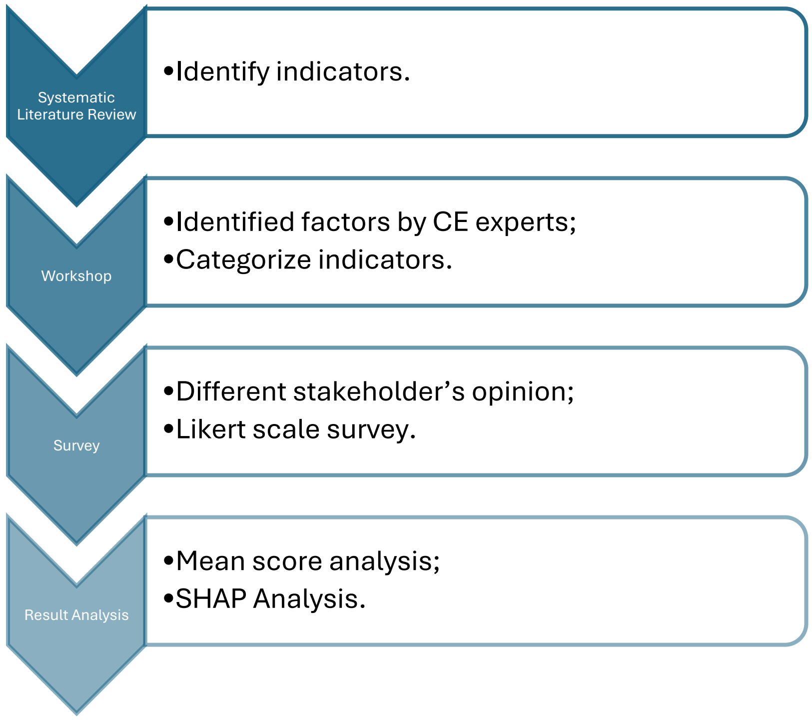

Figure 3.2. Methodology flow

3.1 Research Timeline

According to the thesis outline the work plan can be evaluated. The work is divided into subsections and the period for these subsections can be assigned as follows in Table 3.1. As it can be seen there are the main 4 stages of research that are divided into several subsections. The most time-intensive aspect of the work is conducting the literature review, which extends from the project's inception to the submission of the thesis, as it is integral to all stages of the study. Preparing the survey is also a lengthy process, requiring careful identification of indicators, their categorization into selected factors, and the selection of an appropriate survey methodology. Conducting the survey itself is divided into two stages: the first involves specific stakeholders, followed by the remaining stakeholders. Finally, the analysis of the collected data and results will inform the development of the framework.

Table 3.1. Time periods of the tasks

Main section	Subsection	Time period
Literature review		01/03/2024 – 01/03/2025
	• Identification of circularity indicators for building renovation	
Preparation of questionnaire		01/04/2024 – 01/09/2024
	• Selection of indicators and factors via workshop • Preparation of questionnaire and rating scale	
Conducting survey		01/09/2024 – 30/12/2024
	• Conducting survey (1st part of stakeholders) • Conducting survey (2nd part of stakeholders)	
Analyzing results and tool		01/11/2024 – 31/03/2025
	• Prepare the analysis of results and discussion • Propose circularity assessment framework	

Figure 5.1 in Appendix A illustrates the research timeline in Gantt chart with the main stages of the research. As it can be seen, there were 4 main stages in research, the research work started in March 2024 and ended in March 2025 which means that the whole research was carried out for 1 year. The literature review is carried out during whole research work. This phase entails a comprehensive review of existing frameworks, methodologies, and sustainable practices related to building renovations and the circular economy. The literature review helps shape the research questions and objectives, ensuring that the study focuses on relevant and underexplored areas. The first step is literature review which has been already started, then the questionnaire will be developed based on literature review and experts' opinion after the workshop until the beginning of August 2024.

Then questionnaire is conducted until the end of December 2024, and results is analysed to create stakeholder-informed tool for circularity assessment during building renovation process until the end of March in 2025. The thesis dissertation is written during whole research work to provide successful thesis dissertation.

3.2 Identification of factors and indicators

Two primary components were considered in the selection of circularity indicators: expert opinion and a review of the literature. First, using information from the literature, circularity indicators for evaluating building renovations were determined. Workshops with specialists from a range of fields, including academics, the construction industry, and stakeholders, then was held to complete the selection of important indicators. The first step was a thorough assessment of the literature that forms the basis of the study. During the literature review, current information and already used practices in the field of circularity were considered. Using these resources, key indicators, measurement methods, rehabilitation strategies and concepts of the circular economy were selected for further work. The information obtained for assessing circularity helped in shaping the subsequent phases of the methodology.

A comprehensive systematic literature review (SLR) method was selected for identification of circularity factors and indicators for assessing circularity during building renovation processes. This method is a repeatable process that documents all relevant studies on a specific topic or research question (Balaid et al., 2016). Using this method allows to find and summarize existing data by avoiding narrative reviews and propose a framework for a new research topic.

The literature review process was structured based on a review protocol with the following steps suggested by Balaid et al., 2016: review background, research questions, search strategy, criteria for study selection, data extraction and data synthesis. The research questions and background of this review have been outlined in the introduction section; but the following section will provide detailed summary on study selection for indicator identification.

The initial search for relevant papers was conducted in the Scopus database using the keywords “Building” AND “Circular economy” AND (“Renovation” OR “Refurbishment” OR “Rehabilitation”), which resulted in 213 papers.

The research process began with a systematic search on the Scopus database, employing three specific keyword combinations:

- "building" AND "renovation" AND "circular economy" (122 studies identified)
- "building" AND "refurbishment" AND "circular economy" (63 studies identified)
- "building" AND "rehabilitation" AND "circular economy" (20 studies identified)

An initial search using keywords retrieved 207 studies from the database.

Based on the chosen literature review path there were several criteria for inclusion and exclusion of papers for further analysis. The list of the inclusion and exclusion criteria are shown below in Table 3.1. Based on these criteria the analysis was simplified, and sorting papers was successful.

Table 3.2. Inclusion and exclusion criteria

Inclusion	***Exclusion***
Full text	Full text not available
Written in English or with English translation	Duplicate studies
Additional studies with related research questions	Not related to research questions (title, abstract, full text analysis)

To identify the most relevant articles, several stages of article filtering were performed. The first stage excluded studies that were not available in English and had not been peer-reviewed. As a result of this stage, 13 studies were excluded.

The next stage required the exclusion of duplicate studies that appeared multiple times. A total of 17 duplicates were excluded at this stage.

The remaining studies were then assessed for relevance by checking their titles and abstracts. Checking the title and reading the abstract allowed us to exclude studies that did not contain information or were not close to the topic of circular economy in the context of reconstruction, repair or rehabilitation of buildings. As a result, 102 studies were excluded that were either irrelevant or did not meet the objectives of the study.

For studies that passed the abstract screening, a comprehensive full-text review was conducted. This involved analysing each paper's methodology, findings, and discussions to verify its relevance to the study's goals. Papers lacking sufficient detail or unrelated to the research scope were excluded, reducing the dataset by an additional 53 studies.

An additional manual search of sources was also conducted after the previous steps to identify additional relevant articles that would be needed. This was done by searching for articles that were referenced in the previously found sources and using different keywords. As a result of this step, an additional 14 articles were added to the dataset. This involved searching for studies that were referenced in the reviewed articles or those that may have been missed during the database search.

Following the application of all exclusion criteria and the inclusion of manually identified studies, a final total of 36 studies was selected. These publications were considered highly relevant and were included in the detailed analysis for the review. The detailed systematic literature review workflow is shown in Figure 3.3.

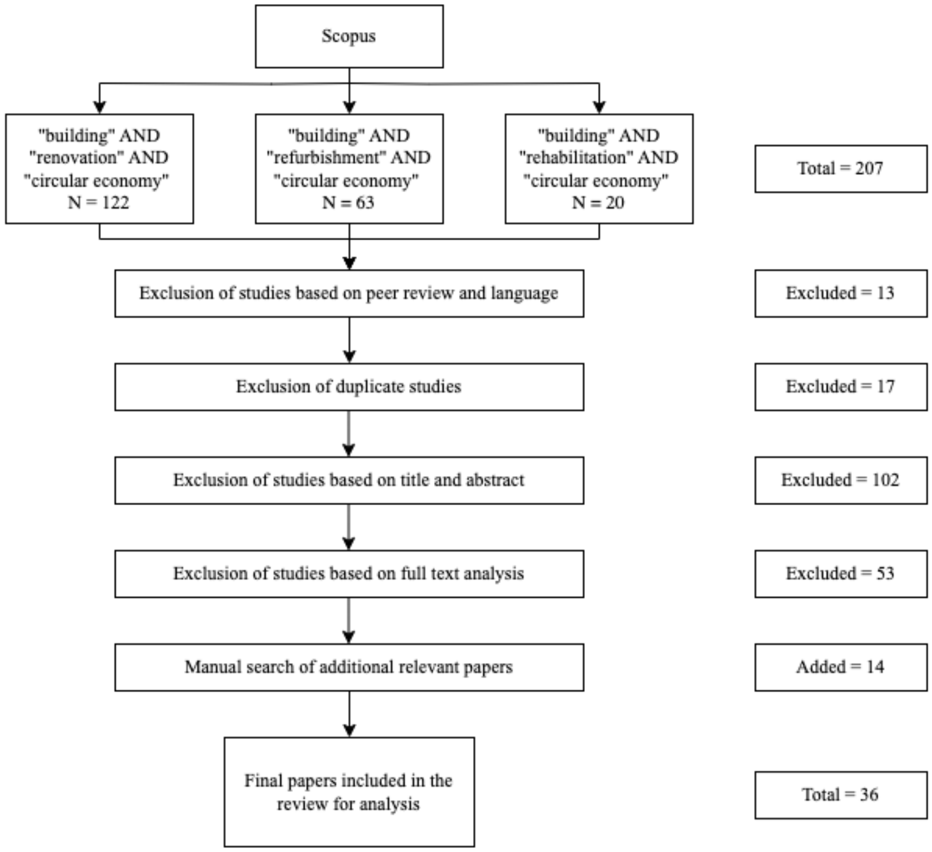

Figure 3.3. Flow Diagram of the Search Strategy and Selection Process for Literature Review

Using articles from the literature review, circular economy indicators were identified that can be associated with the reconstruction of the building. These indicators can be used to assess the circularity during construction work. To collect these indicators and distribute them into groups, a workshop was held with the participation of experts. As a result, the indicators were distributed into groups according to specific aspects of circularity.

3.3 Surveying stakeholders

Relying on the answers received on the indicators from the experts during the workshop, questions were created for a further questionnaire. The questions were based on assessing the circularity of building elements during the renovation of a building. Then the stakeholders were surveyed. Questions were created in such a way that respondents will give answers by rating.

A survey was developed to engage a diverse range of stakeholders, such as building owners, contractors, designers, and academicians. The survey has two main objectives:

• To confirm the relevance of the selected indicators and factors.

• To assess the priority of indicators in the reconstruction of the building based on the opinions of stakeholders.

The survey was conducted in two stages. The first stage will be a survey among academics and researchers. And the second stage was a broad participation of stakeholders, which includes engineers, designers, end users, etc.

A Likert scale ranging from 0 to 5 was used to collect weightings from stakeholders, specifically experts in construction. The scale was defined as follows: 0 represents "Irrelevant" where renovation is not the focus; 1 represents "Minor" where renovation indicators are barely mentioned; 2 represents "Moderate" indicating a partial role in circular renovation; 3 represents "Important," signifying a valuable tool for assessing circularity; 4 represents "Crucial," guiding renovations for maximum circularity; and 6 represents "Essential," as critical for achieving a circular built environment.

Table 3.3. Likert scale distribution

Likert scale value	*Level*	*Explanation*
0	Irrelevant	renovation is not the focus
1	Minor	renovation indicators are barely mentioned
2	Moderate	indicating a partial role in circular renovation
3	Important	valuable for assessing circularity
4	Crucial	guiding renovations for maximum circularity
5	Essential	critical for achieving a circular built environment

The survey contains 8 questions. One question is regarding stakeholder category while other questions aim to identify importance of factors and indicators. The questions are shown below:

1. Select the stakeholder category that you represent the best:
2. How important are the following factors in evaluating the circularity of a building renovation?
3. How would you rate the importance of the following Material Type and Flow Indicators in evaluating the circularity of a building renovation?
4. How would you rate the importance of the following Water and Energy Consumption Indicators in evaluating the circularity of a building renovation?

5. How would you rate the importance of the following Construction and Demolition Waste Management Indicators in evaluating the circularity of a building renovation?

6. How would you rate the importance of the following Cost and Benefits Indicators in evaluating the circularity of a building renovation?

7. How would you rate the importance of the following Building Functions and Services Indicators in evaluating the circularity of a building renovation?

8. How would you rate the importance of the following Renovation Service Provision Indicators in evaluating the circularity of a building renovation?

The likert scale in questionnaire is shown in Figures 5.2 to 5.8. It is the same for all questions that need assessment from stakeholders. The full list of the questions with Likert scale are Appendix B.

The survey was conducted through Qualtrics tool via anonymous link which was sent to the experts via email and distributed to other stakeholders. To conduct this survey the permission was taken from NU IREC (Institutional Research Ethics Comittee) which allows to conduct the survey in accordance with ethical standards that do not violate confidentiality and research standards that include people's opinions. The link to the survey in provided below: https://nukz.qualtrics.com/jfe/form/SV_5cYuVH09TbOhQOi

3.4 Prioritization of factors and indicators

The collected responses were used to determine average weights for each factor and indicator, which allowed them to be ranked by priority. For this purpose, Mean Score (MS) Analysis was used, which reflects the respondents' overall perception of each factor and indicator. This method determines the priority of all factors and indicators measured on a Likert scale. The MS was calculated as follows (Alhawamdeh et al., 2024; Awasho & Alemu, 2023; Tan et al., 2017):

$$MS = \frac{\sum n_0 k_0}{\sum n} = \frac{5n_5+4n_4+3n_3+2n_2+1n_1}{n_5+n_4+n_3+n_2+n_1+n_0} \quad (1)$$

where

- $\sum n$ represents the total number of respondents;
- 1-5 correspond to the Likert scale ratings for each factor and indicator;
- n_1 to n_5 represent the number of respondents who selected each respective rating.

3.5 SHAP values analysis

After identifying MS for each indicator and factor, the SHAP (SHapley Additive exPlanations) value analysis was done to see and display the importance of each indicator and factor as perceived by different stakeholder groups. SHAP value analysis was used to generate the graphics that show the influence of the indicators on circular assessment of renovation. For this purpose, the machine learning model was used. The generated plots visualize which factors are most important across all stakeholder opinions and demonstrate how individual stakeholder input affects the circularity assessment for building renovation project.

Circularity Score (CS)

$$CS = \frac{R_1 + R_2 + R_3 + \cdots + R_k}{k} \tag{2}$$

where

- R_k represents the likert scale (0 to 5) response for each factor and indicators separately given by each respondent;
- k corresponds to the total number of factors or indicators being analyzed.

For analyzing results in SHAP the Python programming language was used. By creating codes in this programming language, the plots were generated. In this study, XGBoost Regressor was used in creating codes to generate the results. For this reason, the results, especially, respondent list, their Likert scale responses regarding each factor and indicator and their stakeholder categories were uploaded in csv file. Using this tool two different figures will be generated to describe results. The first one will show SHAP value analysis of circularity factors/indicators, showing their impact on the model output, with a color gradient representing feature values. It will show the impact of each factor/indicator on the model's output, where positive values indicate a higher contribution to circularity, and negative values suggest a lower contribution. The color gradient will represent the value of the feature, where high values will be shown in red while low values will be in blue. The second figure will be a heatmap of average SHAP values by stakeholder groups. This figure will highlight the differences in the perception of the importance of factors among the Academy, the construction industry and the public sector. The color gradient in this case will represent the magnitude of influence, positive values in red will indicate a higher contribution to the cycle, while negative values in blue will indicate a lower or even adverse impact.

3.6 Preparation of framework

The final stage integrates findings from the survey and stakeholder engagement to develop the circularity assessment framework for building renovation projects. This framework provides a practical tool for evaluating circularity in renovation projects, supporting informed decision-making aligned with circular economy objectives.

Chapter 4 - Results and Discussion

4.1 Circularity assessment factors and indicators during building renovation

Following the literature review, 44 circularity indicators were carefully identified as potentially relevant and important for assessing the circular economy in building renovation projects. As a result of workshop, construction experts identified six categories of factors and assigned the indicators to the appropriate category. Table 8 presents the finalized list of factors and their corresponding indicators, along with the number of articles that reference these indicators. The detailed list of factors and indicators with references are shown in Appendix B.

The following six circularity factors were proposed for categorizing the indicators: “material type and flow”, “water and energy”, “construction and demolition waste (C&DW) management”, “cost and benefits”, “building functions and services”, and “renovation service provision”. Each of these factors includes specific indicators, with some indicators appearing in multiple factors because they may influence various aspects.

“Material type and flow” factor has 9 indicators, “Water and energy” factor has 5 factors, “Construction and demolition waste (C&DW) management” consists of 5 indicators, “Cost and benefits” factor consists of 10 indicators, “Building functions and services” factor has 9 indicators while “Renovation service provision” factor consists of 8 indicators.

Table 4.1. Circularity factors and indicators for building renovation based on literature review and workshop

Factors	*Indicator*	*Freq.*
Material flow and type	Building components for reuse (reusability)	26
	Building components for recycle (recyclability)	24
	Cycled sourced materials usage (secondary, recovered, non-virgin)	12
	Virgin sourced materials usage	4
	Renewable or Non-renewable material usage	7
	Human toxicity potential from material	4
	Material durability and longevity	6
	Material estimated service life	2

Water and Energy	Reuse or recycle of wastewater	7
	Use of rain and storm water	3
	Water consumption (Portable, freshwater resources)	8
	Renewable energy or Non-renewable energy	3
	Energy consumption (electricity, thermal energy)	12
	Materials used for energy recovery	3
C&DW Management	Hazardous or non-hazardous solid waste	2
	Toxic or non-toxic liquid waste	1
	Recoverable waste or reuse of waste	4
	Unacceptable waste for landfilling/disposal	4
	Waste separation and storage	3
Cost and Benefits	Materials cost	5
	Material transportation cost	5
	Resale value of material	3
	Labor cost	6
	Equipment cost	5
	Waste landfilling/disposal cost	3
	Operational energy cost	5
	Operational water cost	5
	Deinstallation/Deconstruction/Dismantling cost	6
	Maintenance cost	7
	Material recovery	1
	Energy recovery	
Building functions and services	Comfort	3
	Functionality	3
	Performance	4
	Adaptability	4
	Flexibility	3
	Natural light	3
	Occupant Safety	5
Renovation Service Provision	Worker's safety	1
	Safety during service	2
	Quality of service	2
	Accessibility & Ease of assembly	6
	Toxicity of materials	5
	Hiring of goods and services	2
	Collaborative design	-
	Client satisfaction	-

Material is the most important element during construction, that is why amount of material, flow of material during construction are important factors to assess circularity Materials utilized during renovation can originate from renewable and recycled sources or from non-renewable and virgin sources. Conversely, the outgoing flow of materials and waste from construction or renovation works can be sent to recycling or to landfill.

Energy is one of the factors in construction. Energy consumption is quantified in terms of primary energy, covering both non-renewable and renewable sources González et al., 2021). The potential renewable energy flows include renewable energy generated on-site or nearby for activities such as material mining, product, and parts manufacturing, and building construction and operation.

Water consumption is another important aspect of construction which depicts the water flow during building construction or renovation. The potential circularity of water involves recycled water sourced from various water reutilization or wastewater sources, such as greywater, blackwater, or rainwater, within the building itself or from upstream sources (González et al., 2021).

Addition of C&DW management is essential because during renovation waste may be generated, and the correct distribution of this waste can reduce the use of new materials, increase the recycling of materials, thereby also reducing the amount of waste for the land fields.

Moreover “building functions and services” and “renovation service provision” factors were suggested according to the indicators identified through literature review.

4.2 Results of the survey and SHAP analysis

The previously designed survey was distributed to interested parties. The first stage of the survey targeted academicians and researchers while the second stage of the survey were focused on other stakeholders such as engineers, designers, architectures, end-user etc. Currently, 42 responses have been received that was used for the analysis in this thesis. Based on the survey results the category of the respondents and number of respondents for each category can be seen in Table 4.2. Based on the results, 17 people from academy, 11 people from public and 14 people from construction industry sector participated in the survey.

Table 4.2. Survey participants summary

Stakeholder categories	***Participant numbers***	***Participated stakeholders***
Academy	17	Professors, researchers, students
Public	11	Householders, end-users, contractor
Construction industry	14	Project manager, technician/engineer, designer architect, urban designer

An analysis of the survey results is presented this section. The framework provided below in in this section is based on the opinions of all stakeholders. All graphs and figures shown were generated using calculations based on the formula specified in the Methodology section.

The relevance assessment of the selected factors for evaluating circularity during renovation reveals that "material type and flow", "cost and benefits, and "C&DW management" have a significantly higher MS, 3.90, 4.09 and 3.79 respectively, compared to other factors (Figure 4.2). It is also important to note that the "water and energy" factor ranks fifth with a MS of 3.36, which is significantly lower than that of other factors, despite the critical role of water and energy in sustainable construction (González et al., 2021a). This can be explained by the fact that water and energy are not components that can be repaired like other elements, water and energy are essential resources required during the construction or renovation process. The renovation service factor ranked the lowest, with MS of 3.23. This suggests that experts perceive this factor as having a less direct influence on circular outcomes and being more challenging to quantify in circular terms. Figure shows that "Cost and benefits" is the most critical factor with a weight of 4.09. This factor is followed by "Material type and flow" which has MS of 3.90. The next ones are C&DW Management with MS of 3.79, "Building functions and services" with MS of 3.74, "Water and energy consumption" with MS of 3.36, "Renovation service provision" with MS of 3.23.

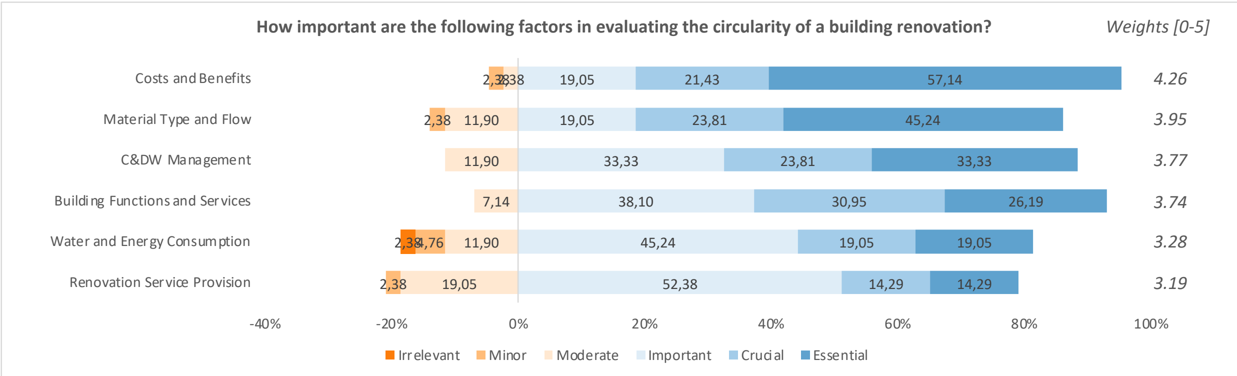

Figure 4.1. Relative Importance of Circularity Factors in building renovation

Figure 4.2 shows compare weights of each factor in accordance with 3 different stakeholder categories such as academy, public and construction industry. The perception of stakeholders for each factor varies since each category has different stakeholders who understand the circular economy differently and factors and indicators are important in different levels. The general weights for each factor from different categories are higher that 3.00, this means that stakeholders assessed these factors as important.

According to the figure 4.2, "Material Type and Flow" and "Costs and Benefits" are rated as the most important factors by all stakeholder groups. As it can be seen the academia group assigns the highest weight of 4.50, followed by construction Industry with 4.13, and the lowest by Public with 3.80. Academy sector stakeholders rated "Material Type and Flow" and "C&DW Management" factors highly with the weights of 4.56 and 4.33, respectively. This shows that academy sector stakeholders prioritize assessing of resource managing to assess circularity in building renovation while the construction industry stakeholders prioritize financial aspects. They rated "Costs and Benefits" with the weight of 4.13 while assigning a lower importance to "Material Type and Flow" and giving it 3.13. Academia places particular emphasis on “Material Type and Flow” while construction Industry prioritizes “C&DW Management”.

In comparison with academy and construction industry sector stakeholders, the public sector stakeholders’ evaluations fall in the middle. "Renovation Service Provision" received the lowest ratings across all groups, indicating it is not perceived as a key factor in assessing circularity in building renovations. “Renovation Service Provision” the weights range from 3.00 for academia to 3.38 for construction Industry indicating a moderate level of importance.

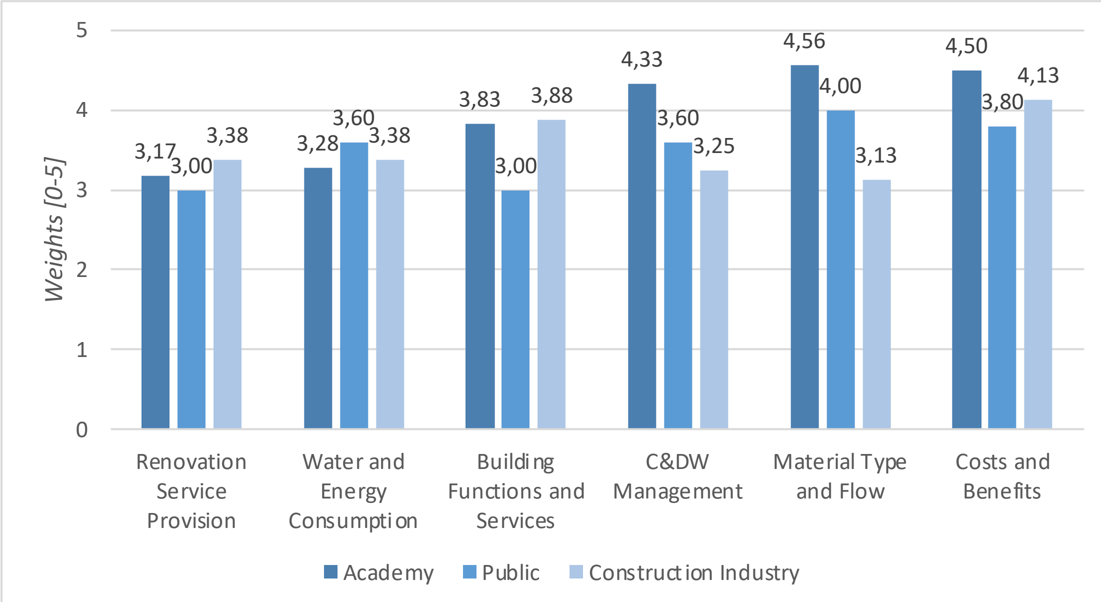

Figure 4.2. Weights of factors based on stakeholders

SHAP Value Analysis results for circularity factors are shown in Figures 4.3 and 4.4. Figure 4.3 presents the SHAP value analysis for circularity factors in building renovations. Based on the figure it can be summarized that "C&DW Management", "Material Type and Flow", and "Costs and Benefits" factors show a significant impact on the model output. While "Building Functions and Services" and "Renovation Service Provision" factors shows lower contributions overall since they are clustering of values around zero.

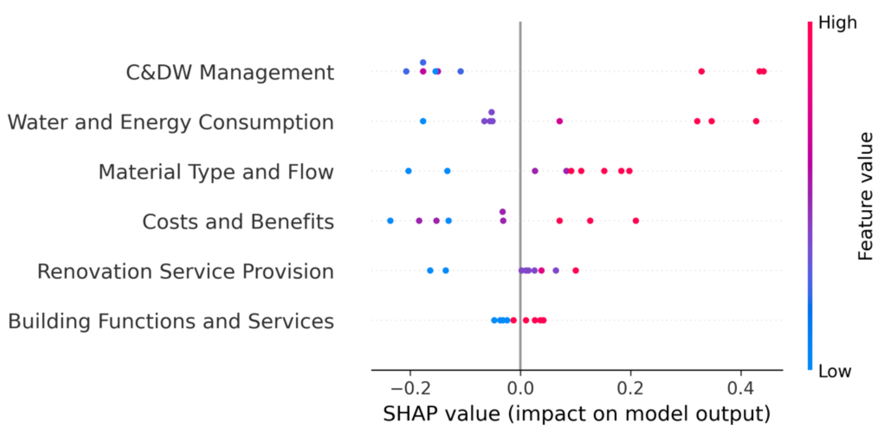

Figure 4.3. SHAP value analysis of factors

Figure 4.4 shows the mean SHAP values for each circularity factor across three stakeholder groups. Notable that academy places the highest emphasis on “C&DW Management” with value of 0.13 and “Material Type and Flow” with value of 0.08, highlighting their recognition of these factors in circularity assessment. in building renovation. While the construction industry assigns negative SHAP values of -0.11 and -0.12 to “C&DW Management” and “Material Type and Flow” respectively. This shows a lower perceived importance compared to other groups. The Public sector generally perceives “C&DW Management” and “Costs and Benefits” as having a lesser contribution with negative value, whereas “Material Type and Flow” has a slightly positive impact with the value of 0.04.

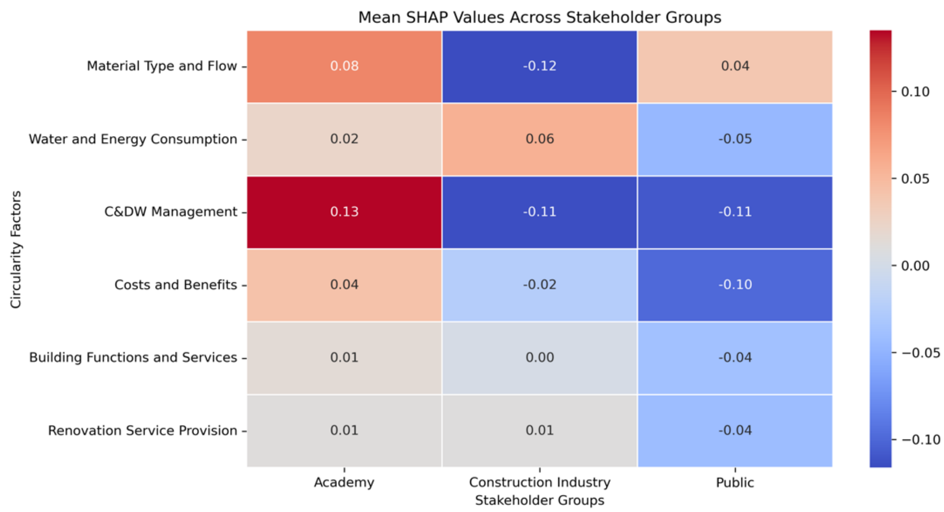

Figure 4.4. Mean SHAP value of factors across stakeholder groups

Figure 4.5 presents a detailed assessment of cost and benefit indicators critical to building renovation projects. The "Cost and Benefits" factor, which contains the largest number of indicators, displays a range of weights from 2.71 to 4.03. Most of these indicators have relatively high weights, generally clustered around or above 3, with material costs receiving the highest weights where more than 55 percent of experts highlighted it as essential for circularity measurement in renovation. “Materials Cost”, “Labor Cost”, and “Material Transportation Cost” indicators have dominantly dark blue shades representing important to essential. This highlights their critical role in circularity assessment in building renovation. “Materials Cost” with the weight of 4.10 is considered as the most relevant in this factor. The next crucial indicators are “Material Transportation Cost” and “Labor Cost” with the weights of 3.73 and 3.55 respectively.

Most of the other indicators have weights about of 3 indicating them as important. But "Operational Water Cost" and "Energy Recovery" indicators have a lower perceived impact on circularity with the weights of 2.76 and 2.86 respectively, showing that stakeholders don't consider them as important in assessing "Cost and Benefits".

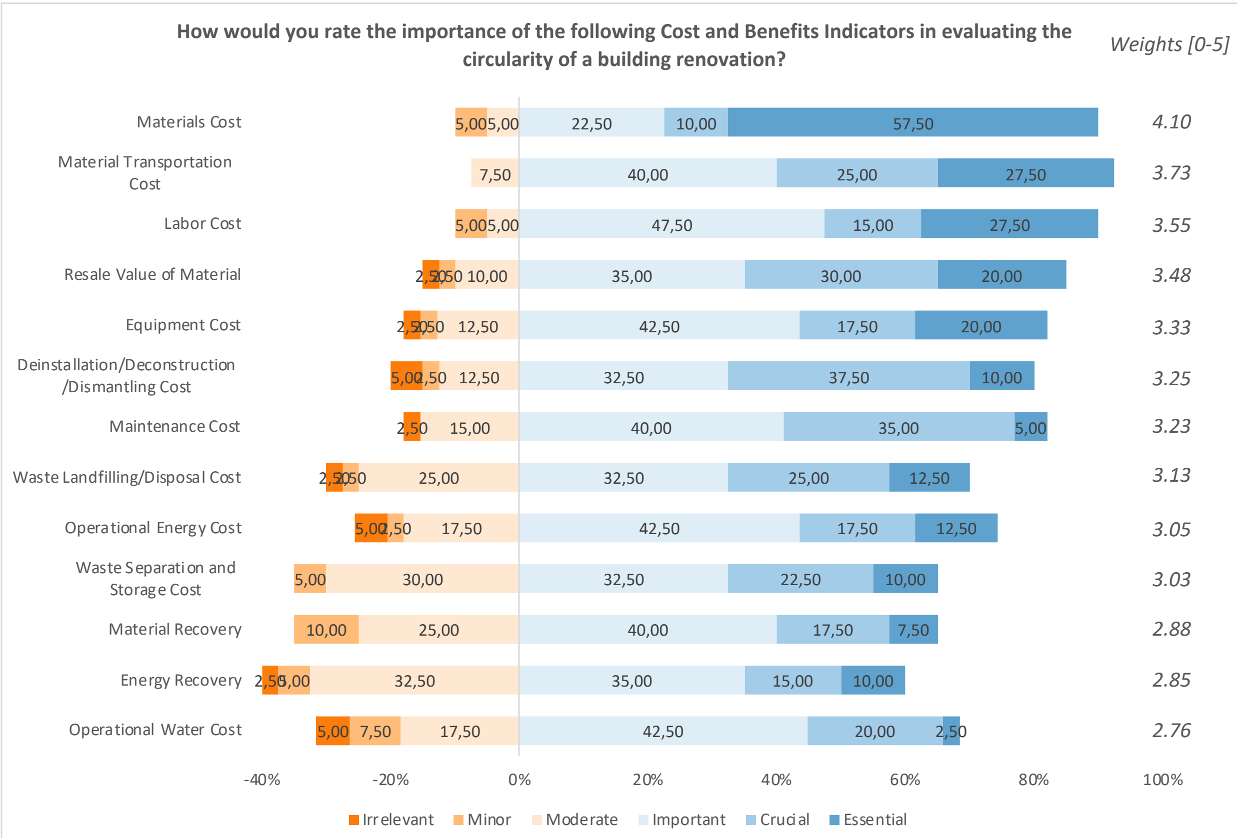

Figure 4.5. Relevance "Cost and benefits" indicators

The figure 4.6 Weights of "Cost and benefits" indicators based on stakeholders illustrated how different stakeholders prioritize cost-related indicators differently. "Materials Cost" indicators is the highest-rated indicator across all groups, with the construction industry ranking it the highest with the weight of 4.7. Factors like "Labor Cost" and "Material Transportation Cost" are relatively consistent across all stakeholders involved. All stakeholder groups give "Operational Water Cost" and "Energy Recovery" indicators lower weights, suggesting that they are not the main indicators in "Cost and Benefits" factor during circularity assessments.

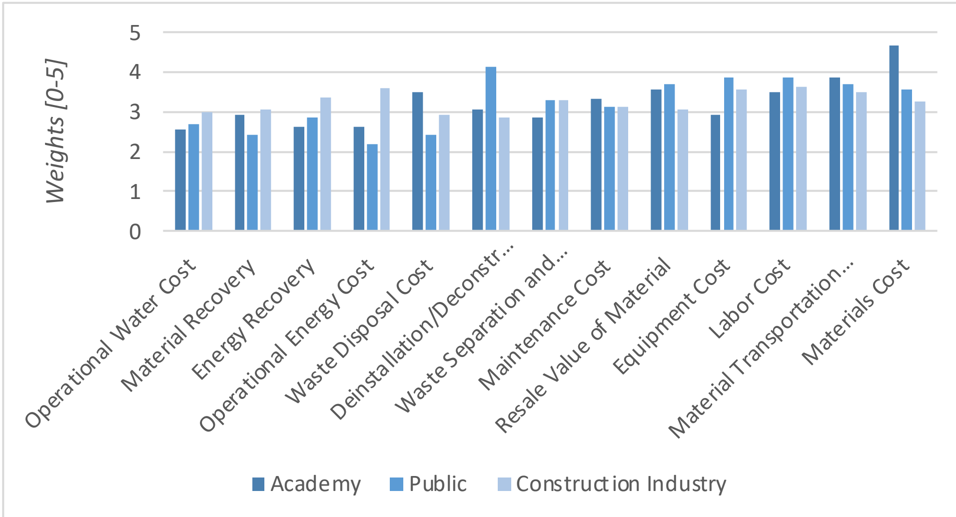

Figure 4.6. Weights of "Cost and benefits" indicators based on stakeholders

In Figure 4.7 SHAP value analysis indicates that "Operational Energy Cost", "Materials Cost", and "Labor Cost" indicators have a wide spread of SHAP values meaning that they have the most significant impact and strongly influence on the model's decision-making. While lower-impact indicators include "Maintenance Cost", "Energy Recovery", and "Operational Water Cost", suggesting they play a lesser role in shaping circularity predictions clustering around zero value.

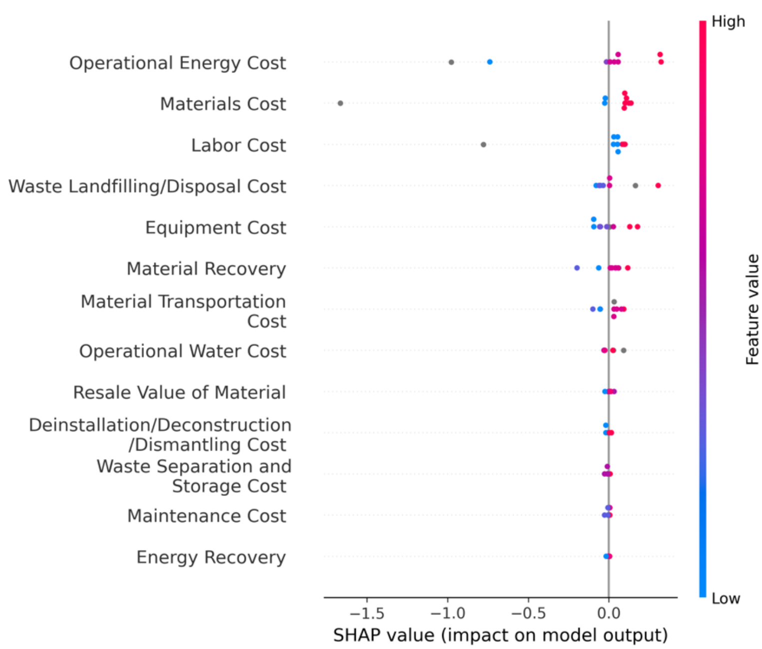

Figure 4.7. SHAP value analysis of "Cost and benefits" indicators

Figure 4.8 shows that “Materials Cost” indicator has a significant influence across all stakeholder groups. Public sector with positive impact of 0.07 and academia with negative impact of -0.11, shows varying perceptions of its role in circularity assessment. “Labor Cost” indicator is rated positively by the public and the construction industry but negatively by academia with -0.05 negative impact. Indicators such as “Maintenance Cost”, “Waste Separation and Storage Cost” show minimal influence since values are close to zero across all groups.

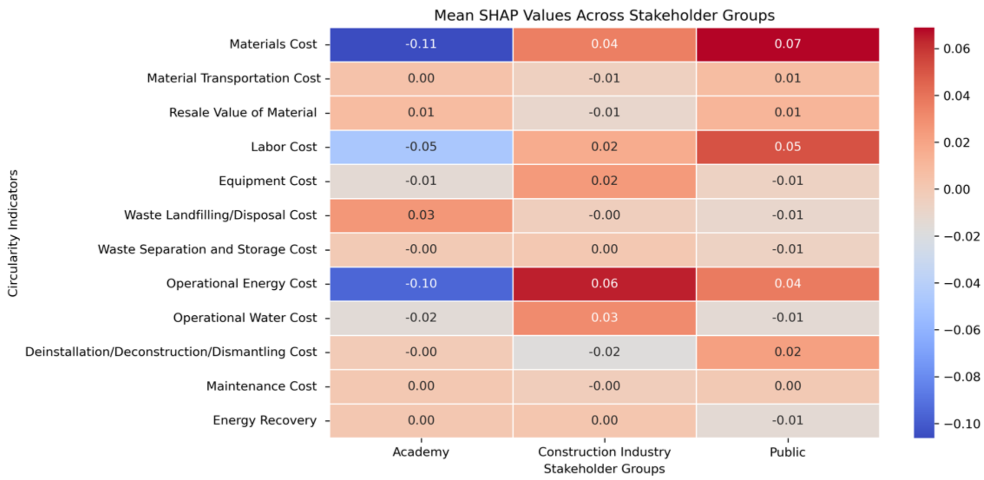

Figure 4.8. Mean SHAP value of "Cost and benefits" indicators across stakeholder groups

Figure 4.9 shows a detailed analysis of the relative importance of the circularity indicators of the factor “Material Type and Flow”. Among the indicators, “Material Durability and Longevity”, “Human toxicity potential” and “Reusability” received higher weights, highlighting their important role in sustainable renovation. The assessment of the indicators of the factor “Material Type and Flow” shows that experts prioritize the recycling which is transforming materials to acquire materials of equivalent or superior quality (Ping Tserng et al., 2021) and reuse of existing building components during renovation which is reusing a product while preserving its function and identity (Morseletto, 2020), this lines with the main goal of circularity. In addition, “Material Estimated Service Life” is considered as a significant indicator with an MS of 3.92, since it may inform decisions regarding the use of components. The indicator " Material Durability and Longevity " has a weight of 4.11.

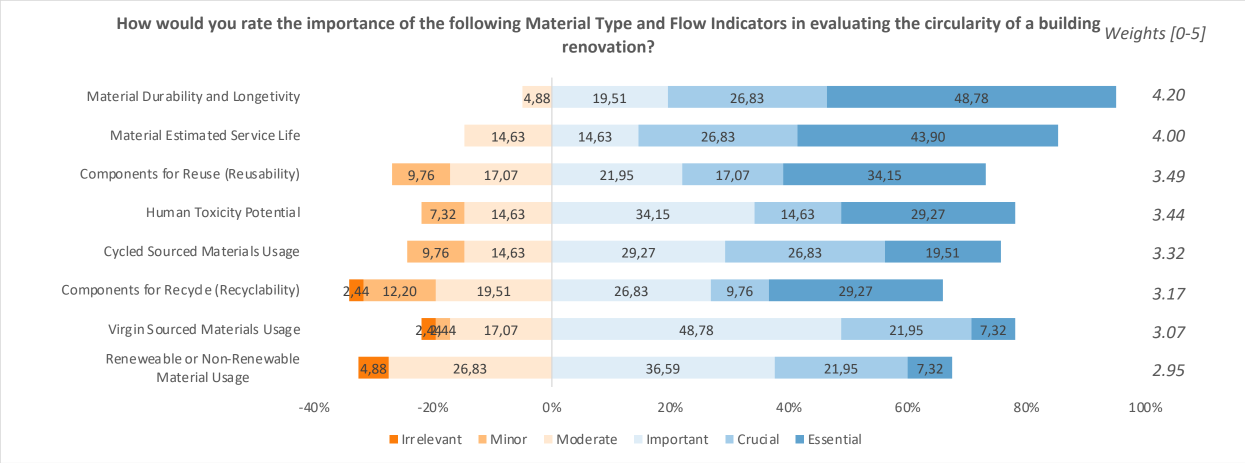

Figure 4.9. Relevance of "Material type and flow" indicators

Figure 4.10 shows that "Material Durability" and "Estimated Service Life" indicators received the highest weights across all stakeholders. The Public stakeholder group gives relatively lower importance on "Material Durability and Longevity" with the weight of 3.4 compared to Academia and the Construction Industry with the weight of 4.1 for both.

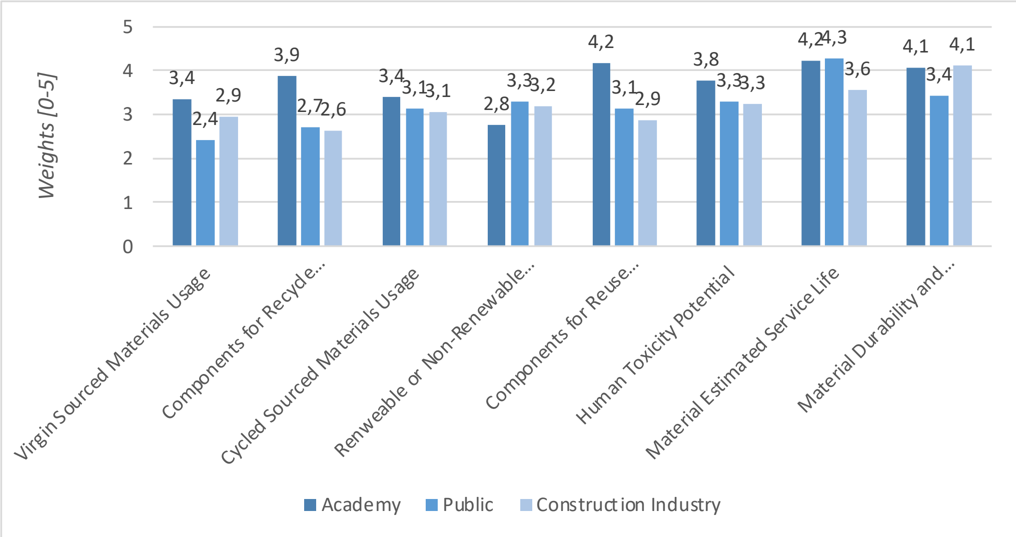

Figure 4.10. Weights of "Material type and flow" indicators based on stakeholders

Figure 4.11 highlights that "Cycled Sourced Materials Usage", "Components for Reuse", and "Human Toxicity Potential" indicators had the most significant SHAP values. This means they have the strong influence on model output. "Renewable or Non-Renewable Material Usage", "Material Durability" indicators had smaller SHAP values, while "Virgin Sourced Materials

Usage" indicator showed the less values among all indicators meaning it contributed less to the model predictions.

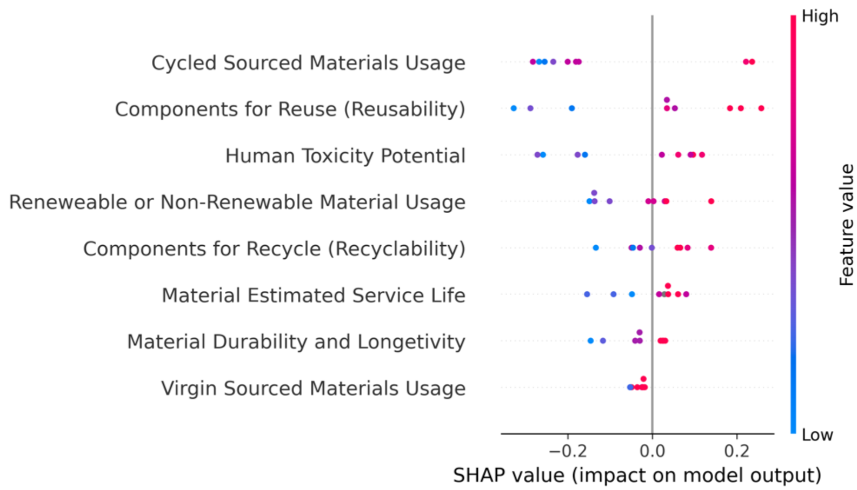

Figure 4.11. SHAP value analysis of "Material type and flow" indicators

The heatmap in Figure 4.12 illustrates that "Components for Reuse (Reusability)" indicator showed a high positive impact in Academia with the impact of 0.09 while Construction Industry and Public showed negative impact of -0.11 and -0.04 respectively. Notably, "Material Durability and Longevity" indicators had almost no effect across all stakeholder groups.

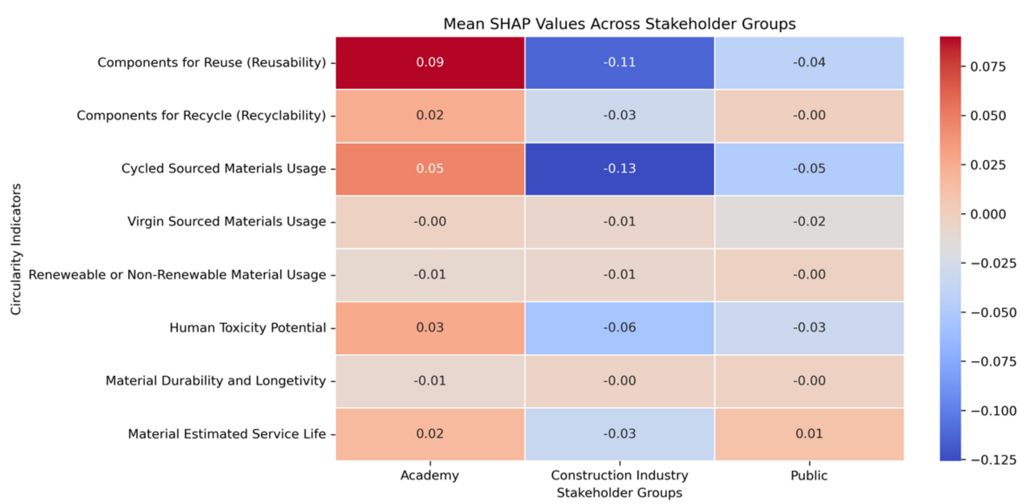

Figure 4.12. Mean SHAP value of "Material type and flow" indicators across stakeholder groups

Figure 4.13 illustrates the importance of the indicators related to C&DW management in sustainable reconstruction projects. The graph shows the priority of the indicators as waste separation and storage, recoverable or reusable waste, hazardous and non-hazardous waste, toxic or non-toxic liquid waste and non-recoverable waste for disposal.

All indicators within the "C&DW management" factor have relatively high weights, exceeding 3.28 (where 3 represents "important" scale) in Figure 4.5, suggesting that these indicators align well with the principles of circularity and are essential in its assessment during renovation projects.

It can be seen in Figure 4.5 that the indicator "Recoverable or Reusable Waste" has the highest weight in this factor which is equal to 3.50 so this indicator can be assumed as crucial in assessing circularity. The next indicator with weight of 3.36 is "Hazardous and Non-hazardous solid waste", following with "Toxic and Non-Toxic Liquid Waste" and "Unacceptable Waste for Landfilling/Disposal" indicators with the weights of 3.36, 3.33 and 3.28 respectively. And the last indicator in this factor with the least weight of 3.28 is "Waste Separation and Storage", but this weight is also "important".

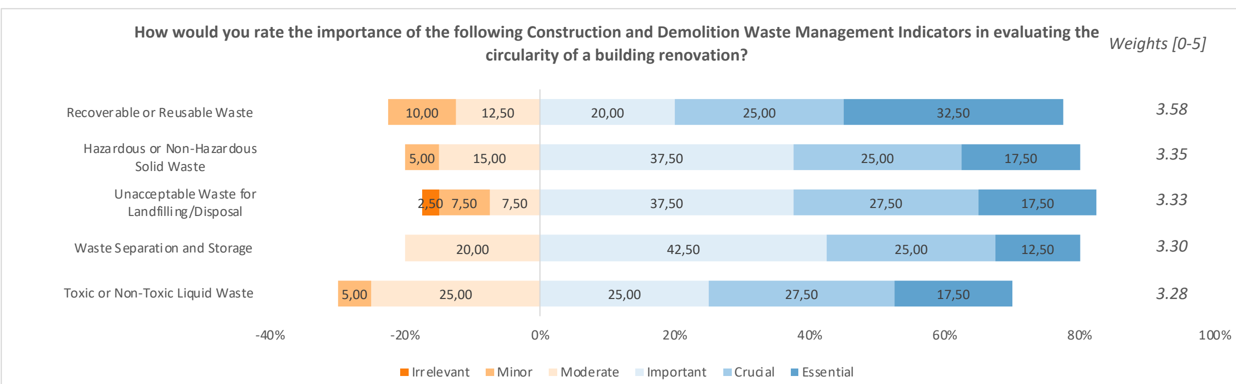

Figure 4.13. Relevance of "C&DW management" indicators

The weights of indicators across stakeholder groups in Figure 4.14 shows that the highest weighted indicator appears to be "Recoverable or Reusable Waste", particularly valued by the Academy group with the weight of 4.4. "Unacceptable Waste for Landfilling/Disposal" has a lower weight from the public group. Academy stakeholder group gives high weights in comparison with other stakeholders for all indicators.

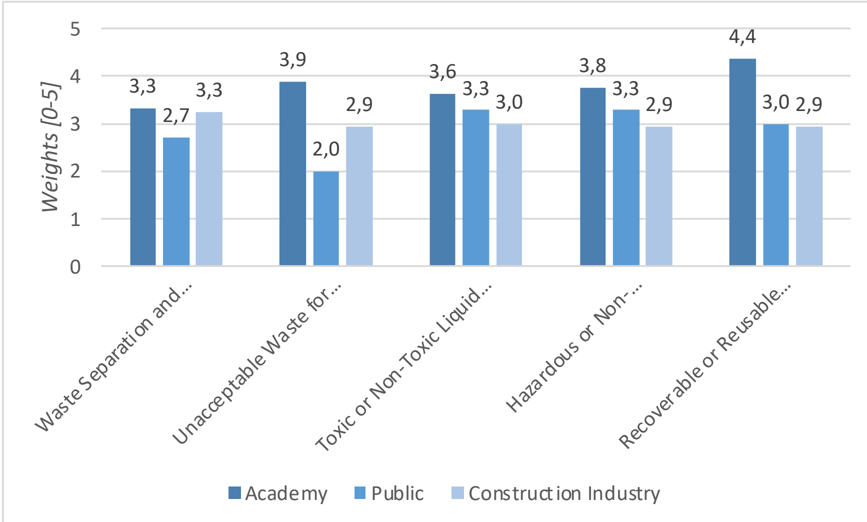

Figure 4.14. Weights of "C&DW management" indicators based on stakeholders

SHAP value analysis in Figure 4.15 shows that Indicators such as "Recoverable or Reusable Waste" and "Hazardous or Non-Hazardous Solid Waste" have the most significant impact, while "Waste Separation and Storage" has the smallest effect.

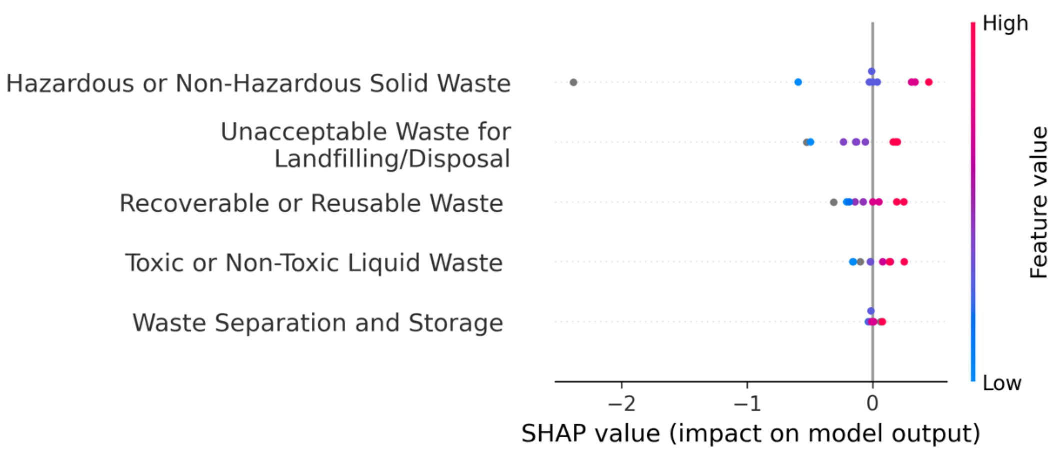

Figure 4.15. SHAP value analysis of "C&DW management" indicators

Heatmap in Figure 4.15 illustrated that "Recoverable or Reusable Waste" has the highest positive SHAP value for the academy group but is rated negatively by the construction industry. Other indicators impact by stakeholder group varies. But "Toxic and Non-Toxic Liquid Waste" and "Waste Separation and Storage" indicators have almost no effect since they are almost zero.

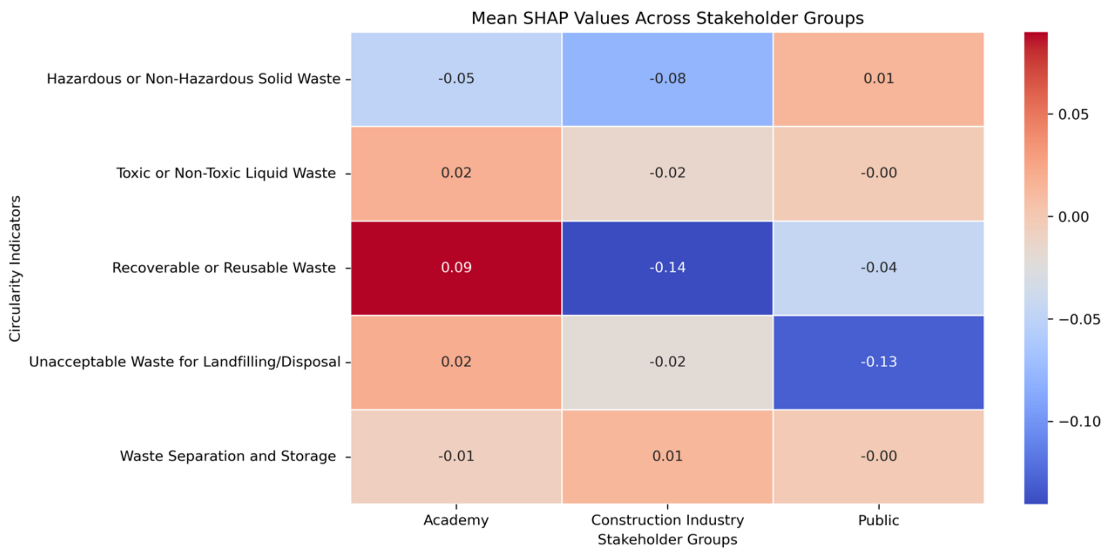

Figure 4.16. Mean SHAP value of "C&DW management" indicators across stakeholder groups

Figure 4.17 show the importance of various indicators related to building functions and services. Based on the figure, indicator "Comfort" reflects an increasing focus on the well-being of building occupants. The indicator "natural light" (5.4 percent of experts considered it irrelevant) received some of the lowest weights among all 7.

The weights of indicators vary from 3.08 (which can be assumed as moderated) to 4.27 (which can be assumed as essential). Based on the stakeholders' responses, the most crucial indicators are "Occupant Safety", "Performance", "Functionality", "Comfort" with the weights of 4.27, 4.22, 3.97, 3.82 respectively.

The next indicators such as "Adaptability", "Flexibility" are ranked as important with the weights of 3.30, 3.27, respectively since they have the MC more than 3. The least ranked indicator is "Natural light" with the weights of 2.69, and it can be ranked as moderate based on Likert Scale ranking.

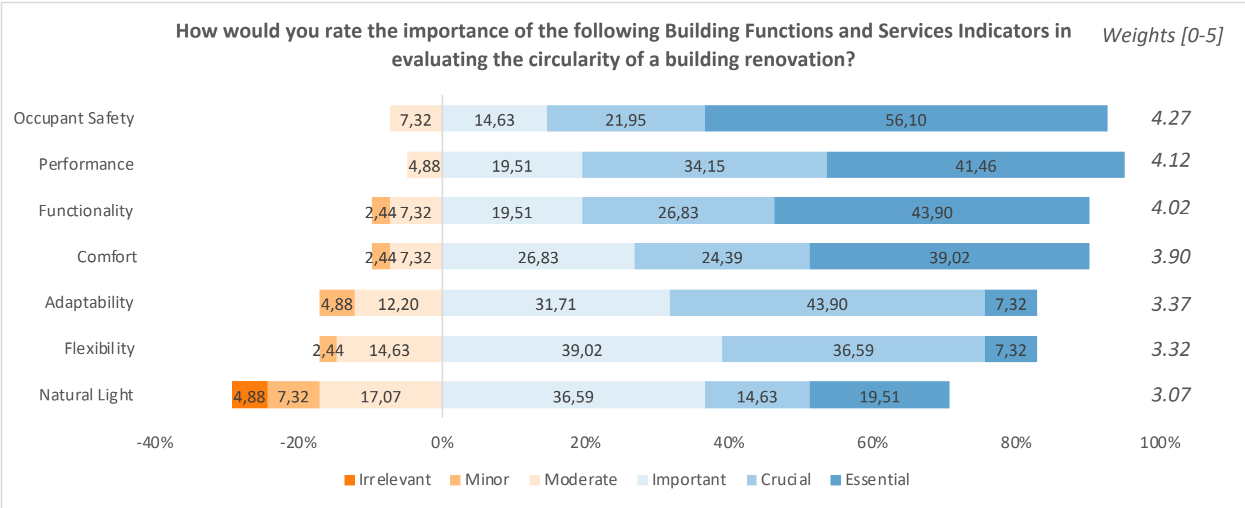

Figure 4.17. Relevance of "Building functions and services" indicators

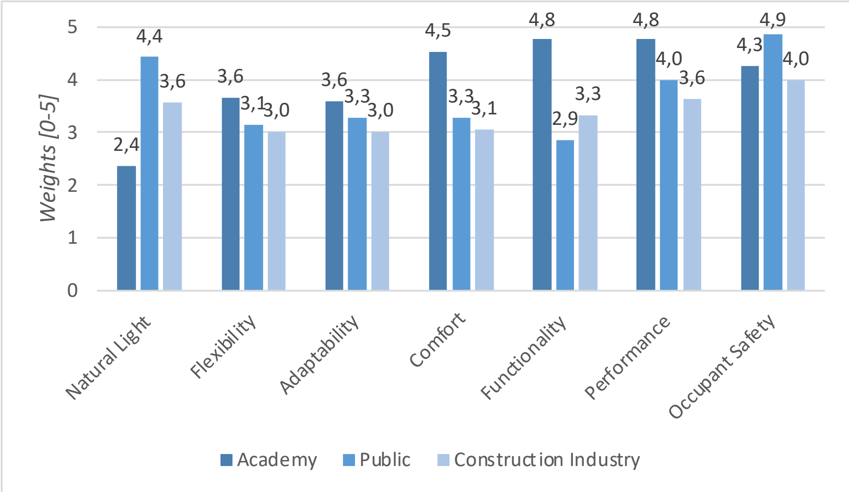

Figure 4.18. Weights of "Building function and services" indicators based on stakeholders

Figure 4.11 highlights that "Performance", "Functionality", and "Comfort" indicators had the most significant SHAP values. This means they have the strong influence on model output. "Adaptability", "Flexibility" and "Natural Light" indicators had medium SHAP values, there are no indicator that has impact value near to zero.

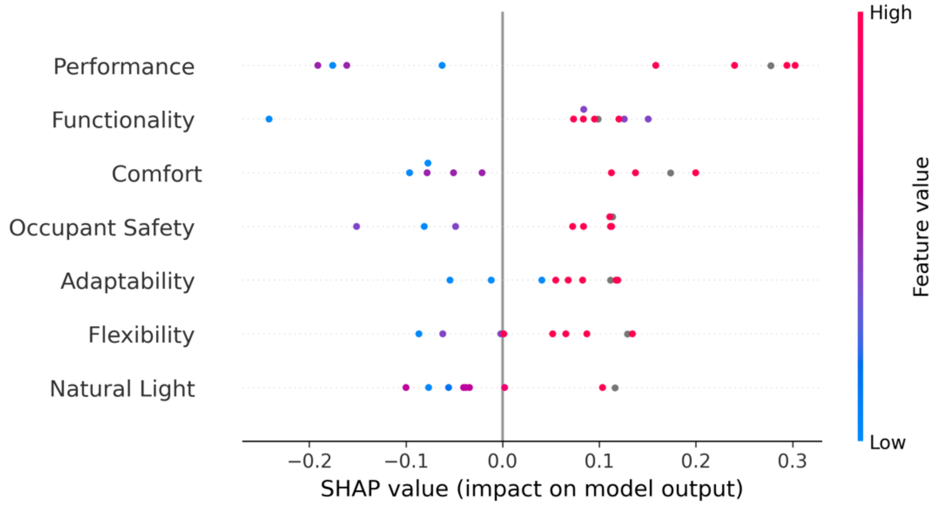

Figure 4.19. SHAP value analysis of "Building functions and services" indicators

Heatmap in Figure 4.20 shows that "Performance" has the highest positive SHAP value for the academy group but is rated negatively by the construction industry and public among all indicators. Other indicators impact by stakeholder group varies. But all indicators have negative mean SHAP value in construction industry stakeholder group.

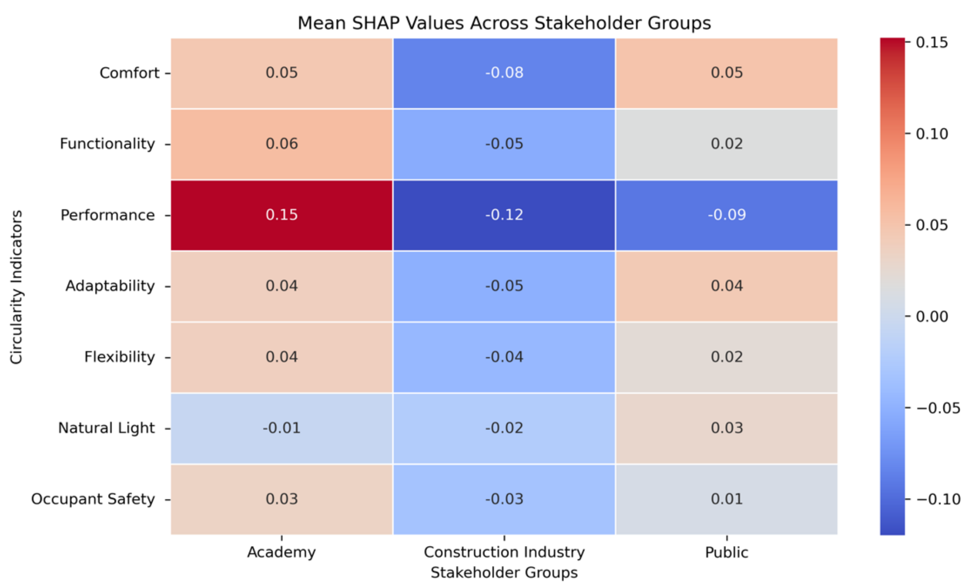

Figure 4.20. Mean SHAP value of "Building functions and services" across stakeholder groups

Figure 4.21 shows the importance of different water and energy consumption indicators in building renovation projects. Among these indicators, "Energy Consumption" and "Water

Consumption" were ranked highly due to their significant impact on both the operational efficiency of buildings and the ecological footprint of renovation projects.

Another key indicator, "Water Reuse and Recycling", also has a high weight in priority because water reuse can significantly reduce the demand for fresh water in renovation projects, which is in line with the principles of circular economy. The survey results show that stakeholders rated the first four factors of "water and energy consumption" as important, while "rainwater and stormwater use" was rated significantly lower.

It is noteworthy that within the "water and energy consumption" factor, the "water consumption" and "energy consumption" received high weights of 3.86 and 3.49, respectively. In contrast, the similar indicators "operational energy cost" and "operational water cost" were among the lowest in the "cost and benefits" factor, with weights of 3.07 and 2.71. This means that in the context of building renovation, operational costs for water and energy often constitute a smaller portion of the total costs compared to capital costs such as materials, labor, and construction work.

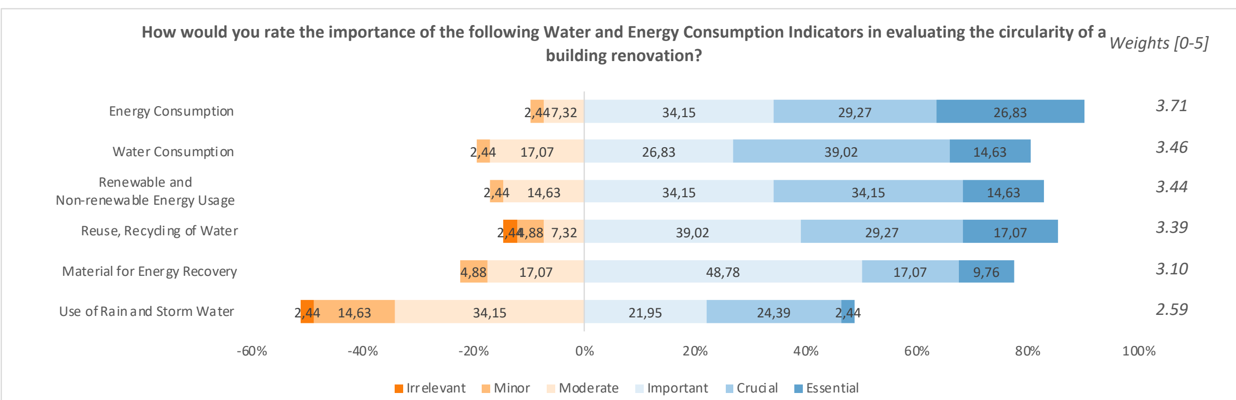

Figure 4.21. Relevance of "Water and energy consumption" indicators

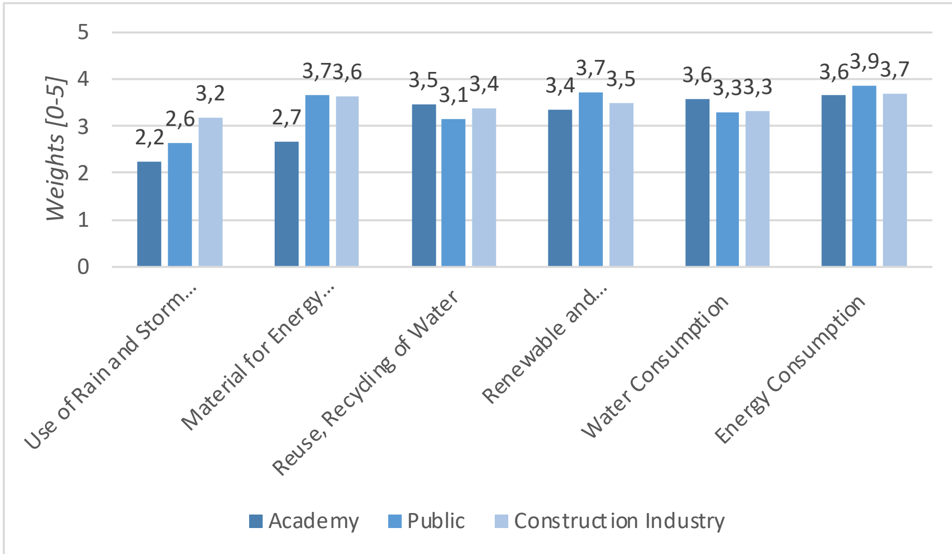

Figure 4.22. Weights of "Water and energy consumption" indicators based on stakeholders

In Figure 4.23 SHAP value analysis indicates that "Use of rain and storm water" and "Water Consumption" indicators have a wide spread of SHAP values meaning that they have the most significant impact and strongly influence on the model's decision-making. While lower-impact indicators include "Renewable and Non-Renewable Energy Usage".

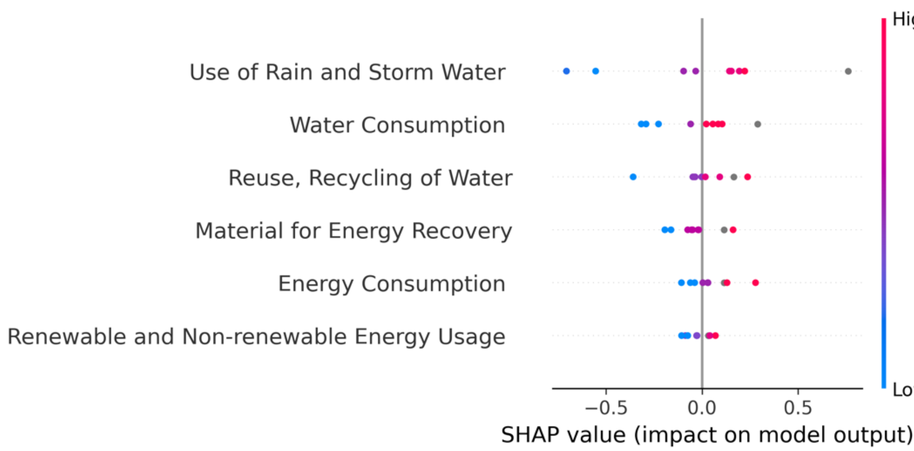

Figure 4.23. SHAP value analysis of "Water and energy consumption" indicators

Figure 4.24 shows that "Use of rain and Storm Water" indicator has a highest influence of 0.15 in construction industry stakeholder, and the minimum negative of -0.14 in public group. All other indicators among different stakeholder groups have nearly neutral mean SHAP values.

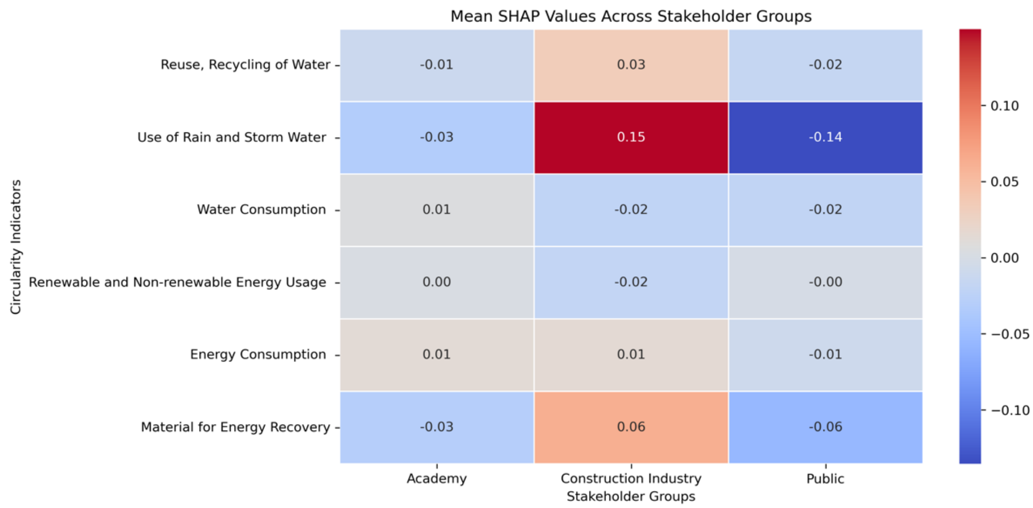

Figure 4.24. Mean SHAP value of "Water and energy consumption" indicators across stakeholder groups

Figure 4.25 assesses the significance of various indicators related to the provision of renovation services in building projects, with a focus on their role in promoting sustainable practices. Among these, "Safety During Service" is ranked the highest, underlining its vital importance in ensuring secure working conditions throughout renovations. This indicator stresses the need for effective safety measures to prevent accidents and comply with health and safety regulations. Likewise, "Worker Safety" is given high priority, reflecting the growing recognition of the well-being of those directly involved in renovation work.

Among the stakeholder assessments, the parameters of the category "renovation service provision", the relevance of all indicators were rated highly, more than 3.24, with the highest scores for “safety during service”, “quality of service “and “worker’s safety” indicators 4.19, 4.08 and 4.03. These critical indicators contribute minimizing disruptions, meeting requirements, reducing costs, and contribute to the overall effectiveness and sustainability of the renovation project.

"Client Satisfaction" is also highly ranked, emphasizing the need to meet the expectations and demands of stakeholders. A successful renovation not only achieves technical goals but also addresses client preferences, ensuring the project is usable and satisfying in the long term.

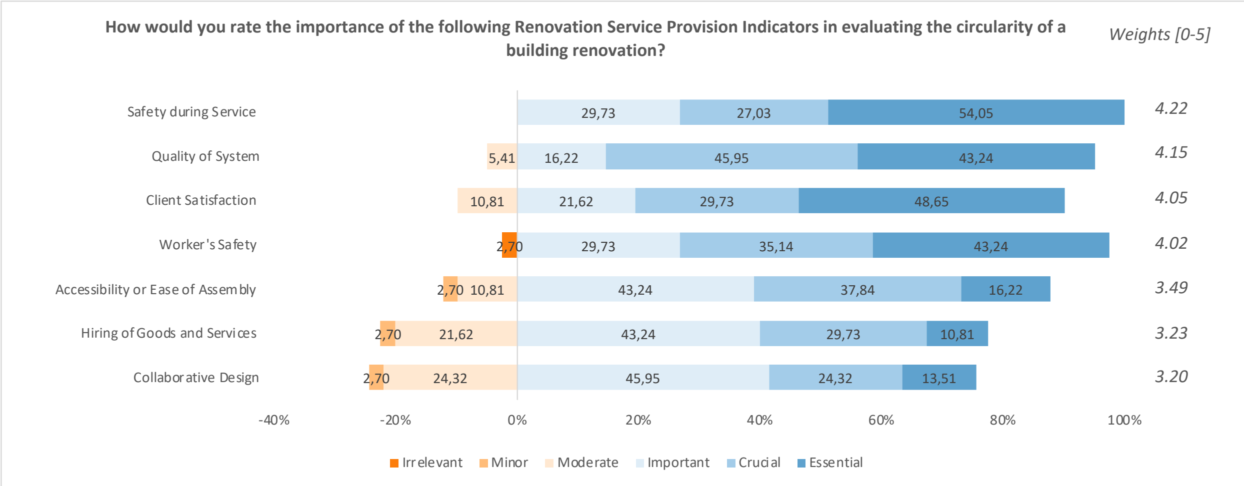

Figure 4.25. Relevance of "Renovation service provision" indicators

From Figure 4.26 it can be seen that

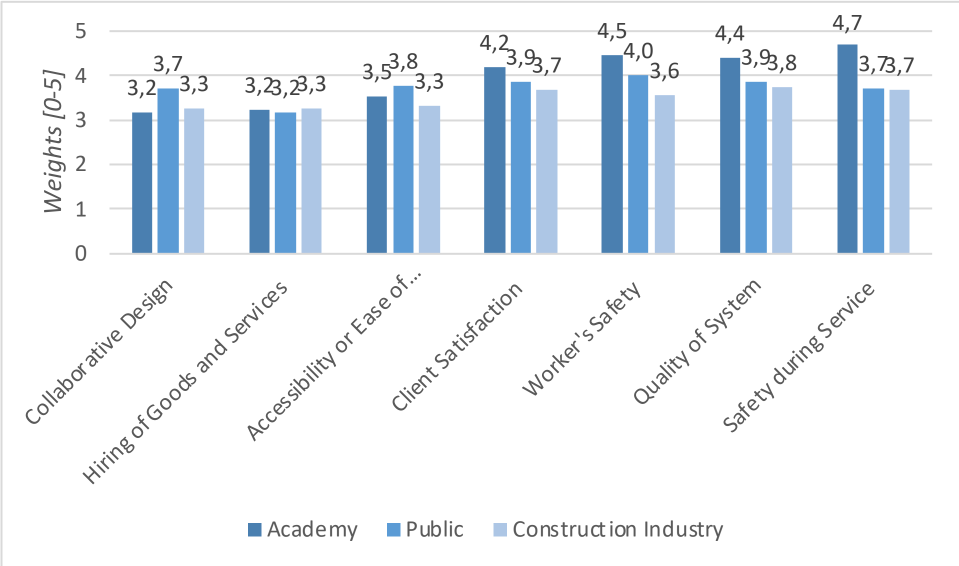

Figure 4.26. Weights of "Renovation service provision" indicators based on stakeholders

SHAP Value Analysis results for circularity indicators in "Renovation service provision" factor are shown in Figures 4.27 and 4.28. Based on the figure 4.27 it can be summarized that "Client Satisfaction" indicator has a significant impact on the model output. While "Quality of System" and "Safety during Service" factors shows lower contributions overall since they are clustering of values around zero.

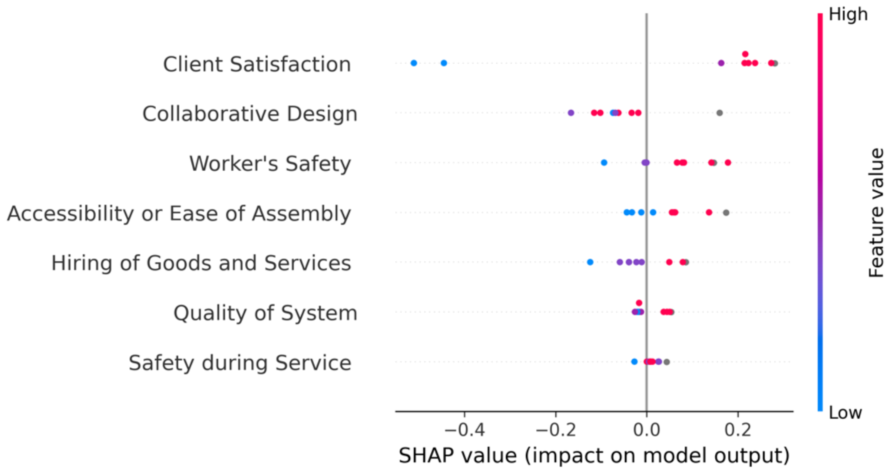

Figure 4.27. SHAP value analysis of "Renovation service provision" indicators

Figure 4.28 shows that the highest mean SHAP value belong to "Client Satisfaction" indicator from public stakeholder group, but it is the most negatively in construction industry group. All other indicators have neutral values near to zero among all other stakeholder groups.

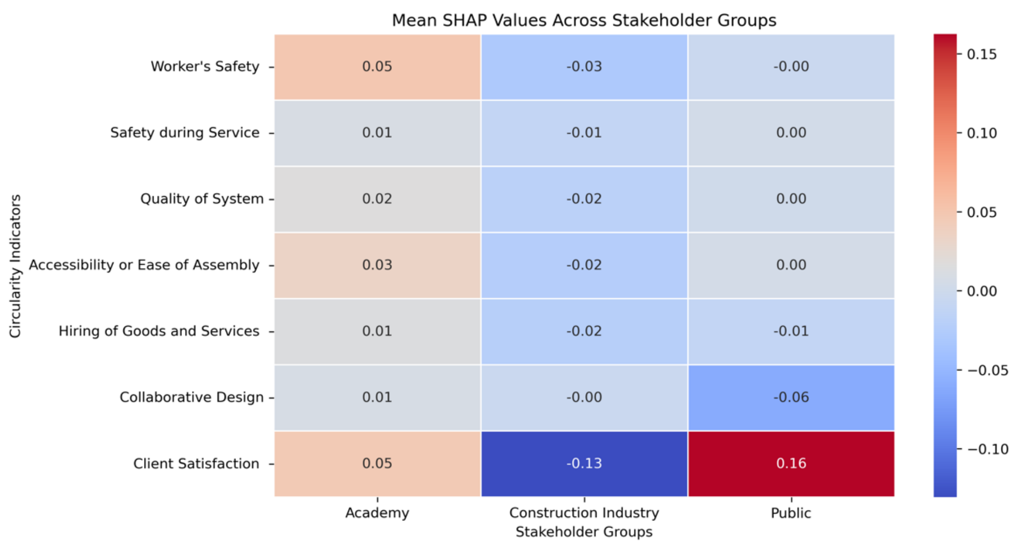

Figure 4.28. Mean SHAP value of "renovation service provision" indicators across stakeholder groups

4.3 Proposed framework

Based on the survey results and MS values, a hierarchical structure of the framework can be constructed, including a summary of weights which is shown in Table 4.3. Weights, assigned on a scale from 1 to 5, are allocated to both levels to reflect the relative importance of each factor and indicator as assessed by construction experts.

Table 4.3 presents a detailed and weighted framework for sustainable renovation practices, offering a structured and balanced method for project evaluation. This framework can be used by stakeholders, government to assess building renovation for circularity to make decision. By following this framework, stakeholders can assess the circularity during renovation work by looking at important points and can therefore make decisions to improve circularity.

Table 4.3. Hierarchical structure of the framework with weights based on construction experts' opinion

Level 1 (Factors)	Weights [1-5]	Level 2 (Indicators)	Weights [1-5]
Costs and Benefits	4.26	Materials Cost	4.10
		Material Transportation Cost	3.73
		Labor Cost	3.55
		Resale Value of Material	3.48
		Equipment Cost	3.33
		Deinstallation/Deconstruction/Dismantling Cost	3.25
		Maintenance Cost	3.23
		Waste Disposal Cost	3.13
		Operational Energy Cost	3.05
		Waste Separation and Storage Cost	3.03
		Material Recovery	2.88
		Energy Recovery	2.85
		Operational Water Cost	2.76
Material type and flow	3.95	Material Durability and Longevity	4.20
		Material Estimated Service Life	4.00
		Components for Reuse (Reusability)	3.49
		Human Toxicity Potential	3.44
		Renewable or Non-Renewable Material Usage	3.32
		Components for Recycle (Recyclability)	3.17
		Components for Recycle (Recyclability)	3.17
		Virgin Sourced Materials Usage	2.95
C&DW Management	3.77	Recoverable or Reusable Waste	3.58
		Hazardous or Non- Hazardous Solid Waste	3.35
		Unrecoverable Waste for Landfilling	3.33

		Toxic or Non-Toxic Liquid Waste	3.28
		Waste Separation and Storage	3.28
Building Functions and Services	3.74	Occupant Safety	4.27
		Performance	4.12
		Functionality	4.02
		Comfort	3.90
		Adaptability	3.37
		Flexibility	3.32
		Natural Light	3.07
Water and Energy Consumption	3.28	Energy Consumption	3.71
		Water Consumption	3.46
		Renewable Energy and Non-Renewable Energy Usage	3.44
		Reuse, Recycling of Water	3.39
		Materials for Energy Recovery	3.10
		Use of Rain and Storm Water	2.59
Renovation Service Provision	3.19	Safety during Service	4.22
		Quality of System	4.15
		Client Satisfaction	4.05
		Worker's Safety	4.02
		Accessibility or Ease of Assembly	3.49
		Hiring of Goods and Services	3.23
		Collaborative Design	3.20

Chapter 5 - Conclusion

5.1 Conclusion of results

Based on the obtained results, considering the survey data and the forecasts of the SHAP analysis, the following conclusions can be drawn:

- All stakeholder categories rated the factor "Cost and Benefits" as the most important in assessing circularity during building renovation, assigning it a score of 4.26. Under this factor, the following indicators were highlighted as especially important: "Labor Costs" (3.55) and " Materials Cost" (4.10).
- "Material Type and Flow" factor scored a noteworthy 3.95 being the next factor in the importance. In this group, the indicator "Material Durability and Longevity" had the highest individual score of 4.20. This indicates that stakeholders place a high value on characteristics such material strength, durability, and reusability.
- "C&DW Management" and "Building Functions and Services" are moderately important factors with almost equal scores (3.77 and 3.74, respectively). In particular, "Occupant Safety" (4.27) in the "Building Functions and Services" section was the highest rated indicator in the entire framework.
- In turn, "Water and Energy Consumption" with 3.28 and "Renovation Service Provision" with 3.19 were rated as the least important among the six main factors. However, "Safety during Service" (4.22) and "Quality of System" (4.15) in the "Renovation Services" category still received high scores at the indicator level, highlighting the importance of safety and quality even in lower-rated categories.

Overall, according to construction experts, cost efficiency, material sustainability and safety were the most valuable aspects of cyclical renovation.

5.2 Implications of the research

As the facts listed at the beginning of the chapter on the circular economy show, the construction industry is one of the first consumers of materials and produces waste during and after construction in large quantities, which leads to the filling of landfills, even though many of the waste and materials can be reused or recycled. The circular economy is a concept that can help the industry cope with these problems. The topic of circular economy is relatively new and even for developed countries it is still new and work and research on this topic is still ongoing due to lack of experience (De Silva et al., 2023b). Research on the topic of circularity in construction and its various forms is just being explored.

Renovation is one of the types of construction when an existing building undergoes work to improve its condition. This type also creates waste materials during operation. There is still little research on the topic of renovation, so this topic is relevant since renovation of an existing building is a good alternative to constructing a new building. Using the opinions of stakeholders, experts and their experience, the created tool can be further used to correctly assess circularity during renovation and use the right methods to reduce waste and consume small amounts of materials during work, which can reduce costs and create an enabling environment for construction.

The objective of this research work is to create a simple and quick to use framework for assessing the circularity in building renovation. This tool is based on stakeholder input and will consider 6 main proposed pillars, such as "material type and flow", "water and energy", "construction and demolition waste (C&DW) management", "cost and benefits", "building functions and services" and "provision of renovation services". The tool is flexible, allowing both the structure and the weighting system to be adjusted depending on the stakeholder request. In addition, it can be applied to both residential and non-residential buildings, since the main value is used in building renovation. In the future, this study will allow for an accurate assessment of the circularity in building renovation. This, in turn, will facilitate the selection of appropriate methods for the transition from a linear to a circular economy. This applies not only to construction companies, but also to other stakeholders interested in building renovation.

5.3 Limitations

For implementation of the framework the survey was conducted among different stakeholders in Kazakhstan. The respondents of the survey are from Kazakhstan, so the framework was created based on the Kazakhstan respondent's opinion. The framework can be used for other developing countries from Central Asia, since the situations in these countries and the standards are similar in these countries. Therefore, this framework cannot be assumed as standard framework and be used in developed countries, since situations and legislations in these countries differs from Kazakhstan.

For further research, the international survey can be conducted to make more standard framework that can be used for variety of countries and compare the differences in respondents. Moreover, more stakeholder categories can be observed to get different perspectives. The main stakeholders in sustainable building renovation and retrofitting include owners, facility managers, and occupants (Ástmarsson et al., 2013). This stakeholder categories can be included in survey for further work.

5.4 Summary of the thesis

In summary, the primary focus of the work conducted during this period, as presented in the paper, was the literature review, conducting survey, analysing results. This encompassed examining circular economy principles within the construction industry, building renovation, circular economy strategies in building construction and identifying circularity assessment factors and indicators for building renovation. The methodology section outlined the detailed research methods and their respective steps to be employed throughout the study.

In the results section, the factors and indicators for the study were presented and their relevance was discussed. In accordance with the factors and indicators, questions were prepared for the survey after the workshop, which was held to obtain the opinion of experts and stakeholders on their relevance. According to the schedule, the development of key indicators and questionnaires, as well as workshops, precedes the survey stage. In accordance with the schedule, all work was carried out, and the last stage of the study is the analysis of the data obtained and the creation of a framework.

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Appendicies

Appendix A.

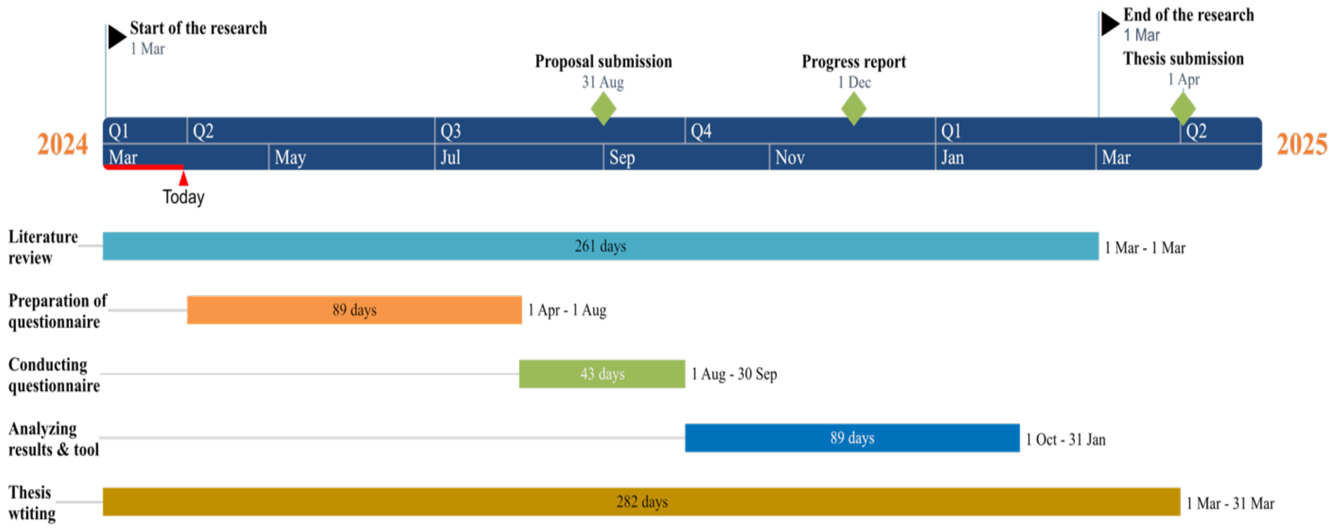

Figure 5.1. Research timeline

Appendix B.

1. Select the stakeholder category that you represent the best:

Academician/Researchers
Householders/End-user
Technician and/or Engineer
Government people/Policymakers
Contractor
Project manager
Environmental agency
Designer and/or Architect
Urban designer
Other, specify

2. How important are the following factors in evaluating the circularity of a building renovation?

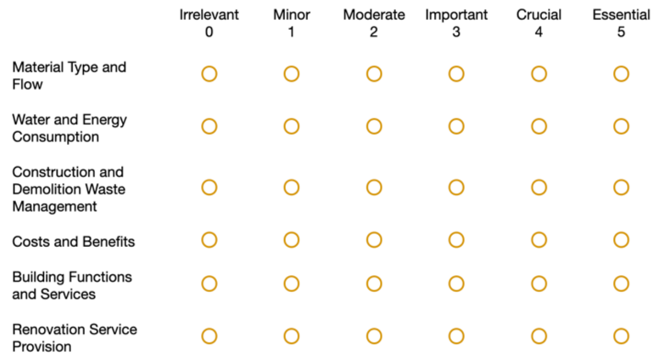

Figure 5.2. Answer choices for Q2

3. How would you rate the importance of the following Material Type and Flow Indicators in evaluating the circularity of a building renovation?

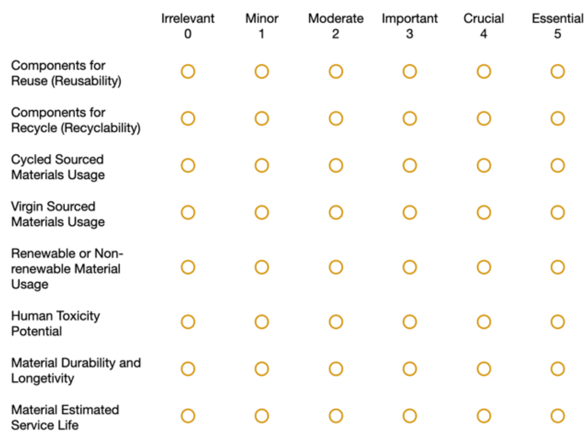

Figure 5.3. Answer choices for Q3

4. How would you rate the importance of the following Water and Energy Consumption Indicators in evaluating the circularity of a building renovation?

	Irrelevant 0	Minor 1	Moderate 2	Important 3	Crucial 4	Essential 5
Reuse, Recycling of Water	○	○	○	○	○	○
Use of Rain and Storm Water	○	○	○	○	○	○
Water Consumption	○	○	○	○	○	○
Renewable Energy and Non-Renewable Energy Usage	○	○	○	○	○	○
Energy Consumption	○	○	○	○	○	○
Material for energy recovery	○	○	○	○	○	○

Figure 5.4. Answer choices for Q4

5. How would you rate the importance of the following Construction and Demolition Waste Management Indicators in evaluating the circularity of a building renovation?

	Irrelevant 0	Minor 1	Moderate 2	Important 3	Crucial 4	Essential 5
Hazardous or Non-Hazardous Solid Waste	○	○	○	○	○	○
Toxic or Non-Toxic Liquid Waste	○	○	○	○	○	○
Recoverable or Reusable Waste	○	○	○	○	○	○
Unacceptable Waste for Landfilling/Disposal	○	○	○	○	○	○
Waste Separation and Storage	○	○	○	○	○	○

Figure 5.5. Answer choices for Q5

6. How would you rate the importance of the following Cost and Benefits Indicators in evaluating the circularity of a building renovation?

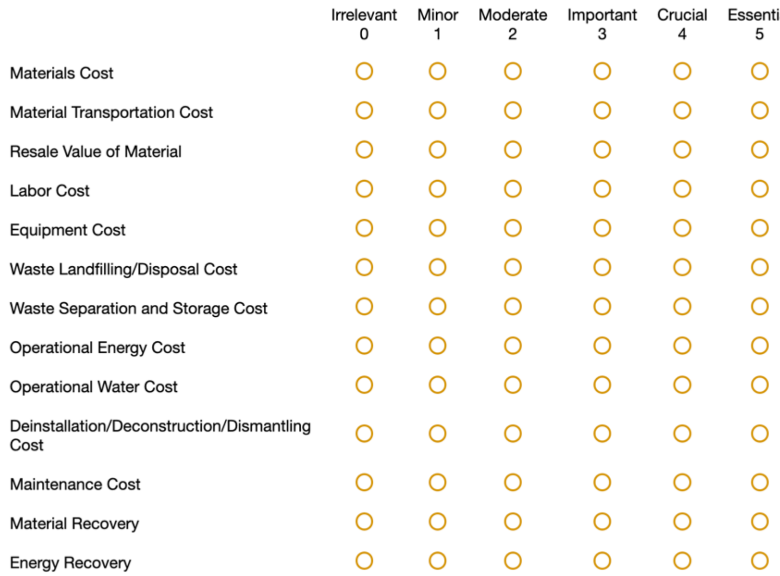

Figure 5.6. Answer choices for Q6

7. How would you rate the importance of the following Building Functions and Services Indicators in evaluating the circularity of a building renovation?

Figure 5.7. Answer choices for Q7

8. How would you rate the importance of the following Renovation Service Provision Indicators in evaluating the circularity of a building renovation?

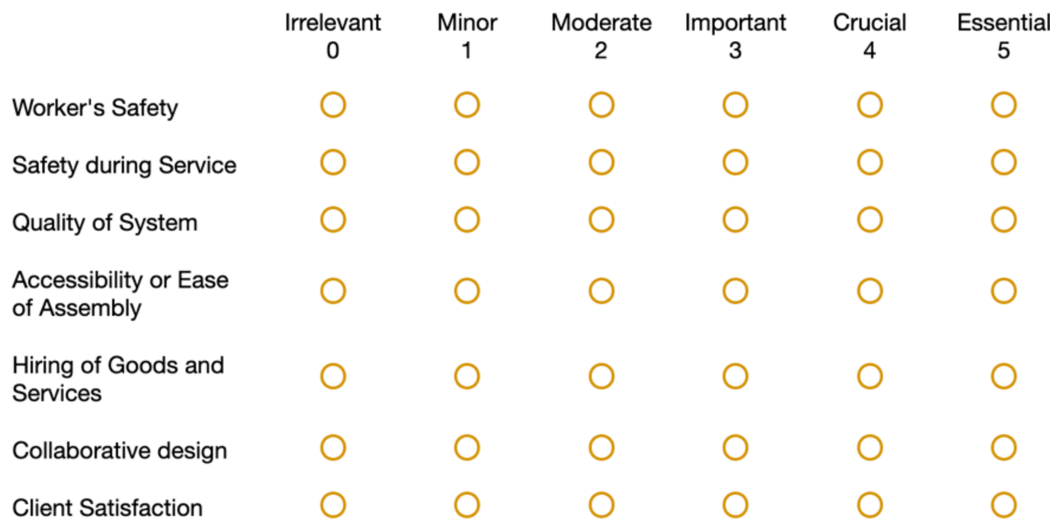

Figure 5.8. Answer choices for Q8

Appendix C.

Table 5.1. List of factors and indicators with references from literature review analysis

Factors	*Indicator*	*Freq.*	*References*
Material flow and type	Building components for reuse (reusability)	26	(Almeida et al., 2018; Bragança et al., n.d.; Buyle et al., 2019; Calvo-Serrano et al., 2020; Çetin et al., 2023; Dams et al., 2021; De Silva et al., 2023b; de Souza Rocha et al., 2024; Fernandes et al., 2022; Gilani et al., 2017; Göswein et al., 2022; Habibi et al., 2020; Jensen & Maslesa, 2015; Karaca et al., 2020; Kylili et al., 2016b; Lovrenčić Butković et al., 2023; Luís et al., n.d.; Masseck et al., 2024; Mazzoli et al., 2022; Riuttala et al., 2024; Saeed et al., 2023; Sanchez et al., 2019; Soto et al., 2020; Stoiljković et al., 2023; van Stijn et al., 2022; Wouterszoon Jansen et al., 2022)
	Building components for recycle (recyclability)	24	(Almeida et al., 2018; Bragança et al., n.d.; Buyle et al., 2019; Calvo-Serrano et al., 2020; Çetin et al., 2023; Dams et al., 2021; De Silva et al., 2023b; de Souza

			Rocha et al., 2024; Fernandes et al., 2022; Finch et al., 2021; Göswein et al., 2022; Habibi et al., 2020; Kosanović et al., 2021; Kylili et al., 2016b; Lovrenčić Butković et al., 2023; Luís et al., n.d.; Masseck et al., 2024; Mazzoli et al., 2022; Saeed et al., 2023; Sáez-de-Guinoa et al., 2022; Sanchez et al., 2019; Soto et al., 2020; van Stijn et al., 2022; Wouterszoon Jansen et al., 2022)
	Cycled sourced materials usage (secondary, recovered, non-virgin)	12	(Almeida et al., 2018; Bragança et al., n.d.; Dams et al., 2021; De Silva et al., 2023a; Fernandes et al., 2022; González et al., 2021a; Göswein et al., 2022; Kosanović et al., 2021; Kylili et al., 2016; Nußholz et al., 2023; Sáez-de-Guinoa et al., 2022; Wouterszoon Jansen et al., 2022)
	Virgin sourced materials usage	4	(De Silva et al., 2023a; González et al., 2021a; Mazzoli et al., 2022; Wouterszoon Jansen et al., 2022)
	Renewable or Non-renewable material usage	7	(Çetin et al., 2023; De Silva et al., 2023a; González et al., 2021a; Karaca et al., 2020; Nußholz et al., 2023; Stoiljković et al., 2023; Wouterszoon Jansen et al., 2022)
	Human toxicity potential from material	4	(Çetin et al., 2023; Dams et al., 2021; Finch et al., 2021; Wouterszoon Jansen et al., 2022)
	Material durability and longevity	6	(Buyle et al., 2019; Dams et al., 2021; Finch et al., 2021; Kosanović et al., 2021; Kylili et al., 2016; Stoiljković et al., 2023)
	Material estimated service life	2	(Buyle et al., 2019; Stoiljković et al., 2023)
Water and Energy	Reuse or recycle of wastewater	7	(Almeida et al., 2018; González et al., 2021a; Jensen & Maslesa, 2015; Karaca et al., 2020; Kylili et al., 2016b; Lovrenčić Butković et al., 2023; Soto et al., 2020)

	Use of rain and storm water	3	(González et al., 2021a; Karaca et al., 2020; Soto et al., 2020)
	Water consumption (Portable, freshwater resources)	8	(Gilani et al., 2017; González et al., 2021a; Göswein et al., 2022; Jensen & Maslesa, 2015; Karaca et al., 2020; Kylili et al., 2016; Nielsen et al., 2016; Vilches et al., 2017)
	Renewable energy or Non-renewable energy	3	(Foster et al., 2020; Göswein et al., 2022; Jensen & Maslesa, 2015)
	Energy consumption (electricity, thermal energy)	12	(Almeida et al., 2018; Calvo-Serrano et al., 2020; Gilani et al., 2017; González et al., 2021a; Habibi et al., 2020; Jensen & Maslesa, 2015; Karaca et al., 2020; Masseck et al., 2024; Mhatre et al., 2024; Nielsen et al., 2016; Sanchez et al., 2019; Stoiljković et al., 2023; Vilches et al., 2017)
	Materials used for energy recovery	3	(Buyle et al., 2019; Fernandes et al., 2022; Göswein et al., 2022)
C&DW Management	Hazardous or non-hazardous solid waste	2	(Göswein et al., 2022; Kylili et al., 2016)
	Toxic or non-toxic liquid waste	1	(Kylili et al., 2016)
	Recoverable waste or reuse of waste	4	(Fernandes et al., 2022; González et al., 2021a; Jensen & Maslesa, 2015; Soto et al., 2020)
	Unrecoverable waste for landfilling/disposal	4	(Fernandes et al., 2022; Kröhnert et al., 2022; Kylili et al., 2016; Vilches et al., 2017)
	Waste separation and storage	3	(Calvo-Serrano et al., 2020; Karaca et al., 2020; Mhatre et al., 2024)
Cost and Benefits	Materials cost	5	(Alba-Rodríguez et al., 2017; De Silva et al., 2023a; Masseck et al., 2024; Mollaei et al., 2023; Wouterszoon Jansen et al., 2022)
	Material transportation cost	5	(Calvo-Serrano et al., 2020; Mhatre et al., 2024; Mollaei et al., 2023; Saeed et

			al., 2023; Wouterszoon Jansen et al., 2022)
	Resale value of material	3	(Finch et al., 2021; Mhatre et al., 2024; Mollaei et al., 2023)
	Labor cost	6	(Alba-Rodríguez et al., 2017; Karaca et al., 2020; Kylili et al., 2016; Mhatre et al., 2024; Mollaei et al., 2023; Sanchez et al., 2019)
	Equipment cost	5	(Alba-Rodríguez et al., 2017; Çetin et al., 2023; Karaca et al., 2020; Mhatre et al., 2024; Sanchez et al., 2019)
	Waste landfilling/disposal cost	3	(Alba-Rodríguez et al., 2017; Mazzoli et al., 2022; Mollaei et al., 2023)
	Operational energy cost	5	(Alba-Rodríguez et al., 2017; González et al., 2021a; Karaca et al., 2020; Nielsen et al., 2016; Sanchez et al., 2019)
	Operational water cost	5	(Gilani et al., 2017; Habibi et al., 2020; Masseck et al., 2024; Nielsen et al., 2016; Saeed et al., 2023; Wouterszoon Jansen et al., 2022)
	Deinstallation/Deconstruction/Dismantling cost	6	(Gilani et al., 2017; Habibi et al., 2020; Masseck et al., 2024; Mazzoli et al., 2022; Nielsen et al., 2016; Saeed et al., 2023; Wouterszoon Jansen et al., 2022)
	Material recovery	1	(Mhatre et al., 2024)
	Maintenance cost	7	(Gilani et al., 2017; Habibi et al., 2020; Masseck et al., 2024; Mazzoli et al., 2022; Nielsen et al., 2016; Saeed et al., 2023; Wouterszoon Jansen et al., 2022)
	Energy recovery		
Building functions and services	Comfort	3	(Kylili et al., 2016; Nielsen et al., 2016; Masseck et al., 2024)
	Functionality	3	(Gilani et al., 2017; Karaca et al., 2020; Luís et al., n.d.)
	Performance	4	(Gilani et al., 2017; Habibi et al., 2020; Karaca et al., 2020; Masseck et al., 2024)
	Adaptability	4	(Karaca et al., 2020; Luís et al., n.d.; Nielsen et al., 2016; Sanchez et al., 2019)
	Flexibility	3	(Gilani et al., 2017; González et al., 2021a; Nielsen et al., 2016)

	Natural light	3	(Habibi et al., 2020; Karaca et al., 2020; Sanchez et al., 2019)
	Occupant Safety	5	(Habibi et al., 2020; Karaca et al., 2020; Kylili et al., 2016; Masseck et al., 2024; Nielsen et al., 2016; Sanchez et al., 2019)
Renovation Service Provision	Worker's safety	1	(Gilani et al., 2017)
	Safety during service	2	(Gilani et al., 2017; Habibi et al., 2020)
	Quality of service	2	(Kosanović et al., 2021; Mhatre et al., 2024)
	Accessibility & Ease of assembly	6	(Bragança et al., n.d.; Dams et al., 2021; Fernandes et al., 2022; Karaca et al., 2020; Masseck et al., 2024; Mazzoli et al., 2022)
	Toxicity of materials	5	(Çetin et al., 2023; Dams et al., 2021; Finch et al., 2021; Karaca et al., 2020; Wouterszoon Jansen et al., 2022)
	Hiring of goods and services	2	(Calvo-Serrano et al., 2020; Karaca et al., 2020)
	Collaborative design	-	*suggested by authors*
	Client satisfaction	-	*suggested by authors*