REINCARNATE

D2.2 – Circular decision making for extending the use life of real estate assets

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement n° 101056773. This document reflects only the author's view and the EU Commission is not responsible for any use that may be made of the information it contains.

Project Title	Reincarnation of construction products and materials by slowing down and extending life cycles.
Project Acronym	Reincarnate
Grant Agreement No	101056773
Instrument	Research & Innovation Action
Topic	HORIZON-CL4-2021-TWIN-TRANSITION-01-11
Start Date of Project	June 1, 2022
Duration of Project	48 months

Name of the deliverable	Circular decision-making for extending the use life of real estate assets
Number of the deliverable	D2.2
Related WP number and name	WP2
Related task number and name	Task 2.2: Building upgrade and renovation
Deliverable dissemination level	R — Document, report, PU - Public
Deliverable due date	31-5-2024
Deliverable submission date	31-5-2024
Task leader/Main author	Brian van Laar (TUD), Angela Greco (TUD), Hilde Remøy (TUD), Vincent Gruis (TUD)
Contributing partners	TUB, DMO, 3L, RAS, VIAS
Reviewer(s)	BAM

Abstract

This report introduces a circular decision-making framework aimed at extending the use life of real estate assets, developed as part of the Reincarnate project funded by the European Union's Horizon Europe program. The framework assists asset managers and building owners in making informed decisions about renovation scenarios, promoting sustainable practices and reducing construction and demolition waste. It is structured across three levels: initial intervention direction, development of renovation scenarios, and product-level decision-making for building components' end-of-life strategies. The report includes a hypothetical case study to demonstrate the application of the framework, while real-world applications will be documented in future Reincarnate demonstration projects. This decision-making process supports the transition towards a circular economy in the construction industry by providing systematic guidelines for extending the functional life of buildings and maximizing resource efficiency.

Keywords

Circular Decision-Making; Renovation; Circular Economy; Lifetime extension; Scenario Development

Revisions

Version	Submission date	Comments	Author
v0.1	17-5-2024	More focus is needed on the readability and structuring of the deliverable	BAM (BAM)
V0.2	22-5-2024	More clearly describe the process and integration with other tasks	TU Berlin (TUB)

Disclaimer

Acronyms and definitions

Acronym	Meaning
TRL	Technical Readiness Level
CP-IM	Circular Potential Information Management
CDW	Construction and Demolition Waste
MCDM	Multi-criteria Decision-making
EoL	End-of-Life
CBA	Circular Building Adaptability
CIB	Cross-Impact Balance
AHP	Analytical Hierarchy Process
CR	Consistency Ratio
CI	Consistency Index
RI	Random Index
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
FNIS	Fuzzy Negative Ideal Solution
CC	Closeness Coefficient

Reincarnate project

The average lifespan of a building is 39 years — in Europe, it is only 25-30 years — and the main reason for demolition is obsolescence. This is why there is a large amount of construction and demolition waste (CDW) — representing approximately 25-30% of all waste in Europe —, in addition to that generated in current construction works.

The recycling rate for CDW is relatively high (above 75%). This activity generated $126.89 billion in 2019 — Europe contributed the largest share, almost two-fifths of the total global market — and is projected to reach $149.19 billion by 2027. Unfortunately, many of the most valuable materials in CDW cannot be meaningfully separated and end up in landfills.

This helps to get an idea of the efficiency potential for climate neutrality that exists in construction.

Reincarnate aims at advancing circular economy practices within the European construction industry and enabling to significantly maximize the life cycle of buildings, construction products, and materials, reduce CDW by 80%, increase the reusability of buildings, construction products, and materials and, as a result, lower the sector's emissions by 70%.

As a result of these actions, Reincarnate will significantly advance circular economy practices within the European construction industry.

First, it will create a Circular Potential Information Management (CP-IM) platform and a set of innovations to use it. These solutions will draw upon emerging digital technologies, such as digital twin representation, artificial intelligence, and robotic automation.

3 empirically proven social science insights will allow fostering widespread adoption of reused high-quality construction products and materials, and business eco-system development frameworks to combine actors within sustainable value chains. All innovations will be demonstrated on eleven selected real-world projects and value chains. Furthermore, business process guidelines and an e-learning platform will be developed to drive the dissemination and exploitation of the Reincarnate results.

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Introduction

The construction industry is on the verge of a significant transformation driven by the growing demand for sustainability and advancements in digital technology. To propel the sector towards a circular economy, it is essential to develop innovations that enhance the utilization of construction and demolition waste, establish new value chains and sustainable business models, reduce CO2 emissions, and boost the EU construction market's independence in the global market for construction products and materials. This report for Deliverable 2.2 in the Reincarnate project introduces a circular decision-making framework designed to extend the use life of real estate assets.

It was created in collaboration with the Reincarnate partners: Technical University of Berlin (TUB), Demo Consultants (DMO), 3L (3L), RagnSells (RAS), and Vias Construction (VIAS). This collaboration under the Reincarnate umbrella has enabled the development of a systematic circular decision-making framework that assists stakeholders in building renovation projects to determine the most appropriate intervention scenario. Deliverables 2.2 and 3.1 together aim to form an innovation in strategic circular decision-making for real estate assets at a Technical Readiness Level (TRL) of 4-6. These deliverables address tasks 2.2 and 3.1 of the Reincarnate project, which has the following objectives: to enable asset managers and decision-makers to avoid construction waste by extending the lifetime of buildings and adapting them to new uses, by utilizing the Circular Potential Information Management (CP-IM) platform.

A comprehensive decision-making approach to renovating buildings with the primary goal of extending their functional lifetime is presented consisting of three decision-making levels. In the first level, a decision-making framework is proposed that can determine the 1st intervention direction of a building based on its current status. This will help building owners and asset managers understand how their building can be upgraded to changing requirements across a real estate portfolio. The 2nd decision-making level is concerned with the development and decision between different renovation scenarios that show possibilities to reuse real estate spaces for different purposes. In the 3rd level, a product-specific decision-making model is proposed that can help find new reuse purposes for building products in a systematic way.

After selecting an appropriate renovation scenario using the 2nd level decision-making model and determining the end-of-life options for building products, a future-oriented building management plan methodology is presented that can be used for the continuous upgrade of buildings throughout their lifecycle based on the lifecycle predictions of task: *3.1 Predictive Life-Cycle Information*[1]. Finally, a methodology is presented that allows for assessing how much waste can be reduced by extending the functional life of buildings.

This report details the scope and limitations of the research conducted. At this stage, the methodologies and concepts are primarily theoretical and remain at a conceptual level. Consequently, the results discussed have not yet been practically tested. However, future testing is planned for various demonstration cases, as outlined in Section 5, which will provide empirical data to validate the findings and methodologies presented in this report.

[1] https://www.reincarnate-project.eu/innovations/

1. Proposed decision-making framework for extending the use life of real estate assets

1.1. Aim and objective of the decision-making framework

The decision-making framework for extending the use life of real estate assets aims to provide asset managers and building owners with potential renovation concepts to extend the lifespan of buildings through various renovation scenarios. This framework organizes the development and decision-making process for renovation scenarios, allowing stakeholders to explore adaptive reuse and renovation options at three different decision-making levels: the initial level establishes the first intervention direction, the second level develops and decides on renovation scenarios, and the third level identifies the most suitable End-of-Life (EoL) strategy for building products. Based on the chosen interventions, a building management plan can be drawn up that allows continuous upgrades of buildings throughout their lifecycle.

The framework starts with a functionally obsolete building that no longer meets the stakeholders' current requirements, necessitating an intervention. Deciding on the type of intervention (renovation, adaptive reuse, deconstruction, etc.), the appropriate scenario, and how to implement it in a circular manner can be challenging. This report aims to assist asset managers and building owners by providing a step-by-step decision-making process guideline to address these challenges effectively.

1.1.1. Stepwise decision-making process guideline

The proposed stepwise structure for the Reincarnate decision-making framework aimed at extending the lifetime of real estate assets is illustrated in Figure 1. This approach includes nine steps distributed across three levels of decision-making. A brief overview of the three levels is provided here, with a more detailed explanation available in sections 2.2, 2.3, 2.4, and 2.5. The decision-making framework presented in this deliverable shares a lot of similarities with the decision-making framework for deliverable *3.1: Circular decision-making for adaptive refurbishment and renovation of real estate assets*[2], as they both correspond to the same innovation: *7. Strategic circular decision-making for real estate assets*. Some parts of the framework are more elaborately explained in deliverable 3.1.

[2] https://www.reincarnate-project.eu/innovations/

1st level decision-making framework – first intervention direction

At the first level, the building is evaluated based on its current condition, utilization, and potential reward. This assessment helps determine the initial intervention direction. The 1st level decision-making framework, which is consistent for both deliverables 2.2 and 3.1, guides stakeholders towards one of three paths: the adaptive reuse decision-making framework (deliverable 3.1), the renovation decision-making framework, or the product-level decision-making framework, depending on the building's characteristics.

2nd level decision-making framework(s) – renovation scenarios

After selecting an initial intervention direction from the 1st level decision framework, stakeholders proceed with either the renovation decision-making framework (deliverable 2.2) or the adaptive reuse decision-making framework (deliverable 3.1). In this stage, stakeholders first identify the objectives and criteria that are important for their future project. Based on these objectives, they can either develop their own scenarios or opt for the default scenarios. Finally, stakeholders quantify their preferences, allowing for a final performance ranking of the scenarios.

3rd level decision-making framework – product-level decision-making

The 3rd level decision-making framework focuses on determining the subsequent lifecycle of building products. Following the selection of a scenario in step 2, requirements are established to identify which products will remain in the building and which will need repurposing. The future use of these building products is then determined using the product-level decision-making framework described in Section 2.4. This framework can also be applied independently of the other levels. A detailed practical example of the 3rd level decision-making framework is provided in Section 3.3.

Comparison on a building portfolio level

Once a decision is made on all three levels, stakeholders have a good understanding of what interventions, both on a building and product level, need to be undertaken. A building management plan can then be drawn up that portrays the interventions over time, making it easier to allow for the continuous upgrade of buildings throughout their life cycle. Based on the scenarios and interventions chosen, stakeholders can also compare their building on a portfolio level in terms of waste reduction, using the methodology in Section 2.4.3.

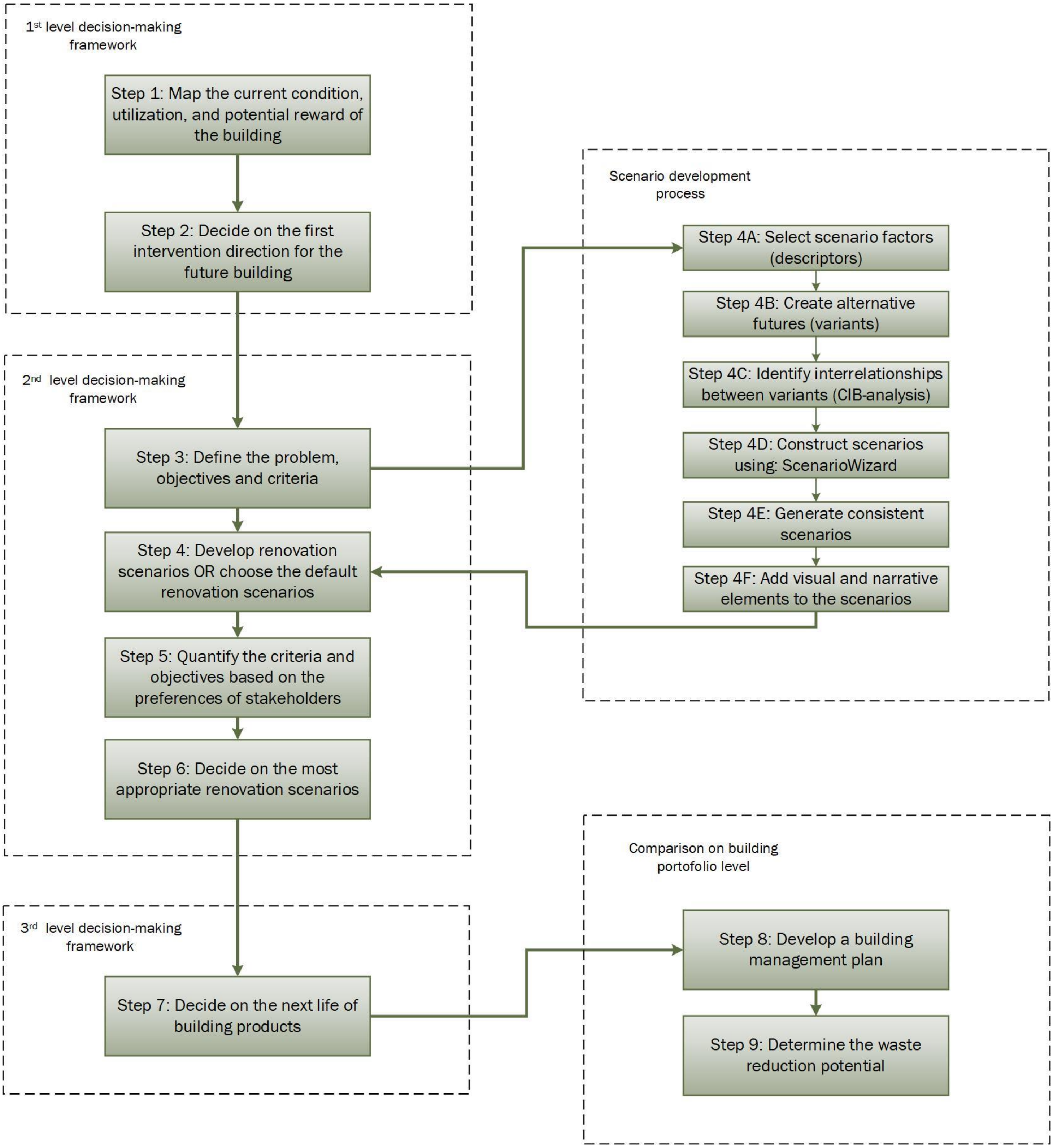


Figure 1: The proposed decision-making framework for the extending the use life of real estate assets

1.2. 1st level decision-making framework – first intervention direction

1.2.1. Adapted IconCUR model

For the initial decision at the 1st level between different intervention options, we adapted the IconCUR model developed by Langston & Smith (2012) for our decision-making framework (Langston & Smith, 2012). The IconCUR model is a conceptual tool designed to improve decision-making regarding the management of built facilities, especially in the early stages of the process. It uses a weighted matrix methodology to evaluate the performance of built assets based on three key factors: condition, utilization, and reward. These factors are assessed to generate performance scores, which are then used to map potential property management decisions in a three-dimensional space over time (see Section 2.2.3, and Figure 2).

The model's application facilitates a practical approach to decision-making through an adaptive management philosophy, allowing property managers to quickly assess, identify, and rank opportunities based on their potential value (Langston & Smith, 2012). This is accomplished by spatially presenting decisions, enabling an objective measurement of the distance between current property performance and the optimal decision points that define the model's cubic boundaries. The IconCUR model thus proves to be a valuable tool in property management by emphasizing the swift assessment and ranking of decisions, demonstrating its practicality and adaptability in real-world settings.

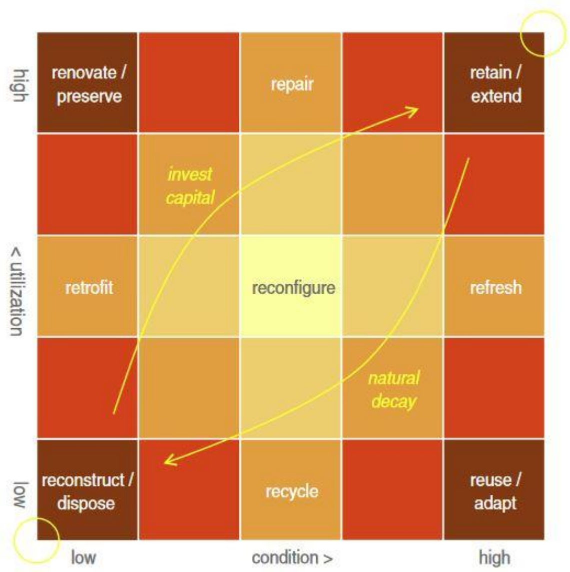


Figure 2: The IconCUR conceptual framework for building intervention decisions (Langston & Smith, 2012)

1.2.2. Step 1: Map the current condition, utilization, and potential reward of the building

The first step in the decision-making framework involves assessing the building's current state in terms of condition, utilization, and potential reward using the adapted IconCUR assessment worksheet (Appendix 1). This worksheet evaluates four main criteria—condition, utilization, collective utility, and stakeholder interest—using a weighted matrix method. Each criterion includes key sub-criteria and elements, both assigned weights based on their importance and impact. The 1st level decision-making framework is more elaborately explained in deliverable 3.1, but a short description is given below.

- **Condition**

  Condition assesses the building's physical characteristics, covering design standards, maintained service levels, and regulatory compliance across five elements: structure, exterior envelope, interior finishes, engineering systems, and external works.

- **Utilization**

  Utilization evaluates the building's occupancy characteristics, including demand, fitness for purpose, and user satisfaction, considering elements like internal space, external space, outdoor site area, equipment and fitout, and engineering systems.

- **Reward**

  Reward measures the collective utility received from the building, incorporating economic performance, culture and heritage, and environmental values, while factoring in stakeholder interest across short, medium, and long-term perspectives.

Using a five-point Likert scale, stakeholders assess each criterion and element. The assessment can be conducted individually or in a workshop setting. Combined scores are calculated to position the building on the 1st level decision-making matrix (see Section 2.2.3). This matrix uses condition and utilization on the axes to determine the initial intervention direction, adaptable to specific regional requirements.

1.2.3. Step 2: Decide on the first intervention direction

Step 2 of the decision-making framework focuses on selecting the best intervention strategy for the current building. Unlike the original IconCUR model, which includes nine intervention options (Langston & Smith, 2012), this framework simplifies the choices into four main options: Deconstruct, Adaptive Reuse, Renovation, and Retain. Based on the building's current condition and utilization, the project is plotted on the 1st level decision-making matrix (Figure 3). The scale for all axes is categorized as follows:

- 0–1 (very low)
- 1–2 (low)
- 2–3 (moderate)
- 3–4 (high)
- 4–5 (very high)

The building's position within the matrix helps assess and rank properties in a portfolio based on their spatial coordinates relative to the corner options. For example, buildings positioned closer to the adaptive reuse corner indicate a stronger inclination towards this type of intervention. Implementing the chosen intervention shifts the building's position within the matrix, ideally enhancing its value across all three coordinates. A significant shift from old to new coordinates indicates a more impactful decision, with increased values suggesting higher anticipated success. An effective intervention would move the building's coordinates closer to the retain/extend corner, symbolizing a high reward. The four intervention options are detailed below.

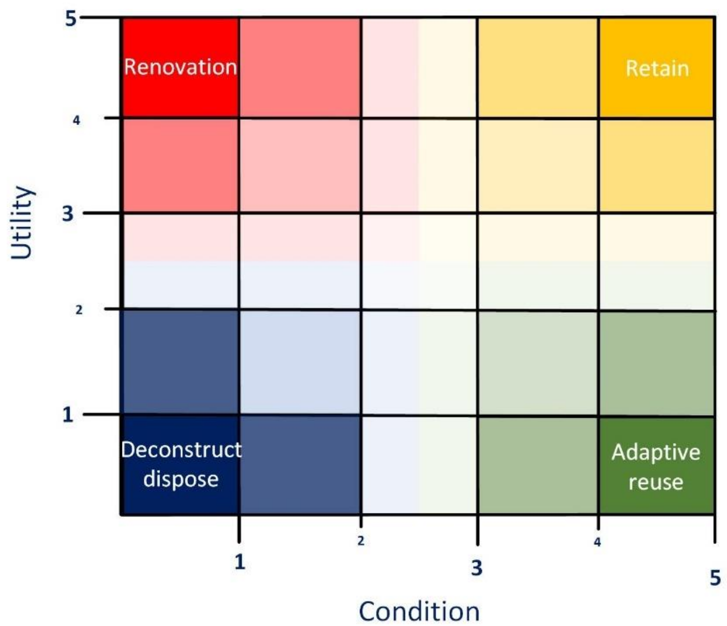


Figure 3: The 1st level decision-making matrix, adapted from the IconCUR model by (Langston & Smith, 2012)

Retain

If both the condition and utilization of the building score high (3-5), the building will be positioned in the top right corner of the matrix. This indicates strong demand for the building in its current use, suitability for its intended purpose, and high user satisfaction. A high condition score signifies that the building meets high design standards, is well-maintained, and complies with regulations. In this scenario, no physical intervention is necessary, and the building should be retained. However, operational strategies to enhance Circular Building Adaptability (CBA), as outlined by Hamida et al. (2023), could still be applied (Hamida et al., 2023).

Deconstruct

If both the condition and utilization of the building score low, the building is placed in the lower left corner of the matrix (Deconstruct). This indicates no demand for the building, it is not fit for purpose, and it fails to meet maintenance and regulatory standards. Essentially, the building can no longer function effectively and needs to be deconstructed. However, as the building still contains valuable materials and products, the product-level decision-making model (Section 3.4.7) should be consulted. This framework evaluates the circularity potential of building products and helps determine new uses for them. In this case, stakeholders move directly from the 1st level decision-making framework to the 3rd level, bypassing the 2nd level, since the building will no longer be used as a building. A detailed description of the 3rd level decision-making framework is available in Section 3.4.

Renovation

When the building scores relatively high on utilization but low on condition, it is placed in the top left corner (Renovation). This indicates that the building is suitable for its original function, there is demand for this function, and users are relatively satisfied. However, the building's condition needs improvement. This may be due to outdated systems, inadequate maintenance, or failure to meet regulatory standards or user needs. In this scenario, the 2nd level decision-making framework for renovation, detailed in Section 3.3.3, should be used to determine the best renovation strategy.

Adaptive reuse

When the building's condition scores relatively high but its utilization scores relatively low, it is placed in the bottom right corner (Adaptive reuse). This indicates that the building is in good physical condition but is either not fit for its original function, lacks demand for its current function, or has low user satisfaction. In this scenario, changing the building's function could enhance its utilization, making adaptive reuse a viable option. Once adaptive reuse is identified as the best option through the 1st level decision-making framework, the 2nd level framework can be used to determine the most suitable adaptive reuse scenario, as detailed in deliverable 3.1.

1st level decision-making framework – decision analysis

After assessing the building's current condition and utilization, an intervention decision can be made using the 1st level decision-making matrix. While the matrix is presented as a 2D model, the third dimension 'reward' is used for validation. Reward measures the potential value added post-intervention. A high reward score indicates minimal opportunity for improvement and value addition, suggesting that another intervention might be considered. Conversely, a low reward score signifies substantial room for improvement and high-value addition, making the intervention more favorable. When a building is firmly within one of the quadrants (close to the corner) and has a low reward score, this intervention option is generally considered appropriate (Langston & Smith, 2012). The closer the building is to a corner in the matrix, the higher the certainty of the intervention decision.

The 1st level decision-making framework is a conceptual tool to help practitioners identify the most suitable intervention direction. However, it is essential to remember that such models are guides, not prescriptive solutions. Stakeholders are not obligated to follow the model's outcomes strictly; it is designed to assist them in finding the best intervention direction based on their input.

1.3. 2nd level decision-making framework – Renovation scenarios

Once the decision to renovate has been made using the 1st level decision-making framework, the 2nd level decision-making framework is applied. This second level focuses on determining the most suitable renovation scenario based on stakeholders' wants and needs. It translates future objectives and requirements into specific renovation plans, making it more future-oriented compared to the 1st level, which assesses the building's current condition and utilization.

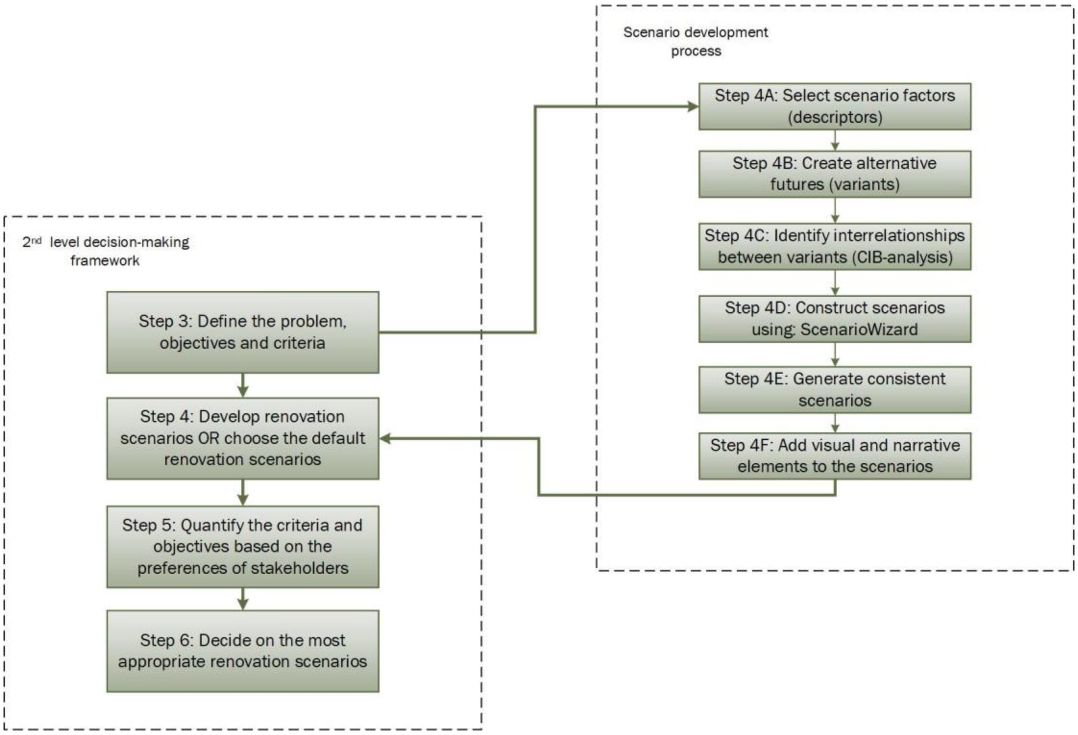


Figure 4: The stepwise approach to the 2nd level decision-making framework and scenario development process

The 2nd level decision-making framework employs a multi-criteria decision-making (MCDM) approach. MCDM is a systematic method used to evaluate and select the best alternative from a set of options in complex decision scenarios (Cinelli et al., 2020). While various MCDM methods exist, they generally follow common steps to reach a final decision. The key steps in a typical MCDM framework, which contribute to effective decision-making, are explained in the next section.

1.3.1. Step 3: Define the problem, objectives, and criteria

The decision-making framework incorporates a set of specific objectives designed to assist stakeholders in effectively representing the important aspects of their project. These objectives, outlined below, were taken from deliverable 7.1 from the EU Horizon Project: BIM Speed[3]. The list of objectives consists of 9 objectives spread out of 3 main categories: Environmental, Social and Economic. These objectives and criteria are both used for the development of scenarios in Section 2.3.2, as well as the decision-model outlined in Section 2.3.3.

Table 1: The criteria and objectives used for the decision-making framework

Main criteria	Objectives
Environmental	To reduce primary energy
	To reduce energy demand
	To reduce environmental impact
Social	To improve indoor conditions
	To increase social acceptance
	To increase social technical benefits
Economic	To reduce cost
	To reduce operational and maintenance cost (O&M)
	To increase financial benefits

[3] https://www.bim-speed.eu/en/results

1.3.2. Step 4: Develop renovation scenarios OR choose the default renovation scenarios

For developing scenarios in this multi-criteria decision-making framework, the Cross-Impact Balance (CIB) analysis is utilized. CIB analysis is a method used in future studies and scenario development to evaluate how various events, decisions, or trends influence each other within a system (Weimer-Jehle, 2023). This method is particularly effective in constructing robust and coherent scenarios by systematically assessing the mutual impacts of different elements, such as economic conditions, technological changes, or policy shifts (Weimer-Jehle, 2023).

CIB is especially useful for developing normative scenarios, which reflect desired or targeted futures rather than merely extrapolating current trends. Its strength lies in ensuring internal consistency among the elements of a scenario, helping align the components towards a common end state, and providing strategic guidance on achieving specific future goals. A detailed description of the CIB method for scenario development can be found in deliverable 3.1, while default renovation scenarios are provided as practical examples in Section 3.2.1.

The following approach can be used for scenario development through the CIB method:

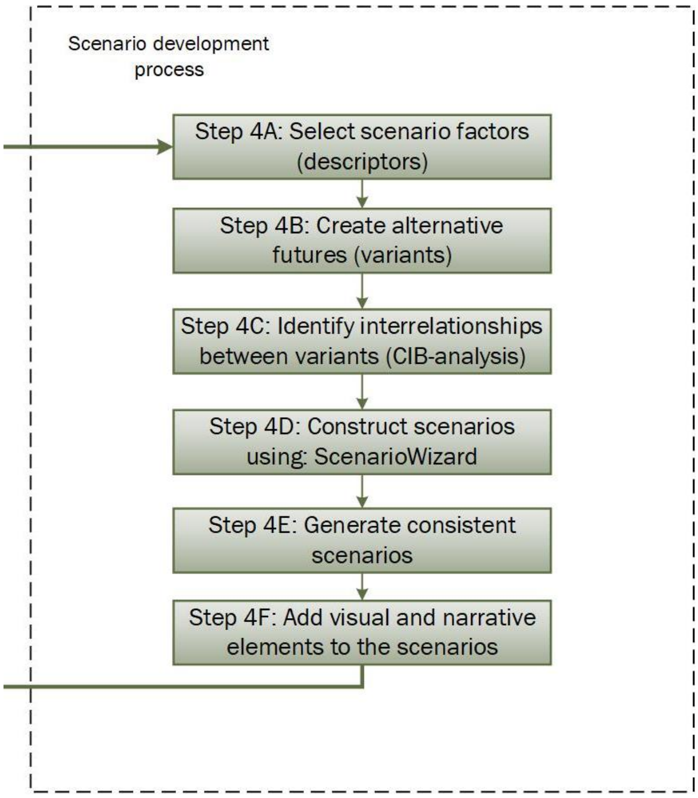


Figure 5: The scenario development process

1.3.3. Step 5: Quantify the objectives and criteria based on the preferences of the stakeholders

After formulating objectives and criteria and generating scenarios, the next step in the decision-making process is to capture stakeholders' importance ratings for each objective. To select the most appropriate renovation scenario, it's crucial that stakeholder preferences are accurately reflected in the decision model outcomes. This involves weighting the objectives and criteria based on their importance.

In multicriteria decision-making, selecting an appropriate weighting method is essential for accurately reflecting the importance of each criterion. Among various methods, the Analytical Hierarchy Process (AHP) is preferred for its structured, hierarchical approach (Saaty, 1990). AHP facilitates systematic comparison of criteria and incorporates stakeholder judgments comprehensively. It also checks the consistency of these judgments, ensuring reliability (Saaty, 1990).

We chose AHP to achieve a balanced and substantiated decision framework suited to the complex nature of renovation projects. The AHP method involves three steps: pairwise comparison of criteria and objectives, computing the weights and checking consistency (Zardari et al., 2015). A detailed description of how the Analytical Hierarchy Process works in relation to scenarios can be found in deliverable 3.1. A brief description of the steps is provided below:

Pairwise comparison (AHP)

To weigh the criteria and objectives, their relative importance must be evaluated using the 9-point Likert scale developed by Saaty (1990) (Figure 6). Stakeholders assess each pair of criteria using this scale, which ranges from 1 to 9: 1 signifies equal importance, and 9 indicates extreme superiority of one element over the other. Intermediate values represent varying levels of importance between these two extremes.

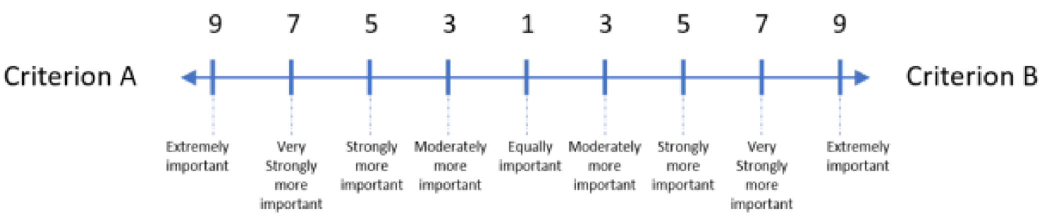


Figure 6: Comparison scale for the pairwise comparison adapted from (Si & Marjanovic-Halburd, 2018)

Computing the weights of objectives

the next step is to derive the weights by normalizing the values within each column to reflect the relative importance of each criterion. This process involves summing the values in each column 'i', then dividing each element a_{kj} by the column total, $\sum \boldsymbol{a_{kj}}$ for $\boldsymbol{n}$ iterations. Finally, the normalized scores for each row 'j' are summed and then divided by the number of criteria 'n' to compute the weights for each matrix. The normalized scores are then aggregated to determine the final weights.

$$w_k = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \; for \; k = 1,2,3,\ldots,n \tag{1}$$

Checking the consistency

In the Analytical Hierarchy Process, the consistency check is crucial for ensuring decision reliability and accuracy (Saaty, 1990). It measures how logically consistent the decision-maker's judgments are in pairwise comparisons. The consistency ratio (CR) is used for this check, comparing the consistency index (CI) to the random index (RI), which reflects expected consistency by chance (Table 2). A CR below 0.10 indicates acceptable consistency, while a CR above 0.10 suggests the need for review.

Table 2: Random Index (RI) for different number of criteria

Number of criteria / objectives	RI
2	0
3	0.58
4	0.9
5	1.12

For example, if a stakeholder ranks "Primary energy" higher than "Energy demand" and "Environmental impacts" higher than "Primary energy," they should logically rank "Environmental impacts" the highest. The CR assesses this logical consistency. Each matrix and stakeholder group should undergo this check to ensure decision-making accuracy. The consistency ratio CR is defined as follows:

$$CR = \frac{CI}{RI} \tag{2}$$

Where CI is the Consistency Index, and RI is the Random Index. The RI values, shown in Table 1, are based on the number of criteria. The CI is calculated as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

Here, λ_{max} is the maximum eigenvalue of the comparison matrix. Ensuring consistency prevents invalid judgments and promotes robust decision-making, maintaining stakeholder trust and achieving optimal outcomes.

1.3.4. Step 6: Decide on the most appropriate renovation scenario

After capturing stakeholders' preferences and weighting objectives, the next step is to evaluate the renovation scenarios based on these preferences. This final phase of the multicriteria decision-making framework involves decision analysis. Each scenario's performance against the objectives is combined with the assigned weights to generate a global performance score, which helps rank the scenarios and streamline the final decision. A detailed description of step 6 is provided in deliverable 3.1 but a brief description of the process is provided below.

Various methods can integrate these scores, such as simple additive aggregation, Analytical Hierarchy Process, Promethee, and TOPSIS (Zanakis et al., 1998). For this MCDM framework, the Fuzzy TOPSIS method is chosen. Fuzzy TOPSIS is ideal for scenarios with uncertainty or ambiguous data (Dymova et al., 2013). Unlike traditional TOPSIS, it uses fuzzy sets to handle imprecise information, making it suitable for subjective judgments and incomplete data. It selects the best alternative based on the distance from an ideal solution and the proximity to a negative solution (Dymova et al., 2013).

Fuzzy TOPSIS is particularly useful for qualitative renovation scenarios, which can have weak, medium, or strong variants across 9 descriptors (see Section 3.2). The following steps outline the Fuzzy TOPSIS method:

- Define the decision matrix
- Construct the decision matrix with fuzzy ratings.
- Normalize the fuzzy decision matrix.
- Calculate the weighted normalized fuzzy decision matrix.
- Determine the fuzzy positive and negative ideal solutions.
- Compute the distance of each alternative from these ideal solutions.
- Calculate the closeness coefficient for each alternative.
- Rank the scenarios based on these coefficients.

Define the decision matrix

Start by constructing a decision matrix D, where each row represents a scenario and each column represents an objective. Let m denote the number of scenarios and n denote the number of objectives (Equation 4). An example of a decision matrix can be found in Table 3.

$$\boldsymbol{D} = \begin{pmatrix} \boldsymbol{X_{11}} & \cdots & \boldsymbol{X_{1n}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{X_{m1}} & \cdots & \boldsymbol{X_{mn}} \end{pmatrix} \qquad (4)$$

Transform the decision matrix into a fuzzy decision matrix - Fuzzification

To convert the decision matrix into a fuzzy decision matrix, start with a matrix containing linguistic variables. For renovation scenarios, this includes strong, medium, or weak variants for each objective. To transform these linguistic variables into fuzzy variables, use a triangular fuzzy method. This method represents the range of the linguistic variable with a minimum value, maximum value, and most common value on a 1-9 scale (Xu, 2007). Tables 3-5 show an example of this fuzzification process, where linguistic variables are converted into fuzzy numbers.

Table 3: an example decision matrix with linguistic variables

	Scenario 1	Scenario 2	Scenario 3
Environmental Impact	Strong	Weak	Weak
Indoor Environmental Quality	Strong	Strong	Weak
Cost	Weak	Medium	Strong

Table 4: An example conversion table for converting linguistic variables into fuzzy numbers

	Minimum value	Most common	Maximum value
Weak	1	3	5
Medium	3	5	7
Strong	5	7	9

Table 5: An example fuzzy decision matrix

	Scenario 1			Scenario 2			Scenario 3		
Environmental impact	5	7	9	1	3	5	1	3	5
Indoor environmental quality	5	7	9	5	7	9	1	3	5
Cost	1	3	5	3	5	7	5	7	9

Normalize the decision matrix

To normalize a fuzzy decision matrix, various methods can be used to convert all values to a common scale, typically [0,1] (Xu, 2007). A common method involves dividing each fuzzy number by the maximum fuzzy number in its column. This ensures that the highest value in each criterion is normalized to one, preserving the relative proportions and inherent uncertainty of the original data. This allows for equitable aggregation and comparison across different objectives and scenarios. The normalization is based on the highest value in each column, as shown in Table 5, using the following Equation:

$$x_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)} \tag{5}$$

Construct the weighted normalized decision matrix

For the construction of the weighted normalized fuzzy decision matrix the objective weights from the pairwise comparison are used (see section 3.4.5). To form the weighted matrix the weights are multiplied with the normalized fuzzy numbers to generate the weighted normalized decision matrix.

Determine Fuzzy Ideal and Negative-Ideal Solutions

In the Fuzzy TOPSIS method, the concepts of the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) are crucial for ranking alternatives. The FPIS represents the optimal fuzzy values for each objective, while the FNIS represents the least desirable fuzzy values (Xu, 2007). These solutions are created by identifying the best and worst fuzzy scores across all criteria. Each alternative's proximity to these ideal solutions is then calculated to determine its rank. The alternative closest to the FPIS and farthest from the FNIS is considered the best option.

FPIS (A*): The FPIS is calculated by selecting the best values for each objective from the set of scenarios. If x_{ij} represents the fuzzy evaluation of the i-th alternative with respect to the j-th criterion, the FPIS for each criterion can be represented as:

$$A_j^* = \begin{cases} max_i x_{ij} \text{ if the criterion is beneficial} \\ min_i x_{ij} \text{ if the criterion is non} - \text{beneficial} \end{cases} \tag{6}$$

FNIS (A−): Conversely, the FNIS is determined by selecting the worst values for each objective. If x_{ij} represents the fuzzy evaluation of the i-th alternative with respect to the j-th criterion, the FNIS for each criterion can be represented as:

$$A_j^- = \begin{cases} min_i x_{ij} \text{ if the criterion is beneficial} \\ max_i x_{ij} \text{ if the criterion is non} - \text{beneficial} \end{cases} \tag{7}$$

Calculate the Distance to Ideal Solutions

The distances from each scenario to the FPIS ($\boldsymbol{d_i^*}$) and FNIS ($\boldsymbol{d_i^-}$) are calculated using the fuzzy distance measure which in this case is the Euclidian distance. The formulas for these distances, using the Euclidean distance are:

$$\text{Distance to FPIS } (\boldsymbol{d_i^*}):\ \boldsymbol{d_i^*} \sqrt{\sum_{j=1}^{n} (\boldsymbol{x_{ij}} - \boldsymbol{A_j^*})^2}$$

(8)

$$\text{Distance to FNIS } (\boldsymbol{d_i^-}):\ \boldsymbol{d_i^-} \sqrt{\sum_{j=1}^{n} (\boldsymbol{x_{ij}} - \boldsymbol{A_j^-})^2}$$

(9)

Here, n is the number of objectives, $\boldsymbol{x_{ij}}$ is the fuzzy score of the i-th scenario on the j-th objective, and $\boldsymbol{A_j^*}$ is the score of the FPIS on the j-th objective, and $\boldsymbol{A_j^-}$ is the score of the FNIS on the the j-th objective.

Using these distances, each alternative's relative closeness to the ideal solution is calculated to rank the alternatives. The alternative closest to the FPIS and farthest from the FNIS is considered the optimal choice.

Compute the Closeness Coefficient

In Fuzzy TOPSIS, the closeness coefficient ranks scenarios based on their proximity to the ideal solution. It measures how close each scenario is to the Fuzzy Positive Ideal Solution (FPIS) and how far it is from the Fuzzy Negative Ideal Solution (FNIS) using the equation:

$$CI_i = \frac{d_i^-}{d_i^* + d_i^-}$$

(10)

Where $\boldsymbol{d_i^*}$ is the distance of the i-th alternative from the FPIS, and $\boldsymbol{d_i^-}$ is its distance from the FNIS. he closeness indicator, $\boldsymbol{CI_i}$, ranges from 0 to 1, where a value closer to 1 indicates that the scenario is closer to the FPIS and farther from the FNIS, making it a more preferable option. This measure effectively integrates both the "goodness" and "badness" measures into a single indicator.

Rank the Scenarios

Finally, the scenarios can be ranked based on the Closeness Coefficient indicator ($\boldsymbol{CI_i}$). The scenario with the highest $\boldsymbol{CI_i}$ value is considered the best choice, balancing desirable and undesirable traits according to the decision matrix objectives. This ranking helps stakeholders identify which scenario best aligns with their preferences and objectives, enhancing transparency and aiding robust, well-informed decisions. This method provides a clear overview of how well each option meets the ideal conditions, ensuring decisions are aligned with strategic goals.

1.3.5. Step 7: Derive building-specific renovation requirements from the scenarios

Building-specific renovation requirements should be crafted based on the chosen renovation scenario, ensuring that all modifications align with the overarching goals and constraints of the project. For instance, if a renovation scenario is focused on enhancing energy efficiency, the requirements might include the installation of high-performance insulation, energy-efficient windows, and advanced HVAC systems. Through the selection of objectives and criteria, and the development of renovation scenarios a broad image of a future renovation scenario is created.

When planning a renovation, starting with a normative renovation scenario provides a structured foundation. This scenario outlines a vision for the building's future by establishing broad objectives based on sustainability, aesthetics, functionality, and compliance with regulations. This overarching vision helps stakeholders visualize the end goals and understand the scope of necessary changes. From this broad scenario, specific renovation requirements can be drawn up. These requirements serve as a detailed program that specifies the materials, technologies, and methods to be used. They also outline the standards to be met and the steps to achieve energy efficiency, improved user experience, and aesthetic enhancements.

By first establishing a general vision, the path to detailed planning becomes clear, allowing for a more organized and focused approach to transforming the building in alignment with both current needs and future sustainability goals. This process ensures that every aspect of the renovation is purpose-driven and tailored to the unique characteristics and challenges of the building. Stakeholders can then determine which building products need replacement by aligning with the chosen renovation scenario, assessing each product's current performance, and identifying discrepancies with the scenario's objectives. These identified products can then be integrated into the product-level decision-making framework (Section 2.4), which evaluates their potential for reuse, recycling, upgrading, etc. This systematic approach ensures that decisions about a product's next life are made strategically, maximizing resource efficiency and aligning with the chosen scenario objectives.

1.4. 3rd level decision-making framework – Product-level

1.4.1. Product-level decision-making framework

When an appropriate renovation scenario is chosen based on the outcomes of the 2nd level decision-making framework, and building-specific renovation requirements are drawn up, the product-level decision-making framework comes into play (Figure 8). This decision-making framework is based on the R-ladder (Figure 7) (Minguez et al., 2021), and guides stakeholders to decide on the next 'life' of building products. In this conceptual model 9 potential end-states for building products are distinguished based on the R-strategies from the R-ladder: Do nothing(refuse), upgrade product on-site (repair / refurbish), remanufacture for the same function (remanufacture), repurpose on-site (repurpose), repurpose off-site (repurpose), remanufacture for different function (remanufacture), recycle (recycle) and recover (recover).

The product-level decision-making framework follows two logics: the circularity potential of products following the R-ladder (options higher on the decision-making ladder show higher circularity potential), and the ease of use in applying the strategies. For example, the option to upgrade a product on-site (repair / refurbish), sits higher on this decision-making ladder compared to reuse in another building, because upgrading a product on-site might be easier than reusing the product in another building, despite being lower on the R-ladder. This conceptual model systemizes the decision-making process for reusing building products but still requires expert judgment for decision-making. For this decision-making framework, it is advised that stakeholders go through the model with an expert (Architect). Below each step in the decision-making framework is explained and potential assessment methods are given for answering the questions.

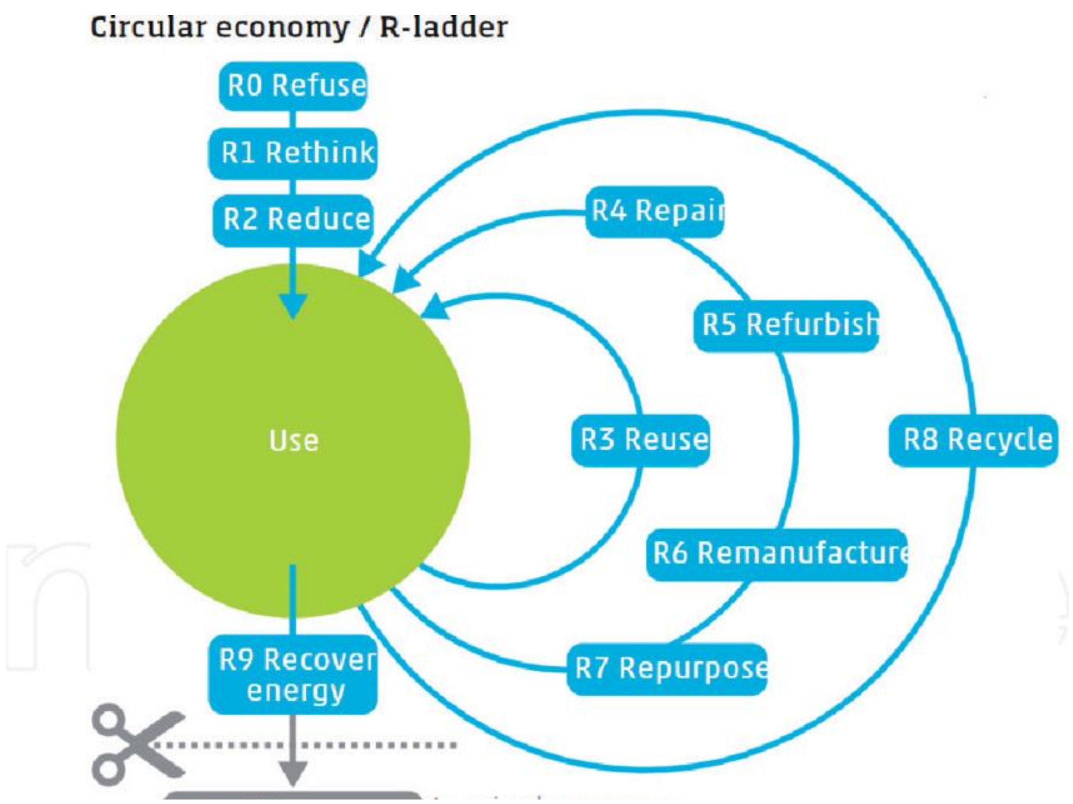


Figure 7: The R ladder of the Circular Economy by (Minguez et al., 2021)

Does the condition of the product fit with the user requirements?

Before deciding on the next life of a building product it is important to know if the product fits with the existing user requirements. If this is the case there might be no reason for taking the product out. Assessing the product based on the user requirement can be done based on the building-specific renovation requirements from step 7. Based on the chosen renovation scenario user requirements can be drawn up. For example in a renovation scenario where there is a specific focus on improving the indoor environmental conditions, the current ventilation system might not fit the user requirements anymore and needs to be replaced. However, in a scenario where there is no specific focus on improving indoor conditions, the current ventilation system could still meet the user requirements (a practical example can be found in Section 4.3). Although user requirements can be specific to each situation it is recommended to at least look at the following aspects when assessing user requirements: safety, health, functionality, comfort, cost, energy efficiency, and aesthetics.

Does the condition of the product fit with the building codes and regulations?

After checking the match between the building product and user requirements, it is also important to assess the product based on the building codes and regulations. For this, it is important to consider both the building-specific and product-specific regulations.

Table 6: Definitions and examples for the different EoL options in the 3rd-level decision-making framework

EoL options	Definition	Example
Refuse (R0)	Get rid of products or materials that you don't actually need. Make a product obsolete by abandoning its function or delivering it with a radically different product.	Choosing not to replace a ventilation system because it still works fine.
Reuse in another building (R3)	Reuse of discarded still a good product, in the same function by another user.	Using a reclaimed door from a demolished building in the construction of a new building.
Repair (R4)	Repair and maintenance of a broken product for use in its former function. This extends the lifespan of products.	Patching a cracked concrete floor instead of replacing the entire area.
Refurbish (R5)	Refurbishment and/or modernization of old product. Create new products from old products.	Sanding and resealing old wooden floors to restore their original luster and functionality.
Remanufacture for same function (R6)	Using parts from discarded products in new products with the same function.	Dismantling old window frames, replacing damaged parts, and reassembling them for use in a different building.
Remanufacture for another function (R6)	Using parts from discarded products in new products with different function.	Dismantling old door frames, replacing damaged parts, and reassembling them for use as a table.
Repurpose on site (R7)	Make new products with a different purpose from discarded products, on site	Transforming a door into a table to be used in the same building
Repurpose off-site (R7)	Make new products with a different purpose from discarded products, off-site	Turning old ceramic tiles into a mosaic for a public art installation.
Recycle (R8)	Processing materials into raw materials with the same (high-quality) or lower (low-quality) quality than the original raw material.	Crushing discarded glass to produce glass wool insulation for buildings.
Recover (R9)	Burning materials to generate electricity or heat	Burning non-recyclable building waste in a waste-to-energy plant to generate electricity.

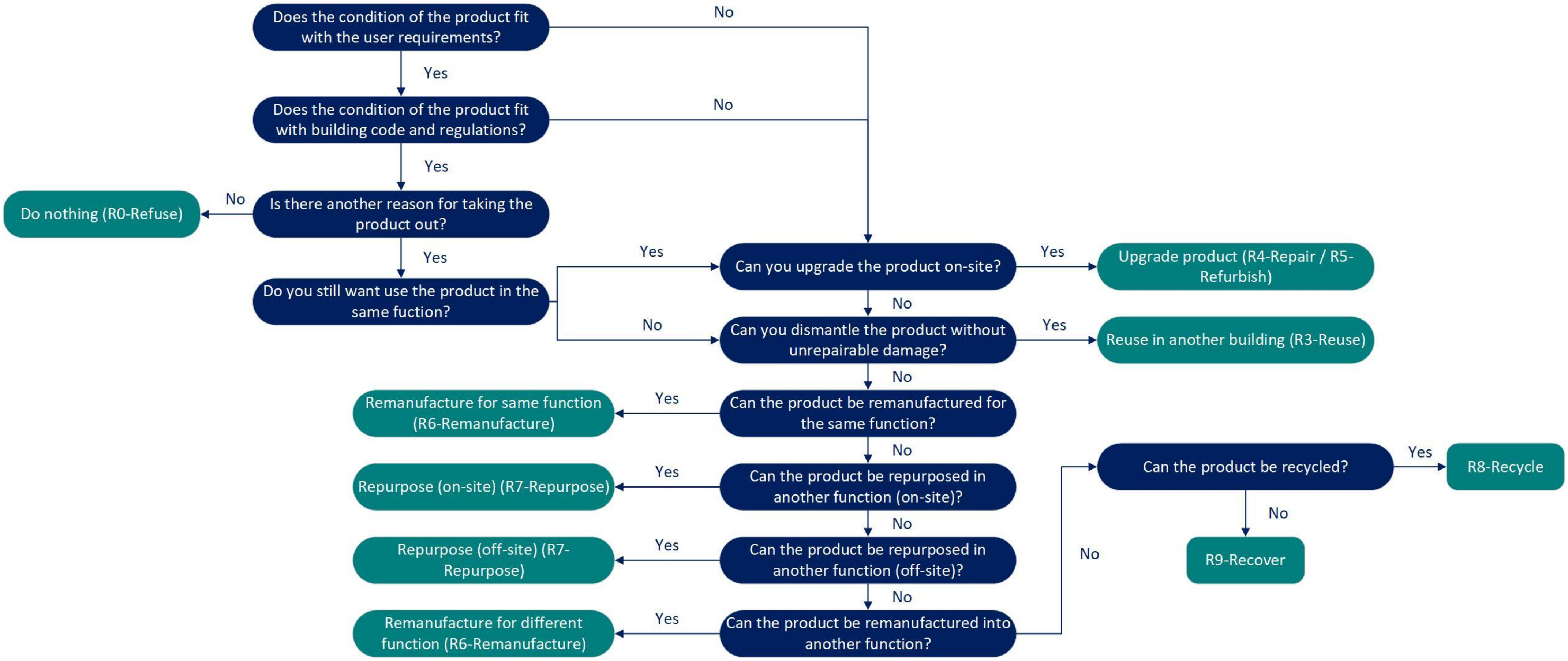


Figure 8: Conceptual framework of the 3rd level decision-making framework

Is there another reason for taking the product out?

After the product is assessed based on the user requirements and building codes and regulations it is important to ask the question whether there is another reason for taking the product out. If the building fits with the user requirements and building codes and regulations and no other reason can be put forward, then the best option is to leave the product in, and “do nothing”. Other reasons for taking out the products can include things like removing the product to make more room, or removing a product to increase the accessibility of the building for cleaning purposes. These questions should be assessed by the building owner or other stakeholders in the decision-making process.

Do you still want to use the product for the same function?

This question assesses whether the product can be used for the same function in the same building. For example, a door that is removed from a building, and then placed back as a door in the same building. This question is more related to the wishes of the stakeholders and less about the technical details of the products. A product might be removed for cleaning purposes, but the stakeholders still want to use that product somewhere else in the building.

Can you upgrade the product on-site?

If the building product does not fit the user requirements or building codes it could be upgraded on site. For this, both the repair and refurbishment R-strategies could be applied. Whether or not a product can be upgraded can be assessed based on expert judgment, through visual inspection, performance testing, safety audits, etc. Upgrading the product on-site can be a relatively easy way of extending the lifetime of a product.

Can you dismantle the product without unrepairable damages?

If the building product cannot be upgraded on-site, or you don’t want to use the product in the same function in the same building, the product should be assessed based on the dismountability potential. Specifically, whether or not the building can be dismantled without unrepairable damages. This can be assessed based on the dismountability index (losmaakbaarheidsindex) developed by the Dutch Green Building Council (DGBC), in which products are assessed based on: connection type, connection accessibility, independence, and geometry of product edge[4]. If the product can be successfully dismantled without unrepairable damages then it can be reused in another building.

Can the product be remanufactured for the same function?

If the product cannot be dismantled without unrepairable damages, then the question remains whether the product can be manufactured for the same function. Remanufacturing of building products refers to the process of restoring used or worn building materials and components to like-new condition. This involves disassembling, cleaning, repairing, replacing faulty or obsolete parts, and reassembling the products to meet or exceed the original manufacturing standards. This assessment should be done based on expert judgment and should include criteria like condition analysis, economic viability, and possibilities for upgrade.

Can the product be repurposed in another function on-site?

If the product cannot be remanufactured for the same function, then repurposing the product for another function should be considered. Repurposing of building products involves reusing materials or components in a different context or for a different function than they were originally designed for. An example can be wooden beams that might be repurposed as furniture or architectural elements. Two aspects need to be assessed, whether there is room and a need for repurposing the product on site: Is there a space where the product can be repurposed, is there a need for the repurposed materials in the building and are there tools and people available on site for the repurposing. The second aspect is whether and how the product can be repurposed. For this, the stakeholders should take examples projects into consideration.

Can the product be repurposed in another function off-site?

Repurposing building products can also be done off-site If there is no room, people, or tools available on site. Assessing whether or not a building product can be repurposed off-site is dependent on expert judgment, and relies on the condition of the product. When deciding on repurposing a product off-site stakeholders have to take into consideration the transport and handling, physical conditions, cost, and aesthetic considerations.

[4] https://www.dgbc.nl/publicaties/circular-buildings-een-meetmethodiek-voor-losmaakbaarheid-v20-41

Can the product be remanufactured into another function?

If the product cannot be remanufactured for the same function or repurposed, remanufacturing into another function might be a good solution. Remanufacturing produces a product that functions as well as a new one and meets the original specifications or better. Remanufacturing is often a complex, technical process that requires specialized skills and equipment. Remanufacturing for another function significantly alters the form of the original product to create an as-good-as-new other product. Assessing whether a building product can be remanufactured into another function is based on expert judgment.

Can the product be recycled?

Assessing whether a building product can be recycled involves a systematic evaluation of several key factors. Firstly, the material composition of the product needs to be identified to determine if it is recyclable. For example, metals like steel and aluminum are highly recyclable, whereas certain plastics and composites may be more challenging due to the presence of additives and fillers. Secondly, the condition of the material is crucial; it must be free from contaminants and impurities such as adhesives or coatings that could complicate the recycling process. Thirdly, local recycling capabilities and regulations should be considered; what materials are accepted by local facilities, and what are the legal requirements for recycling building materials? If a building product cannot be recycled, recovery remains as the only ‘circular’ solution left

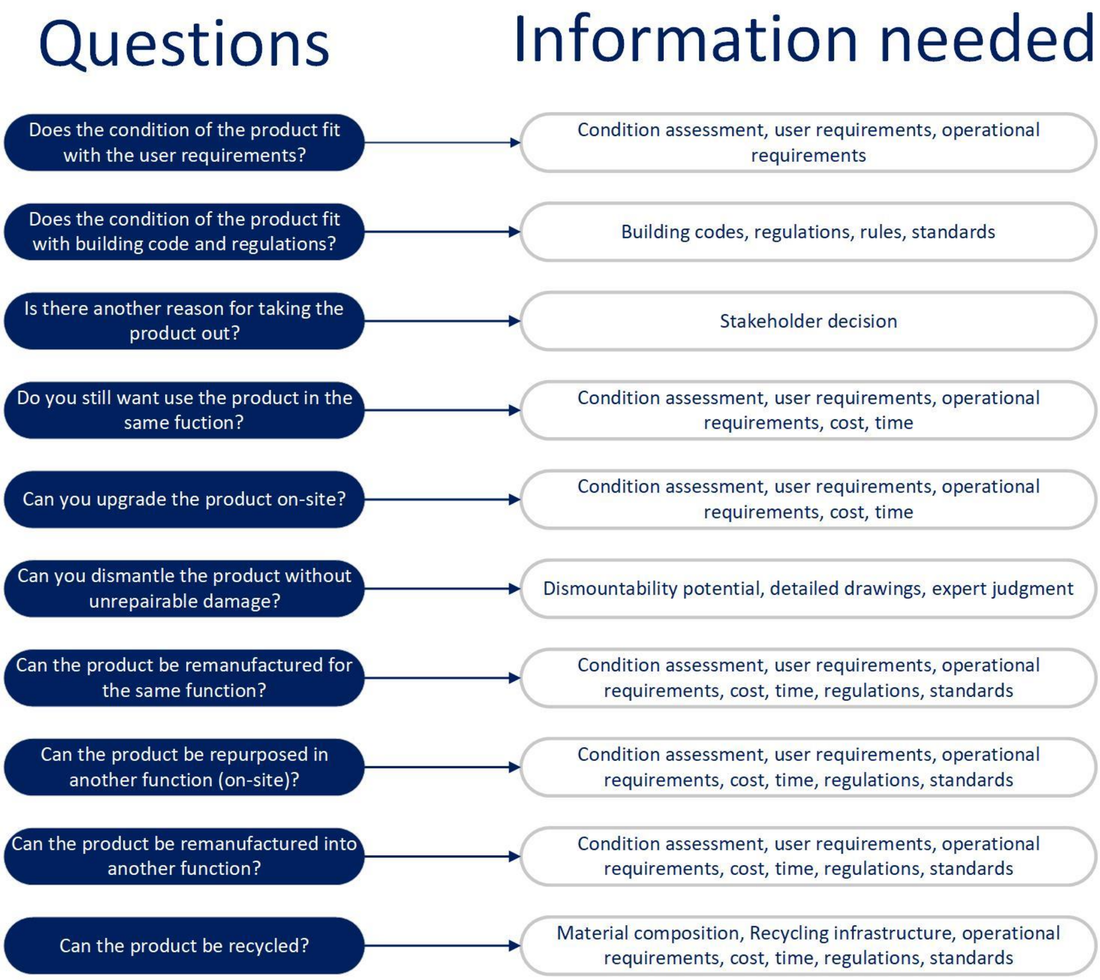


Figure 9: The questions from the 3rd level decision-making framework and the corresponding information needed

Implementing a product-level decision-making framework for End-of-Life scenarios equips stakeholders with a structured approach to decide on the next life of building products. By applying the R-strategies systematically, building owners, architects, and contractors can make more informed choices about how to handle products as buildings are deconstructed or renovated. This method not only facilitates the selection of the most appropriate options but also aligns with the principles of circular economy by following the logic of the R-ladder. However, it's important to recognize that this framework serves as a conceptual model and still requires expert judgment to navigate the specifics of each project. Expertise in material science, construction methods, and local regulations is crucial to effectively implement these strategies. Ultimately, this decision-making process systemizes the choices at the end of a building's life, making the renovation process more circular and sustainable.

1.4.2. Step 8: Develop a building management plan

Based on the chosen renovation scenario and the specific building requirements that can be drawn up, stakeholders get a good idea of what their future project looks like. However, to understand how buildings can be continuously upgraded throughout their lifecycle with respect to changing requirements in occupant comfort and operational requirements, the life-cycle prediction methods from task 1.3 can be used. This task will develop methods for the automated detection of construction components and materials in buildings and provide different methods and algorithms for risk-based assessment and prediction of the lifetime of different components/products[5]. The condition assessment of the building and building products is needed for the 1st and 3rd level decision-making frameworks. However, this condition assessment is based on the current condition. The lifetime prediction of building products from task 1.3 makes it possible to develop a future-oriented building management plan, in which the future conditions of products are taken into account. If the stakeholders of a renovation project know that certain building products have a predictive lifetime of 5 years, this can be taken into account for the 2nd level decision-making framework, when deciding on a relevant scenario. In this case, they might opt for a quick-fix scenario after 1 year, and go for a comprehensive renovation scenario after 5 years, when the lifetime of the abovementioned building products comes to an end. When the predicted lifetime of these building products is only 3 years, then the stakeholders might opt for a "in-between" scenario after three years instead. An illustrative example of this can be found in section 4.4.1.

The lifetime prediction of building products from 1.3 makes it possible to develop a future-oriented building management plan in which multiple renovation scenarios could be combined. The three decision-making frameworks can both be used for the current condition, as well as the future condition, which gives stakeholders the opportunity to know when to intervene, what scenario to follow and to determine the next life of building products in advance.

[5] https://www.reincarnate-project.eu/innovations/

1.4.3. Step 9: Determine the waste reduction potential

Extending the functional life of existing buildings, as opposed to constructing new ones, has significant potential for reducing waste in the construction industry (Rose & Stegemann, 2018). When buildings are renovated or repurposed, the volume of demolished materials and the demand for new construction materials significantly decrease. This reduces the environmental impact associated with the extraction, processing, and transportation of new materials. By maintaining and upgrading the existing built environment, we can conserve resources and energy that would otherwise be expended in the creation of new structures, thereby supporting more sustainable urban development practices.

Based on the scenarios developed in step 4, the lifetime extension of a building can be determined. A comprehensive renovation scenario can significantly extend the functional lifetime of a building compared to a quick-fix renovation scenario in which the lifetime of a building is only slightly extended. Based on the extended use life years of a building, a comparison can be made between scenarios in terms of waste reduction potential. The longer a building can be withheld from demolition, the more waste is reduced. In order for a comparison to be made in terms of waste reduction, two aspects need to be determined, the amount of functional lifetime added through renovation, and the amount of waste if the building is demolished. For all scenarios, the amount of building waste per life year is calculated using the following Equation:

$$W_j = \frac{(AW_j \times SqM_j)}{LtY_j}$$

(11)

When a scenario significantly extends the use life of a building through renovation, the amount of potential demolition waste is spread out over more years, therefore lowering the amount of building waste per life year, compared to a scenario in which the lifetime is only slightly extended. To determine the waste reduction potential of the scenarios a baseline scenario is calculated. In this baseline scenario, the assumption is that the building is demolished immediately, and the amount of building waste per life year is equal to the total amount of demolition waste divided by the lifetime at the point of demolition. The total amount of demolition waste can be determined based on the following matrix:

EWC code	Residential demolition					Non-residential demolition				
	Type of building structure				Confidence degree	Type of building structure				Confidence degree
	Undefined	Timber	Reinforced concrete	Masonry		Undefined	Timber	Reinforced concrete	Masonry	
17 01 01 (Concrete)	–	137–300	492–840	91–216	Fair	–	–	401–768	216–373	Weak
17 01 02 (Bricks)	–	84–90	170–486	118–425	Weak	176–438	–	–	298–438	Weak
17 01 03 (Tiling, roof tiles and ceramic materials)	–	–	10.6–17.6	8.3–27.1	Weak	16–27	–	–	–	Weak
17 01	–	137–390	811–1290	162–541	Fair	–	–	497–1234	541–811	Fair
17 02 01 (Timber)	–	70–275	12–58	12–54	Fair	–	–	20–159	11–32	Fair
17 02 02 (Glass)	0.4–2.6	–	–	–	Weak	0.2–4.4	–	–	–	Weak
17 02 03 (Plastics)	0.4–5.6	–	–	–	Weak	0.4–6.1	–	–	–	Bad
17 03 02 (Bituminous mixtures)	–	–	0.2–1.9	–	Bad	1.0–1.4	–	–	–	Bad
17 04 07 (Metal mixtures)	–	4.8–22.5	9.8–28.4	3.4–4.2	Fair	3.4–55.0	–	28.4–53.0	–	Fair
17 06 04 (Insulation materials)	0.1–2.2	–	–	–	Bad	0.1–2.2	–	–	–	Bad
17 08 02 (Gypsum-based construction materials)	–	10.9–105.4	10.8–64.3	68.9–84.6	Fair	10.8–81.3	–	10.8–75.7	–	Weak
17 09 03 (Construction and demolition waste containing hazardous substances)	0.4–0.6	–	–	–	Bad	0.2–0.6	–	–	–	Bad
Total	–	195–725	805–1371	302–664	Good	600–1750	–	742–1637	664–825	Good

Figure 10: Average demolition waste indicators (kg/m2) by (Mália et al., 2013)

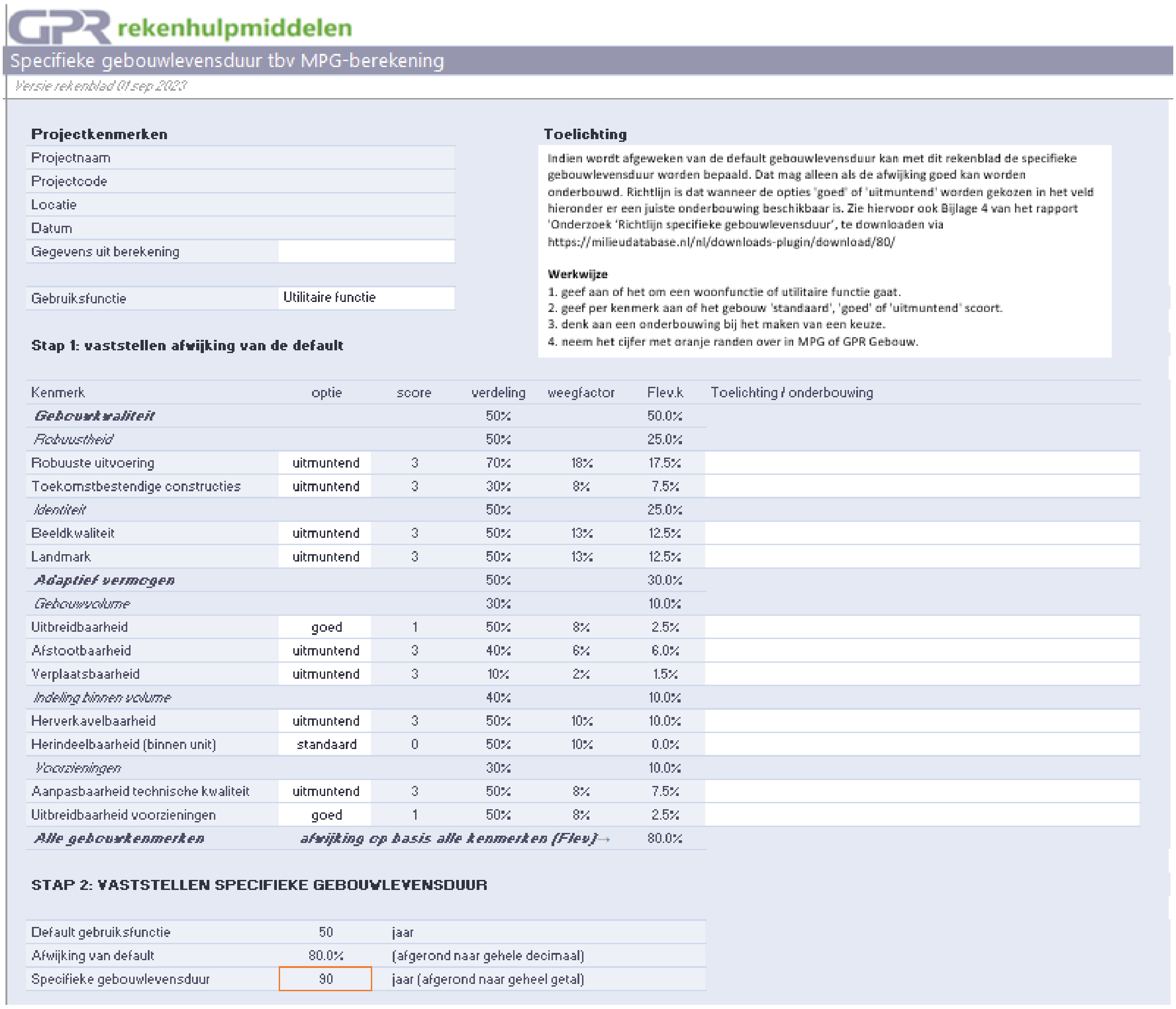
The matrix provides a quick overview of the average amount of demolition waste based on the type of structure assessed. By using the matrix stakeholders are provided with a simple method for comparing the different renovation scenarios based on averages. However, stakeholders can also opt for a more detailed calculation of the demolition waste of their building by using one of the computer-aided waste quantification tools (Table 7) The benefit of this waste reduction calculation method is that the potential demolition waste only needs to be calculated once for the building, and the differences between the scenarios are based on the lifetime years added through renovation.

Table 7: Computer-aided waste quantification tools adapted from (Villoria-Sáez et al., 2020)

Tool	Input data	Results/outcome	Country
Net Waste Tool[6]	General project details. Information regarding the project timeline and quantities is optional and allows to produce a segregation strategy	Estimations of the overall waste generated in a construction project. It also shows where C&DW is likely to arise. This will help to identify opportunities to reduce waste or even set targets for major C&DW streams	United Kingdom
DeconRCM[7]	The exact position of the site (using Google Maps), type of project/building, and other technical characteristics.	Estimations of C&DW quantities generated in renovation and demolition work in all type of buildings.	Greece
Cype software[8]	It uses a predimensioning module, which includes giving information about the type of building/project as well as general information such as size, geometry, location, etc.	Estimations of the amount of C&DW generated for all types of projects and buildings.	Spain

[6] https://www.ciria.org/Resources/REK/Training_materials/Net_Waste_Tool_user_guide.aspx?WebsiteKey=3f18c87a-d62b-4eca-8ef4-9b09309c1c91
[7] https://www.sciencedirect.com/science/article/pii/S0956053X11003254?via%3Dihub
[8] https://info.cype.com/en/new-feature/construction-and-demolition-waste/

Determining the extended lifetime of buildings through renovation in terms of years is very context-dependent and can be done in several ways including consultation with experts and reviewing previous renovation cases. However, for this framework we propose using the calculcation tool: "*gebouw specifieke levensduur*"[9]. This calculation tool provided by 'WE Adviseurs', helps in calculating the expected lifetime of a building based on default values, and prolonging and limiting factors (Appendix 2 and Figure 11). The building-specific lifetime is calculated based on 11 factors on building quality and adaptive capacity and is assessed with either: 'excellent', 'good', or 'standard'. This tool can be filled in separately for all renovation scenarios, based on the qualitative information of the scenarios from step 4.


GPR rekenhulpmiddelen

Specifieke gebouwlevensduur tbv MPG-berekening

Versie rekenblad 01 sep 2023

Projectkenmerken

Projectnaam	
Projectcode	
Locatie	
Datum	
Gegevens uit berekening	
Gebruiksfunctie	Utilitaire functie

Toelichting

Indien wordt afgeweken van de default gebouwlevensduur kan met dit rekenblad de specifieke gebouwlevensduur worden bepaald. Dat mag alleen als de afwijking goed kan worden onderbouwd. Richtlijn is dat wanneer de opties 'goed' of 'uitmuntend' worden gekozen in het veld hieronder er een juiste onderbouwing beschikbaar is. Zie hiervoor ook Bijlage 4 van het rapport 'Onderzoek 'Richtlijn specifieke gebouwlevensduur', te downloaden via https://milieudatabase.nl/nl/downloads-plugin/download/80/

Werkwijze

1. geef aan of het om een woonfunctie of utilitaire functie gaat.
2. geef per kenmerk aan of het gebouw 'standaard', 'goed' of 'uitmuntend' scoort.
3. denk aan een onderbouwing bij het maken van een keuze.
4. neem het cijfer met oranje randen over in MPG of GPR Gebouw.

Stap 1: vaststellen afwijking van de default

Kenmerk	optie	score	verdeling	weegfactor	Flev,k	Toelichting / onderbouwing
Gebouwkwaliteit			50%		50.0%	
Robuustheid			50%		25.0%	
Robuuste uitvoering	uitmuntend	3	70%	18%	17.5%	
Toekomstbestendige constructies	uitmuntend	3	30%	8%	7.5%	
Identiteit			50%		25.0%	
Beeldkwaliteit	uitmuntend	3	50%	13%	12.5%	
Landmark	uitmuntend	3	50%	13%	12.5%	
Adaptief vermogen			50%		30.0%	
Gebouwvolume			30%		10.0%	
Uitbreidbaarheid	goed	1	50%	8%	2.5%	
Afstootbaarheid	uitmuntend	3	40%	6%	6.0%	
Verplaatsbaarheid	uitmuntend	3	10%	2%	1.5%	
Indeling binnen volume			40%		10.0%	
Herverkavelbaarheid	uitmuntend	3	50%	10%	10.0%	
Herindeelbaarheid (binnen unit)	standaard	0	50%	10%	0.0%	
Voorzieningen			30%		10.0%	
Aanpasbaarheid technische kwaliteit	uitmuntend	3	50%	8%	7.5%	
Uitbreidbaarheid voorzieningen	goed	1	50%	8%	2.5%	
Alle gebouwkenmerken	***afwijking op basis alle kenmerken (Flev)*** →				80.0%	

STAP 2: VASTSTELLEN SPECIFIEKE GEBOUWLEVENSDUUR

Default gebruiksfunctie	50	jaar
Afwijking van default	80.0%	(afgerond naar gehele decimaal)
Specifieke gebouwlevensduur	90	jaar (afgerond naar geheel getal)

Figure 11: Screenshot of the calculation tool: 'gebouwspecifieke levensduur' From WE Adviseurs

[9] https://milieudatabase.nl/nl/downloads-nmd/downloads-bepalingsmethode/

Although this tool partly systemizes the calculation of the building-specific lifetime for the scenarios, the input is still dependent on expert judgment and hypothetical future situations. The idea behind using the calculation tool is, therefore, to provide a fair comparison method when determining the remaining use life of the scenarios. It is recommended to fill in the calculation tool together with the stakeholders of the renovation project and use the same logic and decision rules for the different scenarios. The extended use life in terms of years is calculated by subtracting the age of the building from the expected building-specific lifetime.

Before a comparison can be made between different scenarios in terms of waste reduction, the product-level decision-making framework needs to be filled in. The products that find a new life (meaning: all EoL options except for recovery) can be subtracted from the total amount of demolition waste. In the baseline scenario, the assumption is made that no building products find a new life and all waste is either recovered or ends up in the landfill. However, stakeholders can also opt to go through the product-level decision-making framework for the baseline demolition scenario.

To finally determine the waste reduction potential of the different scenarios compared to the baseline case, the following formula is used that expresses the waste reduction potential in terms of the percentage of waste reduced (Equation 12). An Illustrative example of this can be found in Section 3.

$$WrP_j = 1 - \left[\frac{(AW_j \times SqM_j)}{LtY_j} \Bigg/ \frac{(AW_{bs} \times SqM_{bs})}{LtY_{bs}} \right] \times 100 \quad (12)$$

2. Practical implementation of the decision-making framework

To illustrate the functionality of the decision-making framework, a brief fictional case study is provided. This example depicts a scenario where an external user independently applies the step-by-step approach described in Section 2.1.2 to their project. The scenarios in this example can serve as default scenarios within the framework. More detailed real-world applications will be documented in the results from Reincarnate Work Package 5. This work package will utilize the decision-making framework in various Reincarnate demonstration projects (see Section 5).

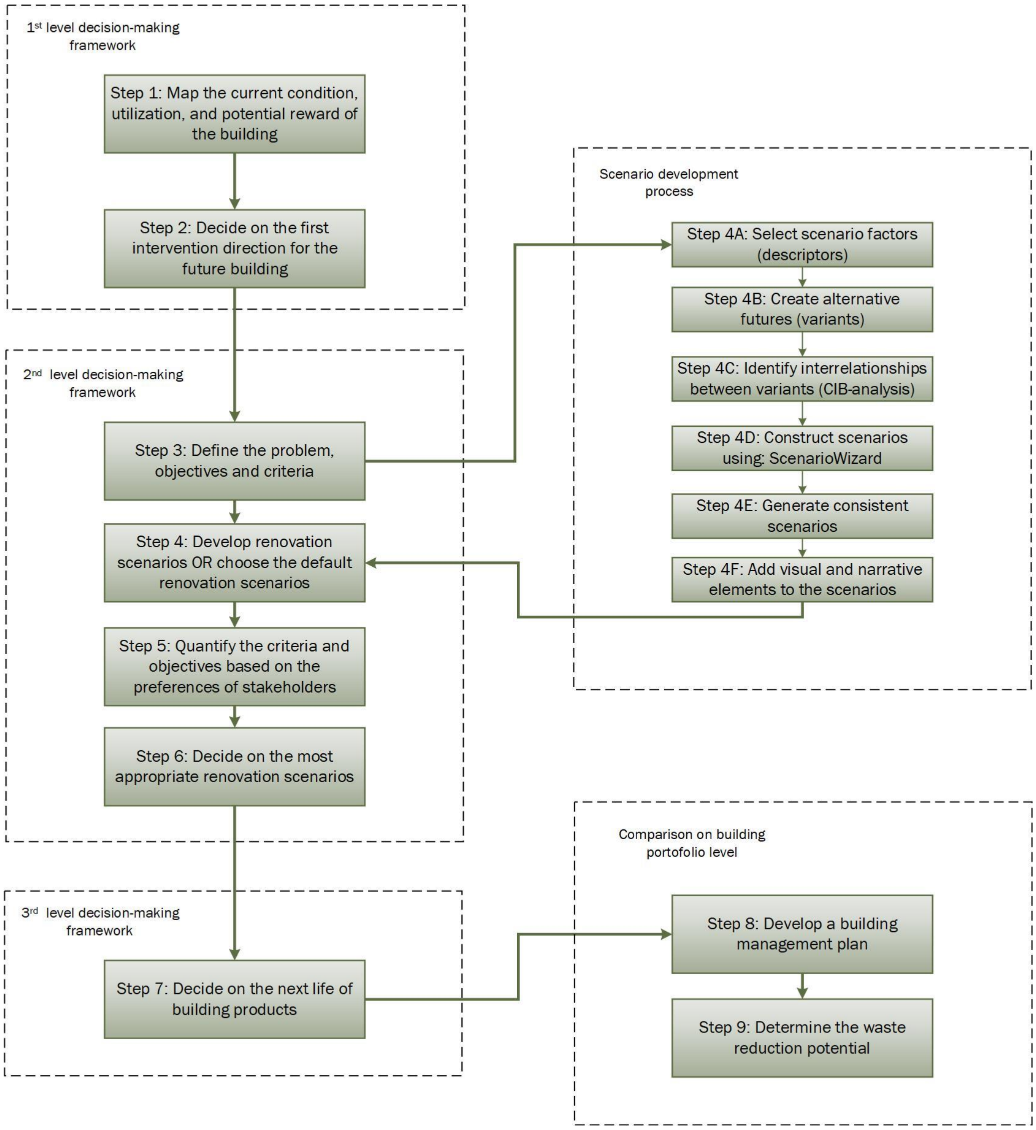


Figure 12: Proposed decision-making framework for the adaptive refurbishment and renovation of real estate assets

2.1. 1st level decision-making framework – Implementation example

2.1.1. Step 1: Map the current condition, utilization, and potential reward of the building

For the practical implementation example, a hypothetical scenario is used where the outcome of the 1st level decision-making framework is directed towards the renovation decision-making model. The first step in the 1st level framework is to identify stakeholders and assign weights to the criteria. This framework includes five common stakeholders: the building owner, building user, facility manager, sponsor/financier, and the community, but it allows for the addition of more stakeholders if needed.

Each stakeholder assigns weights to the sub-criteria using the weighting percentage method (Section 3.1). This should be done from the stakeholder's perspective, and the final weights are determined by averaging these individual weights. An example of this process is shown in Tables 9 and 10.

The weighting of elements for condition, utilization, and collective utility can be done separately by the stakeholders and then combined. However, the importance of weighing different stakeholders' input should be reached by consensus. Although stakeholders are free to weigh the elements as they see fit, weighting suggestions are provided for each element (see Table 8).

Table 8: Suggested weighting methods for criteria in the 1st level decision-making framework

Criteria	Weighing suggestion
Condition	The element weighting can be informed by the importance of the construction cost proportional to each element.
Utilization	The element weighting can be informed by the relative magnitude of each zone/space.
Collective utility	The element weighting can be informed by the importance of these goals to overall project success.
Stakeholder interest	The element weighting can be informed by the relative dominance of stakeholders as controlling entities, taking into consideration issues of power, legitimacy, and urgency. This should be based on consensus between all stakeholders

Table 9: An example of weighting the sub-criteria of the 1st level decision-making framework for 5 stakeholders

	Building owner	Building user	Facility manager	Sponsor financier	comm unity	Final Weight
Condition						
Design standard	50	40	60	55	45	50%
Maintained service level	10	20	30	40	25	25%
Regulatory compliance	10	30	20	30	25	25%
Utilization						
Demand or relevance	20	50	50	40	30	40%
Fitness for purpose	40	45	35	30	50	40%
User satisfaction	20	20	15	15	30	20%
Collective Utility						
Economic performance	20	20	30	10	20	20%
Culture and heritage	25	55	35	45	40	40%
Environmental value	40	50	30	35	45	40%
Stakeholder interest						
Short-term perspective	50	50	45	55	50	50%
Medium-term perspective	15	25	20	30	35	25%
Long-term perspective	10	25	25	25	40	25%

Once the weights for all sub-criteria and elements are established, each stakeholder can rate the performance using the Likert scale survey (Appendix 1). Stakeholders complete the survey individually, and the final performance rating is derived from the average of all responses. Using the weights assigned to the elements and sub-criteria, along with the survey ratings, the final scores for condition, utilization, and reward are calculated. These scores are then plotted on the 1st level decision-making matrix (Figure 13 & 14), allowing for the determination of the initial intervention direction.

Table 10: An example of weighting the sub-criteria of the 1st level decision-making framework for 5 stakeholders (2)

	Building owner	Building user	Facility manager	Sponsor financier	comm unity	Final Weight
Condition						
• **Structure**	20	20	15	20	25	20%
• **Exterior envelope**	35	25	20	40	30	30%
• **Interior finishes / fitout**	10	30	15	25	20	20%
• **Engineering services**	20	25	15	20	20	20%
• **External works**	10	5	15	10	10	10%
Utilization						
• **Internal space**	20	25	35	30	35	30%
• **External space**	5	5	15	15	10	10%
• **Outdoor site area**	10	10	10	10	10	10%
• **Equipment and fitout**						30%
• **Engineering systems**	20	20	30	10	20	20%
Collective Utility						
• **Operational viability**	35	25	20	40	30	30%
• **Locational context**	20	20	15	20	25	20%
• **Risk and opportunity**	20	20	15	15	30	20%
• **Asset valuation**	20	20	30	10	20	20%
• **Profile / mission**	10	5	15	10	10	10%
Stakeholder interest						
• **Building owner**	x	x	x	x	x	40%
• **Building user**	x	x	x	x	x	20%
• **Facility manager**	x	x	x	x	x	10%
• **Sponsor / financier**	x	x	x	x	x	10%
• **community**	x	x	x	x	x	20%

Condtition			design standard	Maintained service level	regulatory compliance	
		weighting	0.5	0.25	0.25	
	Structure	0.2	1	1	1	1
	Exterior enveloppe	0.3	1	2	1	1.333333
	Intior finishing	0.2	2	1	2	1.666667
	Engineering finishing	0.2	1	2	1	1.333333
	External works	0.1	2	1	2	1.666667
		1	1.3	1.5	1.3	1.35

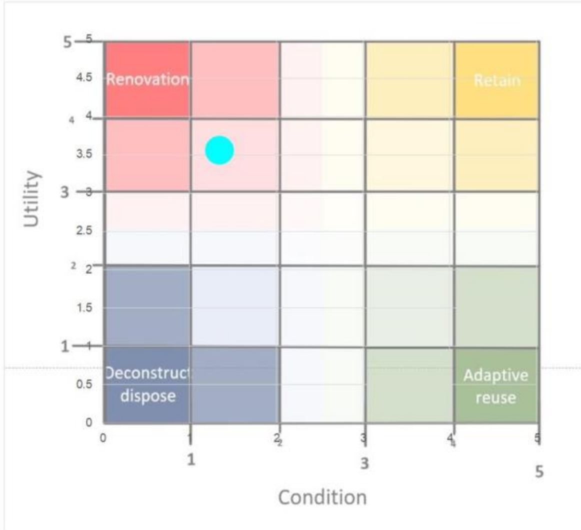
Utilization			demand or relevance	fitness or purpose	user satisfaction	
		weighting	0.4	0.4	0.2	
	Internal space	0.3	4	4	4	4
	external space	0.1	3	3	3	3
	outdoor site area	0.1	4	4	5	4.333333
	equipments and fitout	0.3	4	4	4	4
	Engineering systems	0.2	1	3	3	2.333333
		1	3.3	3.7	3.8	3.56

Collective utility			economic performance	culture and heritage	environmental values	
		weighting	0.2	0.4	0.4	
	Operational viability	0.3	3	3	3	3
	locational context	0.2	5	5	1	3.666667
	risk and opportunity	0.2	4	4	3	3.666667
	asset valuation	0.2	3	5	1	3
	profile/ mission	0.1	4	5	2	3.666667
		1	3.7	4.2	2.1	3.26

Stakeholder interest			short-term perspective	medium-term perspective	long-term perspective	
		weighting	0.5	0.25	0.25	
	building owner	0.4	3	4	5	4
	building user	0.2	3	2	3	2.666667
	facility manager	0.1	5	5	5	5
	sponsor/ finacier	0.1	5	3	4	4
	community	0.2	5	5	5	5
		1	3.8	3.8	4.5	3.975

Reward	2.5917

	condition (x axis)	utilization (y axis)	reward (z axis)
2.500566667			
property status	1.35	3.56	2.5917



1st level decision-making assesment sheet

Figure 13: The 1st level decision-making assessment worksheet adapted from Langston and Smith (2012)

2.1.2. Step 2: Decide on the first intervention direction

Using the 1st level decision-making matrix, a decision can be made between Retain, Renovation, Deconstruct, or Adaptive Reuse (deliverable 3.1). With coordinates of Condition=1.3, Utilization=3.5, and Reward=2.6, Renovation is identified as the most suitable first intervention. A Reward of 2.6 indicates potential benefits from an intervention. The proximity to the Renovation corner suggests a high confidence level in this decision. Based on this initial direction, stakeholders can then use the 2nd level decision-making framework to determine the most suitable renovation scenario. While this model provides a strong indication of the best intervention based on the current building state, stakeholders are encouraged to experiment with the inputs to test the robustness of the outcomes.

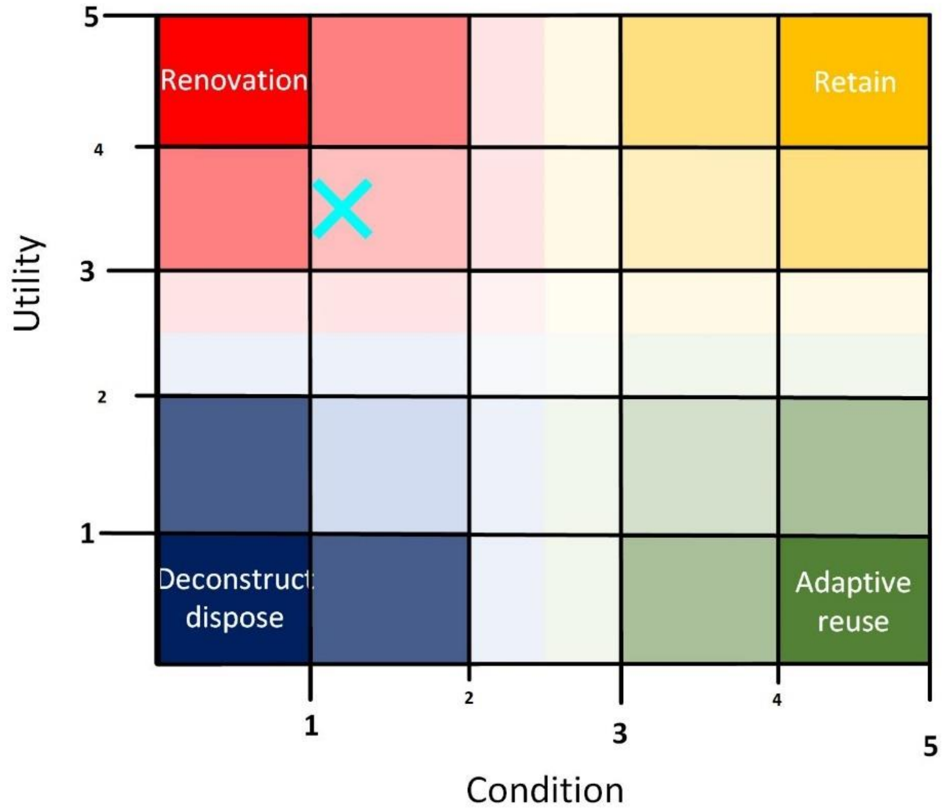


Figure 14: An example of the outcome for the 1st level decision-making framework

2.2. 2nd level decision-making framework - Implementation guideline

2.2.1. Step 4: Develop renovation scenarios OR choose the default renovation scenarios

In this decision-making framework, stakeholders have the choice between developing their own renovation scenarios or choosing the default renovation scenarios. For this practical implementation example, renovation scenarios have been developed through cross-impact balance analysis. These scenarios will serve as the default scenarios if the stakeholders choose not the develop their own. A detailed description of these scenarios can be found in the appendix (Appendix 3). The scenario development process will be explained below.

Step 4A: Selecting scenario descriptors

The scenario descriptors that are used for the scenario development are taken from the BIMSpeed project (see Section 2.3.1). The key aspect of the descriptors is the objectives. Because CIB analyses are typically performed at a high aggregation level, given the constrained number of descriptors, criteria, and objectives can be combined into one comprehensive descriptor. To form the descriptor, the objective can be taken as a starting point and relevant criteria from the list can be added that support the objective. Based on the objective, criteria, and theme, a description can be written that explains the descriptor. A detailed overview of all the descriptors used for the scenarios can be found in the appendix (Appendix 3). For the scenario development process, the following descriptors are used:

- A) Primary Energy
- B) Energy demand
- C) Environmental impact
- D) Indoor conditions
- E) Social acceptance
- F) Social technical benefits
- G) Cost
- H) O & M Cost
- I) Financial benefits

Step 4B: Developing future directions

After the descriptors are defined, the future directions of each descriptor can be drawn up in the form of variants. For each descriptor three different variants are established: a strong variant in which the objective within the descriptor is definitely reached, a medium variant in which the objective is partially reached, and a weak variant in which the objective is not reached. For all 9 descriptors, three variants are established including a name, and detailed description of the variant, which can be found in the appendix (Appendix 4). It is important to repeat that the variants should be mutually exclusive and collectively exhaustive (Weimer-Jehle, 2023), and should describe a comprehensive image of one future direction of the descriptor.

Step 4C: Identifying relationships

For the identification of the relationships between descriptor variants, the cross-impact balance analysis matrix can be used. For the scenario development in this practical example, the matrix was filled in by answering the following question:

If variant x were to occur for descriptor X, would this promote or hinder variant y for descriptor Y?

This question was answered based on a seven-point cross-impact rating scale (see deliverable 3.1), in which *3* means that variant ***x*** strongly promotes variant ***y***, and ***-3*** means that variant ***x*** strongly prohibits variant ***y***. Figure 31 shows the completely filled-in cross-impact balance analysis matrix.

Step 4D: Constructing scenarios

After the cross-impact balance matrix is filled in, the ScenarioWizard software can be used for the construction of scenarios. The ScenarioWizard software was developed to perform CIB analysis and has been used, tested and further developed in numerous application projects and method experiments (Weimer-Jehle, 2023). ScenarioWizard for Windows systems is available as a free download[10]. A manual of the software can also be found that describes in detail how the software works, and how scenarios can be constructed. The project file of the default scenarios that are used in this practical example is also available as a free download (Appendix 4), which can be loaded into the software.

[10] https://www.cross-impact.org/english/CIB_e_ScW.htm

Descriptor	Criteria	Variants	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	F1	F2	F3	G1	G2	G3	H1	H2	H3	I1	I2	I3
A) Primary energy	Renewable energy Operational primary energy demand	A1) Sustainable source				3	2	-3	1	1	-1	0	0	0	1	1	0	2	1	-2	-2	-1	2	2	0	-2	2	1	-2
		A2) Partly sustainable				2	1	-1	1	1	-1	0	0	0	1	0	0	2	1	0	-1	0	1	1	0	-1	1	1	-1
		A3) Fossil fuel				-2	1	3	-2	-1	2	0	0	0	-2	-1	1	-1	0	2	2	0	-2	-1	0	2	-1	0	1
B) Energy demand	Total energy demand Energy savings	B1) Low energy demand	2	1	-1				1	0	0	-1	1	2	1	1	0	0	0	0	-2	-1	2	2	0	-2	3	2	-2
		B2) Medium energy demand	0	0	0				0	0	0	1	0	0	1	0	0	0	0	0	1	1	1	1	0	-1	1	1	-1
		B3) High energy demand	-1	1	2				-1	-1	2	-1	0	2	-1	0	0	0	0	0	2	1	-2	-1	0	2	-1	-1	1
C) Environmental impact	Global warming potential Embodied global warming potential	C1) Environmental heaven	-2	1	-1	2	1	-2				1	0	0	1	1	0	1	1	0	-2	1	2	2	0	-2	2	1	-1
		C2) Environmentally friendly	1	0	-1	1	0	-1				0	0	0	1	0	0	0	0	0	1	1	1	1	0	-1	1	1	-1
		C3) High environmental impact	1	0	2	-1	0	2				0	0	0	-1	0	0	-1	0	1	2	1	-2	-1	0	2	-2	0	2
D) Indoor conditions	Visual comfort Acoustics comfort Indoor air quality Thermal comfort	D1) Indoor Heaven	1	0	-1	-2	1	2	-1	1	1				2	1	-2	2	1	-1	-2	1	2	3	2	-3	2	1	-1
		D2) Decent indoor climate	0	0	0	-1	0	1	1	1	0				1	1	0	1	0	0	1	1	1	2	1	-1	1	1	-1
		D3) Cold and Loud	-2	-1	0	-1	1	3	-2	-1	2				-3	-1	2	-1	1	2	2	1	-1	-3	1	3	-2	-1	2
E) Social acceptance	Accessibility Aesthetic Social reputation	E1) Social paradise	1	0	-1	0	0	0	1	0	0	2	1	0				1	0	0	-2	-1	2	1	0	0	2	1	-1
		E2) Socially acceptable	0	0	0	0	0	0	0	0	0	1	0	0				0	0	0	1	1	1	0	0	0	1	1	-1
		E3) Socially limited	0	0	0	0	0	0	0	0	0	0	0	0				0	0	1	1	1	-2	0	0	1	-2	-1	2
F) Social technical benefits	Renovation time Covered scope Durability	F1) Comprehensive and durable	2	1	-1	1	0	-1	-2	-1	1	3	2	-2	2	1	0				-3	-1	3	2	1	-1	2	2	-1
		F2) Strategic refresh	0	0	0	0	0	0	1	0	0	2	1	-1	1	1	0				1	1	1	1	1	-1	1	1	-1
		F3) Quick fix frenzy	-1	0	0	0	0	0	2	1	-1	-3	-1	1	0	0	0				2	1	-2	-2	1	2	-1	1	-1
G) Cost	Investment cost Payback period LCC cost	G1) Minor investment	-2	-1	1	0	0	0	-3	-1	0	-2	-1	0	0	0	0	-1	-1	2				0	0	0	-1	0	0
		G2) Medium investment	1	1	-1	2	1	-1	1	1	0	2	1	-1	0	0	0	2	1	-1				1	0	-1	0	0	0
		G3) Major investment	2	1	-2	3	2	-2	3	2	1	3	2	-2	2	1	0	-1	-1	3				2	1	-2	1	0	-1
H) O&M cost	Rent increment Maintenance cost Operational energy cost Fuel poverty	H1) Cost efficient	3	2	-2	3	2	-2	-1	0	0	2	1	-2	2	1	0	2	1	-1	-2	1	2				3	2	-1
		H2) Somewhat expensive	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1				1	1	1
		H3) Money drainer	-2	-1	3	-2	-1	2	1	0	1	-2	-1	1	-1	0	1	-2	-1	1	2	1	-2				-3	-1	2
I) Financial benefits	Financial incentives Property value increment	I1) Many financial benefits	3	1	-1	2	1	-1	3	2	-2	3	2	-3	3	2	0	3	2	-2	2	1	-2	2	0	-2			
		I2) Some financial benefits	1	1	0	0	0	0	1	1	-1	2	1	-1	2	1	0	1	1	1	1	1	1	1	0	-1			
		I3) Limited financial benefits	0	0	0	-2	-1	1	-1	-1	1	-2	-1	1	-1	0	0	-2	0	3	-2	0	2	-1	0	1			

Figure 15: The filled out cross-impact balance matrix from the scenario development workshop

Step 4E: Generating consistent scenarios

Through the use of the ScenarioWizard software, consistent scenarios can be generated. A max inconsistency value of 1 is calculated based on 9 descriptors. An inconsistency value of 1 means that marginally inconsistent scenarios with an impact sum of up to minus 1 are still considered as acceptable scenarios. For a detailed description of the scenario development process, deliverable 3.1 is referred to. Based on the input of the CIB matrix and an inconsistency value of 1, the ScenarioWizard software gives back 12 consistent scenarios. A scenario tableau can be generated of the consistent scenarios (Figure 18). These consistent draft scenarios can be integrated into the multicriteria decision framework in: (section 3.2.3).

Step 4F: Adding visual and narrative elements

The Excel sheet with the descriptions of all scenarios (Appendix 3) was used to generate visualizations of the scenarios in DALL-E [11]. DALL-E is an integrated extension within ChatGPT-4 that specializes in generating images based on textual descriptions provided by users. For the generation of images the scenario, the Excel sheets were used as input for the prompt. For this, the following prompt was used (Figure 16):

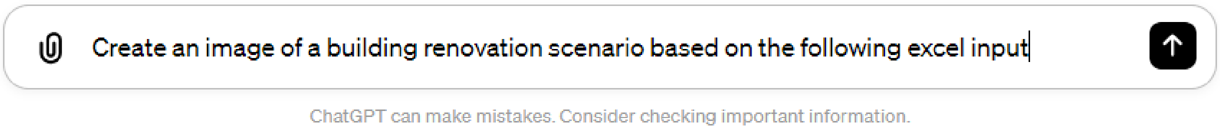


Figure 16: An example input Prompt for ChatGPT 4

The visualizations are not used for the 2nd level decision-making framework but serve as a guiding tool for showing stakeholders of renovation projects what is possible when pursuing renovation. Three scenario visualizations are portrayed in Figure 17:

Figure 17: Visualisation through DALL-E for three renovation scenarios

[11] https://chat.openai.com/g/g-pmuQfob8d-image-generator

<table>
<tr><th>Scenario No. 1</th><th>Scenario No. 2</th><th>Scenario No. 3</th><th>Scenario No. 4</th><th>Scenario No. 5</th><th>Scenario No. 6</th><th>Scenario No. 7</th><th>Scenario No. 8</th><th>Scenario No. 9</th><th>Scenario No. 10</th><th>Scenario No. 11</th><th>Scenario No. 12</th></tr>
<tr><td colspan="3">A) Primary energy:
A1) Sustainable source</td><td>A) Primary energy:
A2) Partly sustainable</td><td>A) Primary energy:
A1) Sustainable source</td><td colspan="2">A) Primary energy:
A2) Partly sustainable</td><td>A) Primary energy:
A3) Fossil fuel</td><td>A) Primary energy:
A2) Partly sustainable</td><td>A) Primary energy:
A3) Fossil fuel</td><td colspan="2">A) Primary energy:
A2) Partly sustainable</td></tr>
<tr><td colspan="6">B) Energy demand:
B1) Low energy demand</td><td>B) Energy demand:
B2) Medium energy demand</td><td>B) Energy demand:
B3) High energy demand</td><td>B) Energy demand:
B1) Low energy demand</td><td>B) Energy demand:
B3) High energy demand</td><td>B) Energy demand:
B1) Low energy demand</td><td>B) Energy demand:
B2) Medium energy demand</td></tr>
<tr><td>C) Environmental impact:
C1) Environmental heaven</td><td colspan="6">C) Environmental impact:
C2) Environmentally friendly</td><td>C) Environmental impact:
C3) High environmental impact</td><td>C) Environmental impact:
C2) Environmentally friendly</td><td>C) Environmental impact:
C3) High environmental impact</td><td colspan="2">C) Environmental impact:
C1) Environmental heaven</td></tr>
<tr><td colspan="2">D) Indoor conditions:
D1) Indoor heaven</td><td colspan="5">D) Indoor conditions:
D3) Cold & Loud</td><td>D) Indoor conditions:
D1) Indoor heaven</td><td colspan="4">D) Indoor conditions:
D3) Cold & Loud</td></tr>
<tr><td colspan="2">E) Social acceptance:
E1) Social acceptance</td><td colspan="2">E) Social acceptance:
E2) Socially acceptable</td><td colspan="3">E) Social acceptance:
E3) Socially limited</td><td>E) Social acceptance:
E2) Socially acceptable</td><td colspan="4">E) Social acceptance:
E3) Socially limited</td></tr>
<tr><td colspan="2">F) Social technical benefits:
F1) Comprehensive & Durable</td><td colspan="5">F) Social technical benefits:
F3) Quick fix frenzy</td><td>F) Social technical benefits:
F2) Strategic refresh</td><td colspan="4">F) Social technical benefits:
F3) Quick fix frenzy</td></tr>
<tr><td colspan="2">G) Cost:
G3) Major investment</td><td colspan="5">G) Cost:
G1) Minor investment</td><td colspan="2">G) Cost:
G2) Medium investment</td><td>G) Cost:
G1) Minor investment</td><td colspan="2">G) Cost:
G2) Medium investment</td></tr>
<tr><td colspan="2">H) O&M Cost:
H1) Cost efficient</td><td colspan="7">H) O&M Cost:
H2) Somewhat expensive</td><td colspan="3">H) O&M Cost:
H3) Money drainer</td></tr>
<tr><td colspan="2">I) Financial benefits:
I1) Many financial benefits</td><td colspan="7">I) Financial benefits:
I2) Some financial benefits</td><td colspan="3">I) Financial benefits:
I3) Limited financial benefits</td></tr>
</table>

Figure 18: The scenario tableau for the renovation scenarios (outcomes from the ScenarioWizard software)

2.2.2. Step 5: Quantify the objectives and criteria based on the preferences of the stakeholders

Pairwise comparison

After developing the scenarios, the objectives, criteria, and stakeholder preferences are quantified using the pairwise comparison method. Each stakeholder performs the pairwise comparison individually, and the weights are then aggregated. For the practical implementation, five hypothetical stakeholders conducted the pairwise comparison: building owner, building user, facilities manager, sponsor/financier, and community. The results of this comparison are shown in Table 11.

Table 11: The pairwise comparison matrix

Pairwise comparison	Building Owner	Building User	Facility Manager	Sponsor / Financier	community	Total
1st level						
Environmental vs Social	1 1/2	1/9	1/5	1/7	1/3	1/2
Environmental vs Economic	1/3	1	5	4	2	2 1/2
Social vs Economic	5	7	9	5	3	5 4/5
2nd level						
Primary Energy vs Energy demand	1	3	1/3	1	1	1 1/4
Primary Energy vs Environmental Impact	1	5	1/5	1	1	1 2/3
Energy demand vs Environmental Impact	1	5	1/5	1/3	3	2
Indoor conditions vs Social acceptance	9	7	5	7	7	7
Indoor conditions vs Socio-technical benefits	5	3	5	7	5	5
Social acceptance vs Socio-technical benefits	1/3	1/5	3	1/3	1/3	5/6
Cost vs O&M Cost	1/7	1/7	1/5	1	1/7	1/3
Cost vs Financial benefits	1/3	1/5	1/5	3	1/5	4/5
O&M Cost vs Financial benefits	1	1/3	1	1	3	1 1/4

Compute the criterion weights

The objectives and criteria are weighted by multiplying the 1st-level weights by the 2nd-level weights. Initially, the weights are normalized within each column, and then these normalized weights are aggregated to obtain a single comprehensive weight for each criterion and objective. The results of this normalization and aggregation process are presented in Table 12.

Table 12: The normalized and aggregated criterion weights

Criteria	Weights	Objectives	Weights	Total weights
Environmental	0.287	Primary energy	0.410	0.11767
		Energy demand	0.369	0.1059
		Environmental impact	0.221	0.0634
Social	0.642	Indoor conditions	0.746	0.4789
		Social acceptance	0.113	0.0725
		Socio-technical benefits	0.142	0.0911
Economic	0.0712	Cost	0.200	0.0142
		O&M Cost	0.487	0.0346
		Financial benefits	0.313	0.0222

Checking the consistency

Once the normalized and aggregated weights for all objectives are established, consistency is evaluated. The Consistency Ratio (CR) is calculated using Equation 2. A CR below 0.10 indicates that the judgments are reasonably consistent, while a CR above 0.10 suggests inconsistency. In this case, none of the pairwise comparison matrices had a CR above 0.10, indicating that the stakeholder judgments were consistent.

2.2.3. Step 6: Decide on the most appropriate renovation scenario

Define the decision matrix

After the stakeholders complete the pairwise comparisons, the decision matrix can be created. For the renovation scenarios, this matrix includes nine objectives, each with qualitative variants of strong, medium, or weak. Each row represents a scenario, while each column represents an objective (Table 13).

Table 13: The linguistic decision matrix

	To reduce Primary energy	To reduce Energy demand	To reduce Environ-mental impacts	To improve Indoor conditions	To increase social acceptance	To increase social technical benefits	To reduce Cost	To reduce O&M Cost	To increase Financial benefits
Scenario 1	Strong	Strong	Strong	Strong	Strong	Strong	Weak	Strong	Strong
Scenario 2	Strong	Strong	Medium	Strong	Strong	Strong	Weak	Strong	Strong
Scenario 3	Strong	Strong	Medium	Weak	Medium	Weak	Strong	Medium	Medium
Scenario 4	Medium	Strong	Medium	Weak	Medium	Weak	Strong	Medium	Medium
Scenario 5	Strong	Strong	Medium	Weak	Weak	Weak	Strong	Medium	Medium
Scenario 6	Medium	Strong	Medium	Weak	Weak	Weak	Strong	Medium	Medium
Scenario 7	Medium	Medium	Medium	Weak	Weak	Weak	Strong	Medium	Medium
Scenario 8	Weak	Weak	Weak	Strong	Medium	Medium	Medium	Medium	Medium
Scenario 9	Medium	Strong	Medium	Weak	Weak	Weak	Medium	Medium	Medium
Scenario 10	Weak	Weak	Weak	Weak	Weak	Weak	Strong	Weak	Weak
Scenario 11	Medium	Strong	Strong	Weak	Weak	Weak	Strong	Weak	Weak
Scenario 12	Medium	Medium	Strong	Weak	Weak	Weak	Medium	Weak	Weak

Transform the decision matrix into a fuzzy decision matrix - Fuzzification

Once the decision matrix is established, it can be converted into a fuzzy decision matrix. To transform linguistic variables into fuzzy numbers, a conversion matrix is utilized (see Table 4). These fuzzy numbers represent a minimum value, a maximum value, and the most common value. The resulting fuzzy decision matrix is shown in Table 14.

Table 14: The fuzzy decision matrix

	Scenario 1			Scenario 2			Scenario 3			Scenario 4			Scenario 5			Scenario 6			Scenario 7			Scenario 8			Scenario 9			Scenario 10			Scenario 11			Scenario 12		
To reduce Primary energy	5	7	9	5	7	9	5	7	9	3	5	7	5	7	9	3	5	7	3	5	7	1	3	5	3	5	7	1	3	5	3	5	7	3	5	7
To reduce Energy demand	5	7	9	5	7	9	5	7	9	5	7	9	5	7	9	5	7	9	3	5	7	1	3	5	5	7	9	1	3	5	5	7	9	3	5	7
To reduce Environmental impacts	5	7	9	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	1	3	5	3	5	7	1	3	5	5	7	9	5	7	9
To improve Indoor conditions	5	7	9	5	7	9	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5	5	7	9	1	3	5	1	3	5	1	3	5	1	3	5
To increase social acceptance	5	7	9	5	7	9	3	5	7	3	5	7	1	3	5	1	3	5	1	3	5	3	5	7	1	3	5	1	3	5	1	3	5	1	3	5
To increase social technical benefits	5	7	9	5	7	9	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5	3	5	7	1	3	5	1	3	5	1	3	5	1	3	5
To reduce Cost	1	3	5	1	3	5	5	7	9	5	7	9	5	7	9	5	7	9	5	7	9	3	5	7	3	5	7	5	7	9	5	7	9	3	5	7
To reduce O&M Cost	5	7	9	5	7	9	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	1	3	5	1	3	5	1	3	5
To increase Financial benefits	5	7	9	5	7	9	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	3	5	7	1	3	5	1	3	5	1	3	5

Normalize the decision matrix

To normalize the fuzzy numbers the following Equation is used:

$$x_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)} \quad (13)$$

This means that the fuzzy numbers in the: maximum/minimum/most common column (see Table 14) are normalized based on the highest value within that column.

Construct the weighted normalized decision matrix

To form the weighted matrix the weights from step 5 are multiplied with the normalized fuzzy numbers to generate the weighted normalized decision matrix. This resulted in the following weighted normalized decision matrix (Table 15).

Determine Fuzzy Ideal and Negative-Ideal Solutions

To rank the scenarios using the Fuzzy TOPSIS method, the Fuzzy Positive Ideal Solution (FPIS) and Fuzzy Negative Ideal Solution (FNIS) must be identified. The best scenario is the one closest to the FPIS and farthest from the FNIS. The FPIS represents the optimal fuzzy value for each objective, while the FNIS represents the least desirable fuzzy value. These are determined by identifying the best and worst fuzzy scores across all criteria for each alternative. The FPIS and FNIS are calculated using Equations 10 and 11, with the results presented in Table 15.

Calculate the Distance to Ideal Solutions

The distances from each scenario to the FPIS (d_i^*) and FNIS (d_i^-) are calculated using the fuzzy distance measure. The equations for these calculations are provided in Section 2.3.4. These distances are then used to determine each scenario's relative closeness to the ideal solution, which is used for ranking. The scenario closest to the FPIS and farthest from the FNIS is deemed the optimal choice. The calculated distances to the FPIS and FNIS are shown in Table 16.

Table 15: The weighted and normalized decision matrix

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
A)	L	0.02	0.05	0.05	0.05	0.05	0.05	0.08	0.05	0.02	0.02	0.02	0.05
	M	0.05	0.08	0.08	0.08	0.08	0.08	0.12	0.08	0.05	0.05	0.05	0.08
	H	0.08	0.12	0.12	0.12	0.12	0.12	0.15	0.12	0.08	0.08	0.08	0.12
B)	L	0.04	0.07	0.01	0.07	0.04	0.07	0.01	0.07	0.01	0.01	0.01	0.04
	M	0.07	0.09	0.04	0.09	0.07	0.09	0.04	0.09	0.04	0.04	0.04	0.07
	H	0.09	0.12	0.07	0.12	0.09	0.12	0.07	0.12	0.07	0.07	0.07	0.09
C)	L	0.03	0.03	0.02	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.01	0.01
	M	0.05	0.05	0.03	0.03	0.05	0.03	0.02	0.05	0.02	0.02	0.02	0.02
	H	0.06	0.06	0.05	0.05	0.06	0.05	0.03	0.06	0.03	0.03	0.03	0.03
D)	L	0.03	0.03	0.01	0.03	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.03
	M	0.05	0.05	0.02	0.05	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.05
	H	0.06	0.06	0.03	0.06	0.05	0.05	0.03	0.05	0.03	0.03	0.03	0.06
E)	L	0.03	0.01	0.01	0.01	0.01	0.03	0.01	0.02	0.01	0.01	0.01	0.01
	M	0.05	0.02	0.02	0.02	0.02	0.05	0.02	0.03	0.02	0.02	0.02	0.02
	H	0.06	0.03	0.03	0.03	0.03	0.06	0.03	0.05	0.03	0.03	0.03	0.03
F)	L	0.02	0.02	0.03	0.01	0.01	0.01	0.02	0.03	0.01	0.01	0.01	0.01
	M	0.03	0.03	0.04	0.02	0.02	0.02	0.03	0.04	0.02	0.02	0.02	0.02
	H	0.04	0.04	0.05	0.03	0.03	0.03	0.04	0.05	0.03	0.03	0.03	0.03
G)	L	0.02	0.02	0.09	0.09	0.05	0.02	0.09	0.02	0.02	0.02	0.09	0.09
	M	0.05	0.05	0.12	0.12	0.09	0.05	0.12	0.05	0.05	0.05	0.12	0.12
	H	0.09	0.09	0.16	0.16	0.12	0.09	0.16	0.09	0.09	0.09	0.16	0.16
H)	L	0.01	0.01	0.03	0.03	0.01	0.01	0.01	0.02	0.01	0.01	0.03	0.02
	M	0.02	0.02	0.05	0.05	0.02	0.02	0.02	0.03	0.02	0.02	0.05	0.03
	H	0.03	0.03	0.06	0.06	0.03	0.03	0.03	0.05	0.03	0.03	0.06	0.05
I)	L	0.03	0.01	0.03	0.03	0.01	0.01	0.02	0.01	0.01	0.01	0.03	0.03
	M	0.04	0.02	0.04	0.04	0.02	0.02	0.03	0.02	0.02	0.02	0.04	0.04
	H	0.05	0.03	0.05	0.05	0.03	0.03	0.04	0.03	0.03	0.03	0.05	0.05

Table 16: The FNIS and FNIS values for all scenarios

FNIS	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
A)	0.2882545	0.288255	0.327272	0.114949	0.09412	0.09612	0.096013	0.09412	0.240528	0.2695411	0.2405282	0.2405282
B)	0.2977745	0.297774	0.343751	0.102626	0.102697	0.102626	0.121364	0.102697	0.246546	0.286834	0.2465461	0.249217
C)	0.3317406	0.345457	0.3592	0.145887	0.146506	0.145887	0.145439	0.146506	0.290695	0.3029744	0.2785852	0.2785852
D)	0	0	0	0.003241	0.007064	0.003241	0	0.007064	0	0	0	0
E)	0.3245493	0.324549	0.328203	0.128977	0.14774	0.146964	0.146382	0.129509	0.277601	0.2776012	0.2776012	0.2776012
F)	0.3097395	0.30974	0.314343	0.137918	0.138702	0.137918	0.137333	0.138702	0.264934	0.2649337	0.2649337	0.2649337
G)	0.3771057	0.377106	0.374026	0.171274	0.171971	0.171274	0.170748	0.171971	0.318834	0.3160695	0.3160695	0.3165016
H)	0.3545724	0.354572	0.356318	0.156575	0.157239	0.156575	0.156083	0.157239	0.301382	0.3032813	0.3032813	0.3032813
I)	0.3645031	0.364503	0.365622	0.165751	0.16645	0.165751	0.165226	0.16645	0.310547	0.3117754	0.3117754	0.3117754
Di*	2.6482396	2.661956	2.768734	1.127198	1.132489	1.126356	1.138586	1.114258	2.251068	2.3330107	2.2393207	2.2424236
A)	0.0888601	0.08886	0.049312	0.057518	0.082694	0.077179	0.077179	0.082694	0.080177	0.0468733	0.0778347	0.0781184
B)	0.0793415	0.079341	0.032032	0.073174	0.073174	0.073174	0.050552	0.073174	0.076255	0.029594	0.0739945	0.0691622
C)	0.0453851	0.03171	0.015928	0.025706	0.025706	0.025706	0.025706	0.025706	0.028691	0.0134981	0.040047	0.0403367
D)	0.3771057	0.377106	0.374026	0.170748	0.170748	0.170748	0.170748	0.170748	0.318834	0.3163944	0.3163944	0.3166574
E)	0.0525732	0.052573	0.046029	0.043036	0.024526	0.024526	0.024526	0.043036	0.041257	0.038818	0.038818	0.0390713
F)	0.0673788	0.067379	0.059963	0.033524	0.033524	0.033524	0.033524	0.033524	0.053918	0.0514785	0.0514785	0.0517346
G)	0	0	0	0	0	0	0	0	0	0.001987	0.001987	0.0009445
H)	0.0225763	0.022576	0.017782	0.014811	0.014811	0.014811	0.014811	0.014811	0.017782	0.013193	0.013193	0.0134243
I)	0.0126815	0.012681	0.008439	0.005523	0.005523	0.005523	0.005523	0.005523	0.008439	0.0048473	0.0048473	0.0050161
Di-	0.7459021	0.732227	0.60351	0.424039	0.430705	0.425191	0.402569	0.449216	0.625351	0.5166836	0.6185949	0.6144654

Compute the Closeness Coefficient

In the fuzzy TOPSIS method, the closeness indicator is an essential metric for ranking scenarios based on their proximity to the ideal solution. It measures how near each scenario is to the Fuzzy Positive Ideal Solution (FPIS) and how distant it is from the Fuzzy Negative Ideal Solution (FNIS). This indicator is calculated using the Equation:

$$CI_i = \frac{d_i^-}{d_i^* + d_i^-}$$

(14)

The Closeness Coefficent for each scenario can be found in Table 17.

Rank the Scenarios

Once the Closeness Coefficient is calculated for all scenarios, the ranking can be determined. The scenario with the highest $\boldsymbol{CI_i}$ best aligns with stakeholder preferences. This scenario strikes the optimal balance between maximizing desirable traits and minimizing undesirable ones, according to the objectives set in the decision matrix. The final ranking results are presented in Table 17, with scenario **8** identified as the most suitable option based on stakeholder input.

Table 17: The closesness coefficient and the final rank of the scenarios

Scenario	Closesness Coefficent (CC)	Rank
Scenario 1	0.219761624	6
Scenario 2	0.215729989	9
Scenario 3	0.178964047	12
Scenario 4	0.273355501	4
Scenario 5	0.275529078	2
Scenario 6	0.274043107	3
Scenario 7	0.261212333	5
Scenario 8	0.287318988	1
Scenario 9	0.2174062	7
Scenario 10	0.181311953	11
Scenario 11	0.216449665	8
Scenario 12	0.215082	10

2.2.4. Step 7: Derive building-specific renovation requirements from the scenarios

After the ranking of the scenarios, scenario 8 was found to be the most appropriate based on the stakeholder preferences. This hypothetical scenario serves as a starting point for deriving building-specific renovation requirements for the renovation project. Although the scenarios are general potential future visions, they can still be used for drawing up more specific renovation requirements. In scenario 8, the focus lies on improving the indoor environmental conditions, with a lesser focus on improving the energy performance of a building.

Figure 20: Visualisation of scenario 8 using DALL-E

Scenario no.	8.
Primary energy	Fossil Fuel
Energy demand	High energy demand
Environmental impact	High environm. impact
Indoor conditions	Indoor Heaven
Social acceptance	Socially acceptable
Social technical benefits	Strategic refresh
Cost	Medium Investment
O&M Cost	Somewhat expensive
Financial benefits	Some financial benefits

Figure 19: Overview of the scenario composition of scenario 8

Based on the descriptions of the different variants in this scenario it can be derived that there is little focus on improving the energy performance or reducing the environmental impact of the building. This might mean that the current energy systems (gas boiler) is upheld and no further improvements are made to improving the energy label. However the variant 'Indoor Heaven', tells us that there is a significant improvement needed in terms of indoor environmental conditions. From this variant, stakeholders might decide to install a new state-of-the-art ventilation system as well as a floor heating/cooling installation, in order to improve the indoor conditions for the building users.

The variant ‘Strategic refresh’ for the descriptor: ‘Social technical benefits’ reveals that there is a slight improvement needed in terms of social technical benefits. This could mean that the flooring needs to be replaced, (also to place floor heating/ cooling), and an extensive paint job is needed to give the building a refreshed look. These more specific building requirements derived from the scenario composition, form the basis for the product-level decision-making framework.

These building-specific building requirements are an oversimplification of how the building requirements can be derived from the scenarios. However, it is recommended to sit together with the stakeholders of the renovation project, and comprehensively go through all the scenario descriptors to come up with specific building requirements. This can be an iterative process, that can take up several months, but by first establishing a general vision, the path to detailed planning becomes clear, allowing for a more organized and focused approach to transforming the building in alignment with both current needs and future goals. Deriving building-specific requirements from the renovation scenario not only provides an organized and focused approach, it also provides a first overview of what building products become available after renovation, to be plugged into the 3rd level decision-making framework.

2.3. 3rd level decision-making framework – product-level

From the building-specific building requirements, building products can be derived that become available after renovation, that can be used in the 3rd-level decision-making framework. For this practical implication, three building products are chosen based on the building-specific requirements from scenario 8, to be included in the product-level decision-making framework. For these three products, the journey through the decision model is explained below. It should be highlighted that this practical example is an oversimplification of the use of the decision model, and decisions might require more assessments based on the information needed in Figure 9.

Double glazed window

Based on the variants in scenario 8, it can be concluded that there is little focus on improving the energy performance of the building but, a strong focus on improving the indoor environmental conditions of the building. The windows in the building and their respective insulation value, are important for both the energy performance as well as the indoor environmental conditions. Currently, the hypothetical building in this practical example has double-glazed windows. In order to find the next life of this building product the 3rd level decision-model is used below:

- *Does the condition of the building product fit with the user requirements? – Yes*

This question can be answered with a yes. Based on the variants from scenario 8 we see that there is no specific focus on improving the energy performance of the building, and therefore the current double-glazed window fits the user requirements. Although there is a strong focus on improving the indoor conditions, the double-glazed windows are still fine in terms of acoustics and insulation, and therefore fit with the user requirements on indoor conditions.

- *Does the condition of the building fit with building codes and regulations? – Yes*

The answer to the question is also yes. The condition of the windows is still fine and there are no changes in building codes and regulations.

- *Is there another reason for taking the product out? – No*

The answer to this question is no. Although the product still fits with user requirements and regulations there could be other reasons for taking the product out, for example, to make the building more accessible for cleaning. However, this is not the case for the double-glazed windows. When comparing the windows to the description of scenario 8, it can be concluded that there is no real reason to take the windows out and the best option is therefore to leave them in. The most appropriate End-of-Life option in this case is to do **nothing (R0-Refuse).**

Ventilation system

The second building product under review is the building's current ventilation system. From scenario 8 it can be concluded that there is a significant improvement needed in terms of indoor conditions. The ventilation system is important when it comes to indoor air quality and indoor comfort. From the building's specific requirements, we can see that a new state-of-the-art ventilation system is required to improve the indoor conditions. Therefore the current ventilation system becomes available for the 3rd level decision-making model:

- *Does the condition of the building product fit with the user requirements? – No*

The answer to this question is no. From the building-specific requirements, it can be concluded that there is a need for a new state-of-the-art ventilation system, and therefore the current system does not fit with the user requirements.

- *Can you upgrade the product on-site? – No*

Although the building product does not fit the user requirements now, it could be upgraded on-site to fit with the requirements later. However, for the current ventilation system, it is hard to upgrade the product on site to match the characteristics of the state-of-the-art ventilation system. Therefore the answer to this question is also no.

- *Can you dismantle the product without unrepairable damages? – Yes*

The answer to this question is yes. The ventilation system has little or no wet connections and can relatively easily be dismantled. The condition of the ventilation system is also still good but just doesn't fit with the future vision of scenario 8. , it can be concluded that the most appropriate End-of-Life option in this case is: **Reuse in another building (R3-Reuse).**

Linoleum flooring

The third building product under review is the current linoleum flooring. Based on the building-specific requirements related to scenario 8, we see that there is a need for floor cooling/ heating, and therefore the current flooring needs to be removed. There is also a focus on improving the social-technical benefits, and the buildings need a 'Strategic refresh'. Therefore the current linoleum flooring becomes available for the 3rd level decision-making model:

- *Does the condition of the building product fit with the user requirements? – No*

The answer to this question is no. As we can read above, a strategic refresh is needed and the current flooring is ready for an upgrade. The product therefore does not fit with the user requirements.

- *Can you upgrade the product on-site? – No*

The linoleum flooring is outdated and cannot be upgraded on-site to the point that it fits with the user's requirements. The answer to this question is therefore no.

- *Can you dismantle the product without unrepairable damages? – No*

Unfortunately, the linoleum flooring is glued to the ground, which makes it hard to remove it without unrepairable damage. The answer to this question is therefore no.

- *Can the product be remanufactured for the same function? - No*

Removing the linoleum flooring significantly damages it, which makes it costly and almost impossible to remanufacture it for the same function. The answer to this question is therefore no.

- *Can the product be repurposed in another function on-site? - No*

The answer to this question is no. There is no space, people, and tools available on-site to repurpose the product. Also repurposing the linoleum floor is energy-intensive and costly and therefore not an appropriate option.

- *Can the product be repurposed in another function off-site? - No*

The answer to this question is no. Repurposing the linoleum floor is energy-intensive and costly and therefore not an appropriate option.

- *Can the product be remanufactured into another function? - No*

Removing the linoleum flooring significantly damages it, which makes it costly and almost impossible to remanufacture it. The answer to this question is therefore no.

- *Can the product be recycled? - Yes*

The answer to this question is yes. It is relatively easy to recycle linoleum flooring, and therefore an appropriate option. Although *recycling* sits relatively low on the R-ladder, It can still be a good option to keep building products in a resource recovery loop, it can be concluded that the most appropriate End-of-Life option in this case is: **Recycle (R8-Recycle).**

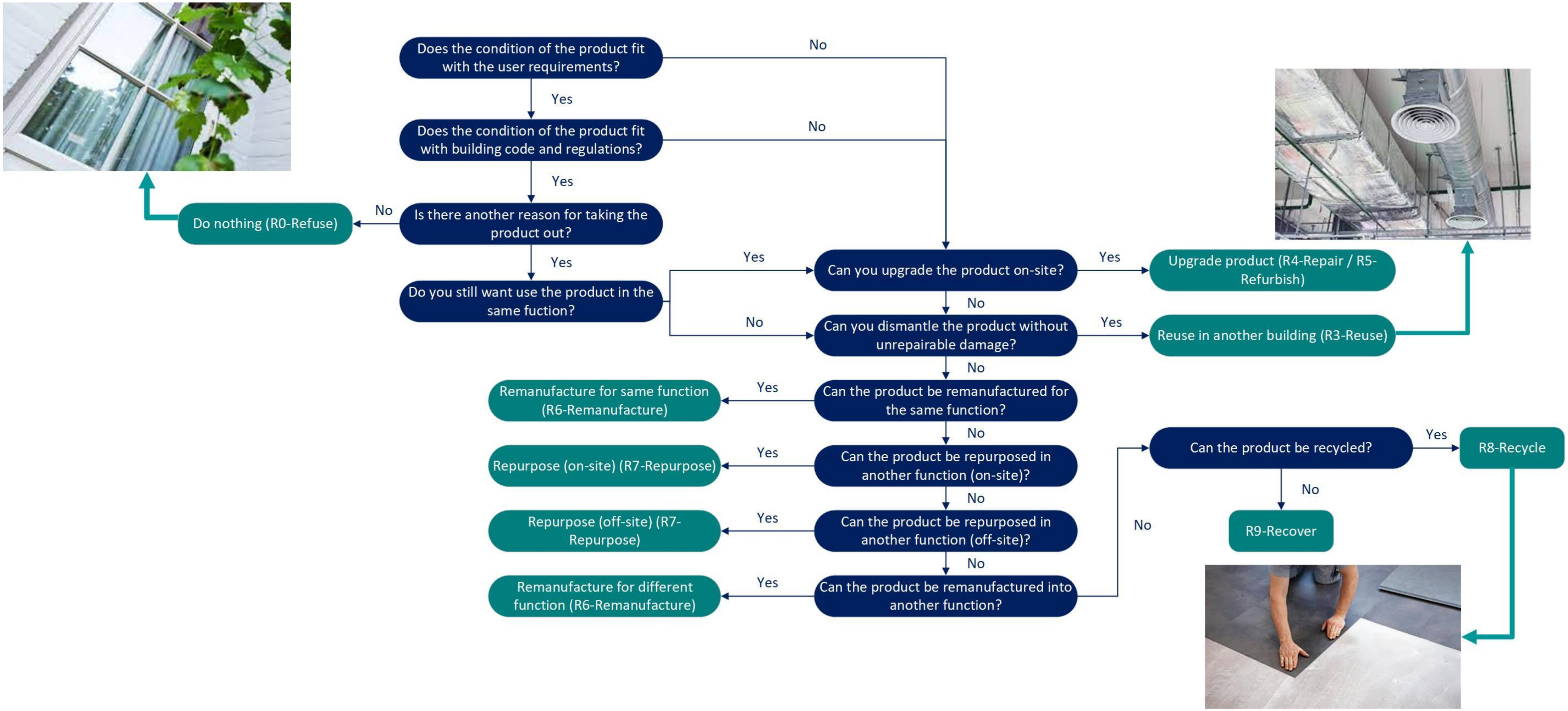


Figure 21: The outcomes of three building products when using the 3rd level decision-making framework

2.4. Comparison on building portfolio level

2.4.1. Step 8: Develop a building management plan

After an appropriate renovation scenario is chosen following the 2nd level decision-making model and End-of-life options are determined for building products, a future-oriented building management plan can be drawn up. This is based on the lifecycle assessments of building products from task 1.3. This task will develop methods for the automated detection of construction components and materials in buildings and provide different methods and algorithms for risk-based assessment and prediction of the lifetime of different components/products.

In this practical example, an overview is given of how the lifetime predictions from task 1.3 could be used to develop a future-oriented building management plan. In this hypothetical example two replacement scenarios are distinguished: scenario A in which the three building products from section 4.3. have a remaining lifetime of 5 years, and scenario B in which the products have a remaining lifetime of 3 years. The two scenarios give a good impression of how a building management plan can be dependent on the predicted lifecycle of products.

Scenario A

In scenario A the three building products: *double-glazed windows, ventilation system,* and *linoleum flooring*, have a hypothetical predicted remaining lifetime of 5 years, following the assessment of task 1.3. This means that after 5 years all three products need replacement. In the three different decision models, the condition of the building and building products are taken into account. However, following the predicted lifetime of building products from task 1.3, stakeholders might decide to go for a different renovation scenario, if they have a better understanding of when building products need replacement.

With the understanding that the building products need to be replaced after 5 years. The lifecycle of the building might look like this (Figure 22). In this graph, the building condition is portrayed by the green line, and the building requirements by the blue line. The building condition is sloping down as the building deteriorates over time, whereas the building requirements are sloping up, as the building users require more from a building following social and technical improvements over time. In this hypothetical example, the building conditions slowly fall below the building requirements, which indicates that an intervention is needed. However, because stakeholders know that critical building products only need replacement after 5 years, they might opt for a quick-fix renovation scenario (scenario 10), after 2 years, and a comprehensive scenario after 5 years (scenario 1). In this case, a cheap quick-fix renovation scenario could slightly bump the building conditions above the building requirements line, therefore extending the lifetime of the building. By knowing the predicted lifetime of building products stakeholders have a better understanding of when to pursue what scenario, thereby saving money and time.

Figure 22: Hypothetical lifecycle of scenario A

Scenario B

In scenario B the hypothetical predicted remaining lifetime is only 3 years. In this case, an intermediate scenario might be the best option for the stakeholders. Figure 23 gives a hypothetical lifecycle of the building under scenario B. In this scenario, stakeholders might not decide on a two-scenario approach, with a quick fix scenario after two years, and a comprehensive scenario after 5 years, but go for an intermediate option (scenario 8) after 3 years, when the building products reach the end of their lifetime. Knowing the predicted remaining lifetime of critical building products in this case causes stakeholders to go for a one-scenario approach, instead of a two-scenario approach.

Figure 23: Hypothetical lifecycle of scenario B

The two hypothetical examples give an overview of how the predicted lifetime of building products could alter the renovation decisions in the 2nd level decision-making framework. The knowledge on the predicted lifetime of building products in the 2nd level decision-making framework is mostly internalized through the pairwise comparison but is not explicitly taken into account through the outcomes of the model. The idea is that stakeholders who know the predicted lifetime of building products use this knowledge in weighting the objectives. In scenario A, for example, stakeholders might value the objective: 'Cost' more for the first intervention, knowing that in a second intervention, a more comprehensive and expensive scenario might be appropriate.

2.4.2. Lifetime prediction in the 1st and 3rd level decision-making frameworks

The lifetime predictions of building products is more explicitly taken into account, however, in the 1st and 3rd level decision-making frameworks. In the 1st level decision-making framework, the building condition is assessed on a building level. However, this could also be done by assessing the condition of separate building products and then aggregating this for the whole building. Because, *'condition'*, is an important aspect of the 1st level decision-making framework, knowing the predicted lifetime of building products could significantly influence the initial intervention direction. By knowing the lifetime predictions of building products, the overall condition of the building can be mapped over time (Figure 24), which makes it possible to track changes in the initial intervention directions. This makes it possible for stakeholders to know when what 1st intervention direction is appropriate and draft a building management plan accordingly.

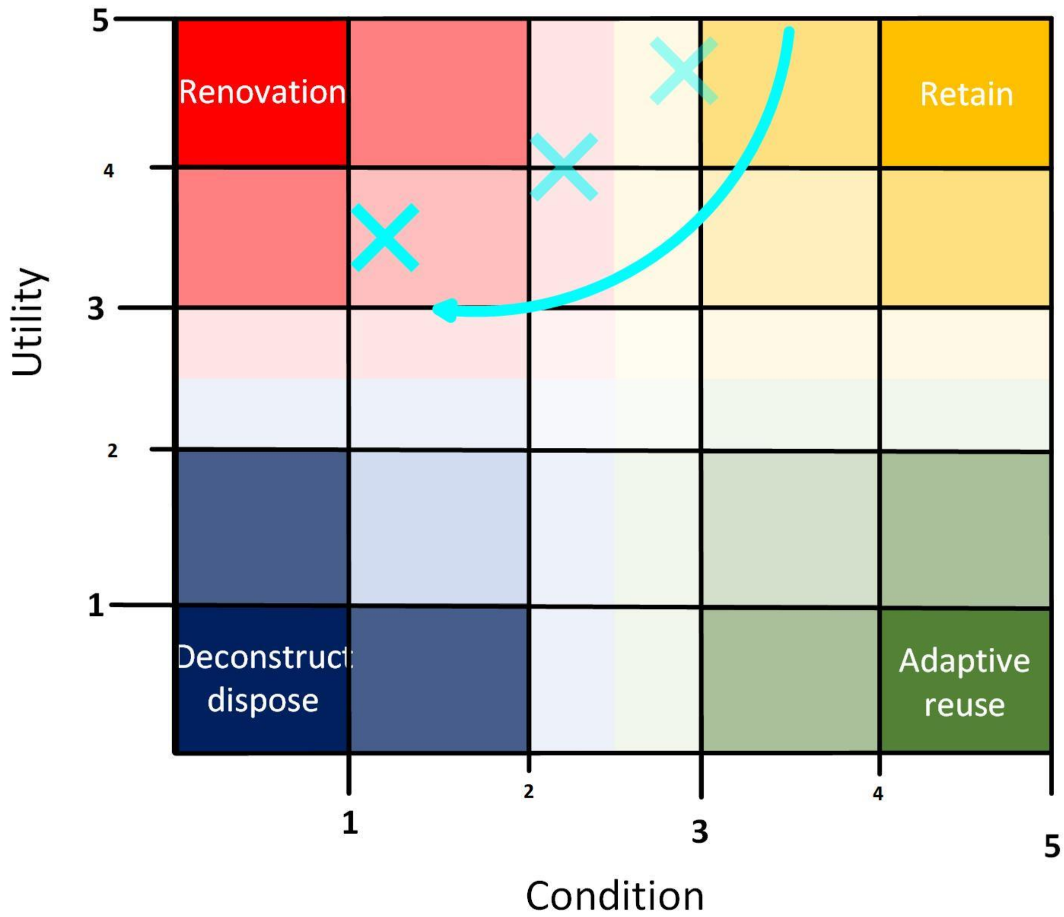


Figure 24: Building assessment mapped over time

For the 3rd level decision-making framework, the condition is also an important aspect for determining the most appropriate End-of-Life option. When knowing the predicted lifetime of building products, stakeholders can map the most appropriate End-of-Life options over time. A building product like the double-glazed window, might be fine for the first intervention in Scenario A, therefore ending up at the: “Do nothing” option, but needs to be replaced during the second intervention, and ends up at the “recycling” option after 5 years. By knowing the predicted lifetime of building products stakeholders can proactively plan the next life of these products, by for example getting in touch with potential buyers in a timely manner.

The lifetime predictions from task 1.3 can help stakeholders throughout the three decision-making levels, to map the most appropriate intervention decisions over time. This will not only provide stakeholders with the right tools to make a decision in the present but also allow for the continuous upgrade of buildings throughout their life-cycle.

2.4.3. Step 9: Determine the waste reduction potential

In order to determine the waste reduction potential of a renovation scenario, and compare different scenarios on a building portfolio level, two aspects need to be calculated: the functional lifetime years added through renovation, and the total amount of waste if the building is demolished. The functional lifetime years added are dependent on the renovation scenario and are determined based on the calculation tool: ‘specifieke levensduur gebouw’. For all scenarios it is assumed that the building is non-residential, 2000m^2, the type of structure is reinforced concrete, and the building is 50 years old. The total amount of waste if the building is demolished is dependent on the building and is the same for all scenarios. This number is calculated using the matrix in section 3.4.3. (Figure 10 and Equation 11). For this hypothetical example, 4 scenarios are compared: scenario 1, scenario 8, scenario 10, and a: baseline scenario, in which the building is demolished immediately. For simplicity, it is also assumed that for all scenarios the products that are taken out of the building are not reused/recycled. Therefore the waste reduction potential is dependent on the lifetime years added through renovation.

Total amount of waste if the building is demolished

The total amount of waste if the building is demolished is calculated by multiplying the average amount of waste per building structure by the surface area of the building in m². For this hypothetical example, the average amount of building demolition waste for a non-residential reinforced concrete building is between 742-1637 kg per m² (Figure 10). For this calculation the higher value of 1637kg is used for all scenarios. The total amount of waste if the building is demolished comes down to:

$$W_j = 1637kg \times \mathbf{2000}m^2 = \mathbf{3.274.000}\ kg \tag{15}$$

Functional lifetime years added through renovation

For all scenarios the functional lifetime years added through renovation is calculated using the tool: '*specifieke levensduur gebouw*' (Appendix 2). Table 18. shows for all scenarios the expected lifetime, and the lifetime years added through renovation:

Table 18: Expected lifetime and lifetime years added through renovation

	Expected lifetime	Lifetime years added through renovation
Scenario 1	85	35
Scenario 8	67	17
Scenario 10	56	6
Baseline scenario	50	0

Waste reduction potential

The percentage waste reduction is calculated against the baseline scenario using Equation 16. Table 19 shows the amount of building waste per functional lifetime year, as well as the percentage waste reduction in comparison with the baseline case. The results for this hypothetical example show that by comprehensively renovating a building based on renovation scenario 1, a waste reduction potential of 42 percent can be attained compared to demolition.

Table 19: The waste reduction potential of the three renovation scenarios

	Building waste per functional lifetime year	Waste reduction percentage compared to baseline scenario
Scenario 1	38.200 kg	42%
Scenario 8	48.866 kg	25%
Scenario 10	58.464 kg	11%
Baseline scenario	65.480 kg	0%

3. Integration with CPIM

At the centre of the Reincarnate project stands the CP-IM (Circular Potential – Information Management). In this software tool the ten innovations of the Reincarnate project come together trying to remove the bottlenecks in current practice with respect to collecting and tracing information about construction and demolition waste (CDW), avoiding CDW in the first place, and being able to reuse CDW in high product quality. In this paragraph the potential (data) integration of deliverable 2.2 into the CP-IM will be elaborated on. When it comes to the proposed decision-making framework for extending the use life of real estate assets, the three decision-making levels each have their own potential areas of data integration. For the potential data integration for the 1st and 3rd level decision-making frameworks we refer to deliverable 3.1. The potential data integration for the 2nd level decision-making framework is provided below.

3.1. 2nd level decision-making framework

When it comes to the data integration possibilities for the 2nd level decision-making framework, a potential for further enhancement of the decision-making framework can be observed. The current decision on the most appropriate renovation scenario is based on fuzzy logic. For all scenarios descriptors three different potential variants are created that describe the possible future directions of the descriptor. These variants are qualitatively described, which makes them suitable for a fuzzy decision-making model like the Fuzzy TOPSIS model. To arrive at the most appropriate scenario, only the preferences of the stakeholders are needed through pairwise comparison as well as the fuzzy number ranges for the variants, which leaves little room for data integration. However, although not included in this deliverable, there is a possibility to extensively quantify the scenario based on actual performance, instead of qualitative variants. For this a regular TOPSIS model could be used that ranks the scenarios based on actual data (An example of this model can be found in the BIMSpeed project deliverable 7.1). If this potential avenue for further enhancement of the model is followed, existing data from the RE – Suite software can be extracted for integration into the model. Table 20 shows the criteria for the 2nd level decision-making model and the potential for data extraction from the RE-Suite software:

Table 20: Data integration possibilities 2nd level decision-making framework

Criteria	Data available in RE-SUITE	Data placeholder in place	Data not available
Renewable energy	X		
Operational primary energy demand	X		
Total energy demand	X		
Energy savings	X		
Global warming potential	X		
Embodied global warming potential		X	
Total water consumption		X	
Visual comfort	X		
Acoustic comfort	X		
Indoor air quality	X		
Thermal comfort	X		
Accesibility			X
Aesthetic			X
Social repuation			X
Renovation time	X		
Covered scope	X		
Investment cost		X	
Payback period		X	
LCC Cost		X	
Rent increment	X		
Maintenance cost	X		
Operational energy cost	X		
Fuel poverty			X
Financial incentives			X
Property value increment	X		

4. Implementation on the Reincarnate demonstration projects

The decision-making framework outlined in this report will be implemented to support the selection of the most appropriate intervention scenario in selected Reincarnate demonstration sites. Table.. presents the characterization of four dedicated demonstration cases in which the innovation: strategic circular decision-making for real estate assets, will be implemented. For the selection of the demonstration cases for this innovation, the four quadrants of the 1st level decision-making framework were taken: Retain, Adaptive Reuse, Renovation, and Deconstruction. For the *Retain* demonstration example, only the 1st level decision-making framework will be demonstrated, for the *Deconstruct* demonstration example, the 1st and 3rd level decision-making frameworks will be demonstrated, and for the *Renovation* and *Adaptive Reuse* demonstration examples, the whole decision-making framework will be demonstrated. All four demonstration cases intend to involve relevant stakeholders in the decision-making process such as architects, building owners, building users, and facility managers to develop scenarios and go through the decision-making frameworks.

Table 21: Reincarnate demonstration case characterization for innovation 7

Demonstration case	Location	Demonstration case owner/contact partner	Intended demonstration
3L Office Building (Retain)	Menden (Germany)	3L	1st level decision-making framework
Apartment Building Paris Habitat (Renovation)	Paris (France)	Paris Habitat	The whole decision-making framework inc. scenario development
Kathreiner Haus (Adaptive Reuse)	Berlin (Germany)	TUB	The whole decision-making framework inc. scenario development
Lagemaat building (Deconstuction)	The Netherlands	Lagemaat	1st and 3rd level decision-making frameworks

5. Conclusion

This report outlines a comprehensive circular decision-making framework aimed at extending the use life of real estate assets. The framework integrates theoretical concepts with a practical implementation example to assist stakeholders in making well-informed decisions regarding the future utilization of buildings. By offering a systematic approach across three decision-making levels, the framework enables asset managers and building owners to explore and implement suitable renovation scenarios.

The initial level of decision-making provides a framework for determining the first intervention direction based on the current status of a building. This assists stakeholders in understanding how to upgrade buildings to meet changing requirements within a real estate portfolio. The second level focuses on developing and selecting between various renovation scenarios, showcasing possibilities for repurposing real estate spaces. The third level introduces a product-specific decision-making model that identifies new reuse purposes for building products systematically.

Following the selection of a renovation scenario and determining end-of-life options for building products, the report presents a future-oriented building management plan methodology. This methodology supports continuous upgrades throughout the building's lifecycle based on predictive lifecycle information. Additionally, the report includes a methodology for assessing waste reduction potential by extending the functional life of buildings.

This report aims to support stakeholders by offering a stepwise process guideline, ensuring that the interventions are not only appropriate and effective but also aligned with circular economy principles. The comprehensive framework presented enables informed decision-making, promoting the extensions of the use life of buildings, and ultimately contributing to reducing construction and demolition waste.

Future empirical testing will provide essential data to validate and refine these methodologies. The planned demonstration projects will be pivotal in showcasing the practical application and benefits of this framework in a real-world context. By promoting a circular economy approach within the construction industry, this initiative aims to significantly reduce construction and demolition waste, extend the lifecycle of buildings, and encourage sustainable building practices.

6. References

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7. Appendix

7.1. The first-level decision-making assessment worksheet [12]

7.2. Lifecycle assessment tool: ‘specifieke levensduur gebouw[12]

7.3. Detailed description for the default renovation scenarios[12]

7.4. Default renovation scenarios for the Scenario Wizard software[12]

[12] https://github.com/BrianvLaar98/Reincarnate-Deliverable-2.2